APPLICATION PROBLEMS OF THE PROBABILISTIC APPROACH TO THE ASSESSMENT OF RISK FOR STRUCTURES AND SERVICES

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Abstract: The paper deals with the development of the probabilistic approach to the assessment of risk due to lightning. Sources of damage, types of damage and types of loss are defined and, accordingly, the procedure for risk analysis and the way of assessment of different risk components is proposed. The way to evaluate the influence of different protection measures (lightning protection system; shielding of structure, cables and equipment; routing of internal wiring; surge protective device) in reducing such probabilities is considered. The paper has been prepared within the framework of the activity of IEC TC81-WG9/CLC TC81-WG4 directed to prepare the draft IEC 62305-2 Risk Management, in cooperation with the Secretary of IEC/CLC TC81.

Keywords: lightning protection system, risk assessment, protection measures

1. INTRODUCTION

Lightning is a natural random event that affects structures and power and communication systems, electrical and electronic systems. Effects of lightning flashes on structures and systems depend on the characteristics of: lightning current, of protected structures and systems as well as on protection measures.

Lightning affecting a structure can cause damage to the structure itself and to its occupants and its contents, including failure of equipment and especially of electrical and electronic systems. The damages and failures may also extend to the surroundings of the structure and may even involve the local environment. The scale of this extension depends on the characteristics of the structure and its equipment. Consequential effects of the damages and failures - loss - may be extended to the surroundings of the structure or may involve its environment. To reduce the loss protection measures may be required. Whether they are needed and to which extent should be determined by risk assessment.

The risk, defined in [3] as a probable average annual loss in a structure due to lightning flashes, depends on:

- the annual number of lightning flashes influencing the structure,
- the probability of damage by one of the influencing lightning flashes,
- the mean amount of consequential loss.

Aim of this paper is to give scientific background and essential assumptions to be introduced for practical assessment of the risk due to lightning and for evaluation of the number of dangerous events, the probabilities of different damages and the amount of consequential loss. The way to evaluate the influence of different protection measures, namely: lightning protection system (LPS); shielding of structure, cables and equipment; routing of internal wiring; surge protective device (SPD), in reducing such probabilities is considered.

2. LIGHTNING DATA FOR THE PROTECTION PURPOSES

Lightning flashes influencing the structure may be divided into the:
direct flashes to the structure,
indirect flashes to the structure, namely to the ground surface near the structure and/or near the incoming lines and services and/or to the incoming lines (mains, telecommunication and data lines) or other services.

Direct flashes striking the structure or incoming lines may cause physical damages and life hazards. Indirect flashes as well as direct flashes may cause failures of electrical and electronic equipment due to overvoltages resulting from resistive and inductive coupling of this equipment with the lightning current.

Lightning protection concept is based on actual lightning data measured over years in observation stations. Such data give a continuously distributed probability function for each lightning current parameter as reported in the CIGRE [1,2] in the shape of logarithmic normal distributions. The lightning parameters include waveforms, amplitudes and frequency of occurrences. Values of flash density (number of flashes to ground per km^2 and per year) are available starting from maps of annual thunderstorm days of the regions under consideration and, more recently, from lightning location systems (LLS).

For engineering purposes (design of lightning protection measures and definition of test parameters) fixed nominal data are required. Four protection levels (I to IV) are defined. For each protection level a set of maximum and minimum lightning current parameters is fixed. The maximum values define the lightning threat (current and field) for lightning protection components and for the equipment to be protected. They are used to design e.g. cross sections of conductors, characteristics of SPDs, separation distances against dangerous sparking, mitigation of magnetic field effects and to define test parameters simulating the effects of lightning on such components and equipment. The minimum values define the interception efficiency of LPS. They are used together with the related rolling sphere radius for positioning of air terminations and to define areas protected against direct lightning strikes.

3. HISTORICAL APPROACH IN IEC 61024

In IEC 61024 only the design and installation of LPS, intended to protect structures and contents against direct lightning flashes, are considered. Shock of living beings and physical damages are only taken into account.

In IEC 61024 four types of lightning protection systems LPS (I to IV) were distinguished according to the four protection levels: I to IV. Despite the LPS types are not strongly correlated to the protection levels (see paragraph 2), they were reciprocally equated and named "protection level". No evaluation of the residual risk of damage for the LPS types was given. As a simplified first approach, it was assumed instead, that every lightning flash, exceeding the lower or upper limits defined in the corresponding protection level, will cause damage. Based on this, an "efficiency" E was defined to show the percentage of all possible flashes, which can be controlled by the LPS without damage. IEC 61024 originally provided only predefined protection bundles LPS type I to IV as protection measures. Therefore it was sufficient to give a selection procedure to determine the required LPS type I to IV without considering the residual risk after installation. IEC 61024-1-1 (Guide A) gave such a procedure taking into account the local ground flash density N_g, the type of the structure, consequent damages etc. resulting in an accepted frequency of lightning flashes N_c, which cause damages. Comparing this value with the expected frequency of direct flashes to the structure N_d the "required efficiency" $E = 1 - N_c/N_d$ was used to select the required LPS type I to IV.

4. NEW GENERAL IEC 62305 APPROACH

Lightning flashes direct and nearby to structures, and direct and nearby to services are considered as sources of damage.

The following damages are considered: shock of living beings, physical damage, failure of electrical and electronic systems. As consequence of these damages loss of human life, loss of service to the public, loss of cultural heritage and loss of economic values may arise.

The protection design should consider the protection of structures and their contents, the electrical and electronic systems as well as the services in order to reduce the risk due to lightning to a tolerable level.

Among different protection measures, the following are considered in the IEC 62305 standard documents:

- **LPS** to intercept, conduct and disperse the lightning current into the earth; bonding measures to minimise potential differences and to limit surges using a meshed bonding network and bonding all metal parts or conductive services directly or by suitable surge protective devices (SPDs) are included in internal LPS;
- **SPD** at the point of entry of incoming services reduces essentially the risk related to the overvoltages by resistive coupling due to direct flashes to the structure and/or the overvoltages transmitted through the lines;
- **SPD** at the point of entry of equipment reduces essentially the risk related to the overvoltages by inductive coupling due to direct and/or nearby
- **spatial shielding** to reduce the impulsive magnetic field due to lightning current from direct or nearby lightning flashes; total or partial shielding of the structure and/or of the internal circuits by using shielded cables or cable ducts are effective measures to mitigate the penetration of magnetic field;
- **line routing** and shielding to minimise voltages and currents induced into electrical and electronic system using minimised loop area by adjacent routing of electrical and signal lines.

Other protection measures able to reduce the probability of damage are the following:

- increasing of the surface resistivity of the soil around the structure,
- increasing of the surface resistivity of internal floors,
- increasing of the impulse withstand voltage level of equipment,
- screening of the incoming lines.

Other protection measures able to limit the amount of damage are:

- extinguishers,
- hydrants,
- fire alarm installations
- fire extinguishing installations
- fire-proof compartments
- protected escape routes to provide protection for personnel.

Protection measure to avoid contact with external dangerous parts:

- barriers,
- warning notices.

The designer has the possibility to select a wide range of protection measures, which can be also combined to different complex solutions in relation to the peculiarity of the structure and its content, of the internal and external systems : e.g. using a very effective spatial shield of lightning protection zone 1 (LPZ1) may not require line routing and shielding measures inside or vice versa.

It should be noted that inherent installation rules ought to be observed (e.g. LPS type I to IV or any LPZ mandatory requires bonding of incoming services).

To find the optimum combination of protection measures it is necessary to validate each separate protection measure as well as the resulting combination of several protection measures.

IEC 62305-2 gives a risk management method to be used to ascertain the need of protection, to select optimal combination of protection measures and finally to check the residual risk after the installation of the complete protection system. This method is based on a probabilistic approach to assess the risk and to evaluate the effect of different protection measures to mitigate such risk. This approach is based on statistical distributions of different lightning parameters and of different consequential effects (thermal, electromagnetic, etc.) responsible for the damage.

The lightning protection zone (LPZ) concept is used for the risk analysis: either in the simplified method (object to be protected identical to LPZ 1) or in the detailed method (object to be protected subdivided into several LPZs). Performing a separate risk analysis for each relevant LPZ allows a tailored solution with optimum protection at minimum cost.

5. RISK ANALYSIS

The risk analysis has to ascertain for each relevant type of loss that the risk is lower than its tolerable value.

The risk R can be calculated as a sum of its components R_x

$$\mathbf{R = \sum R_x} \tag{1}$$

Each component, caused by different flashes and being relevant to a kind of damage, may be calculated by the following relation

$$\mathbf{R_x = N_x\, P_x\, D_x} \tag{2}$$

where:

$\mathbf{N_x}$ is the annual number of flashes,
$\mathbf{P_x}$ is the resulting probability of damage,
$\mathbf{D_x}$ is the relative amount of consequential loss.

Each risk component $\mathbf{R_x}$ depends on the point of lightning strike. Four cases of lightning flashes allow to distinguish the components generated as follows:

- Lightning flashes striking directly the structure may generate:
  - component $\mathbf{R_A}$ related to touch and step voltages in the areas up to 3 m outside the structure [3] (the risk inside the structure, in such case, being assumed negligible);
  - component $\mathbf{R_B}$ related to physical damage caused by dangerous sparking triggering fire or explosion inside the structure, which may endanger also the environment;
  - component $\mathbf{R_C}$ related to failure of electrical and electronic systems caused by overvoltages via resistive or inductive coupling.
- Lightning flashes striking the ground near the structure may generate:
  - component $\mathbf{R_M}$ related to failure of electrical and electronic systems caused by overvoltages induced by the lightning current on internal installations.
- Lightning flashes striking directly a service incoming to the structure may generate:
  - component $\mathbf{R_U}$ related to touch voltage inside the structure due to the injected lightning current in an incoming line;
  - component $\mathbf{R_V}$ related to physical damage ~~-~~ (fire or explosion) triggered by sparking between external installation and metallic parts generally at the entry point of the service into the structure;
  - component $\mathbf{R_W}$ related to failure of electrical and electronic systems caused by overvoltages due to lightning current on incoming service.
- Lightning flashes striking the ground near an incoming line may generate:
  - component $\mathbf{R_Z}$ related to failure of electrical and electronic systems caused by overvoltages induced on incoming lines.

For each type of loss, the total value of **R** may be subdivided with reference to:

a) the type of lightning flash:

$$\mathbf{R = R_D + R_I} \tag{3}$$

with components due to direct flashes to the structure

$$\mathbf{R_D = R_A + R_B + R_C} \tag{4}$$

and components due to indirect flashes to the structure

$$\mathbf{R_I = R_M + R_U + R_V + R_W + R_Z} \tag{5}$$

(It should be noted that formula (4) is valid at assumption that the product of relevant risk components due to direct flashes to the structure is negligible in comparison with the sum);

b) the types of damage **:**

$$\mathbf{R = R_S + R_F + R_O} \tag{6}$$

with components due to shock of living beings

$$\mathbf{R_S = R_A + R_U} \tag{7}$$

components due to physical damages

$$\mathbf{R_F = R_B + R_V} \tag{8}$$

and components due to the failure of electrical and electronic systems caused by overvoltages

$$\mathbf{R_O = R_M + R_C + R_W + R_Z} \tag{9}$$

6. ASSESSMENT OF RISK COMPONENTS

6.1. Involved parameters

In the assessment of risk components several parameters are involved, relevant to:

a) the number of dangerous events $\mathbf{N_x}$, affected by:
- lightning ground flash density,
- dimensions of the structure and the characteristics of surroundings,
- characteristics of incoming services;

b) the probability of damage $\mathbf{P_x}$, affected by:
- characteristics of the structure,

- characteristics of soil surface inside and outside the structure,
- content of the structure,
- characteristics of internal installations,
- characteristics of incoming services,
- protection measures provided;

c) the consequent damage $\mathbf{D_x}$, affected by:
- use to which the structure is assigned,
- number and attendance time of persons in the structure,
- type of service provided to public,
- value of goods affected by damage,
- measures provided to limit the amount of damage,
- factors increasing the amount of damage due to special hazard (e.g. panic, contamination, etc..)

6.2. Assessment of annual number N_x of dangerous events

The annual number $\mathbf{N_x}$ of lightning flashes influencing the structure and its content with the incoming lines depends on the thunderstorm activity of the region where the structure and the incoming lines are placed and on the characteristics of the structure and of the lines. It is generally accepted to evaluate the number $\mathbf{N_x}$ by the product of the lightning ground flash density $\mathbf{N_g}$ and an equivalent collection area $\mathbf{A_x}$ of the structure or of the line.

Application of mathematical and physical models [4] allows to introduce simplified formula, generally validated by field data [5-7], which allow to calculate such equivalent area in different conditions:

- structure isolated or surrounded by objects, in territories with different topography;
- overhead line or underground cable influenced by direct or nearby flashes.

In Table 1 the formula proposed in [3] are reported with reference to the overhead and underground buried cables influenced by direct and nearby flashes.

Table 1 – Collection areas of overhead and underground cables relevant to direct (A_l) and nearby flashes (A_i)

	Overhead line	Underground cable
A_l	$(L - 3(H+ H_a))\cdot 6\ H_c$	$(L - 3(H + Ha)) \cdot 0{,}4\sqrt{\rho}$
A_i	$L \cdot 100\sqrt{\rho}$	$L \cdot 50\sqrt{\rho}$

with

H_c = height (m) of the line conductors above ground ;
ρ = resistivity (Ωm) of the ground in which the cable is buried ;
L = lenght (m) of the line from the structure to the first distribution node or the first point where SPD are installed on the line, with a maximum value of 1000 m;
H = height (m) of the structure ;
H_a = height (m) of the adjacent structure .
In formula of Table 1 if the value of L is unknown, L = 1000 m is to be assumed; for lines running entirely within a highly meshed earth termination, ρ = 0 may be assumed

In this way it is possible to calculate the number of lightning flashes striking directly the structure, the earth in the vicinity of the structure and influencing the internal systems by resistive and inductive coupling, the incoming lines and the earth near the incoming lines.

6.3. Assessment of resulting probability P_x

- The resulting probability $\mathbf{P_x}$ shall range from 1 (no protection) to 1> $\mathbf{P_x}$ >0 to 0 (not relevant or theoretically 100% protected).
- The probablity of damage is always the result of correlation between the stress (e.g. an overvoltage), given by its statistical distribution density function, with the value of withstand (e.g. withstand level of insulation), given by the cumulative probability distribution. The basic protection measures tend to limit the level of stresses and then the probability of damage.
- Each resulting probability $\mathbf{P_x}$ depends on one ore more protection measures and may be expressed:
  - by a product of probability in the case of damage resulting from two events in series; this is the case of probability of fire, which is the result of probability p_1 of appearing an overvoltage triggering a spark and the probability p_2 that this spark could initiate a fire, namely:

$$\mathbf{P_x} = p_1\ p_2$$

  - or by the following expression

$$\mathbf{P_x} = 1 - (1 - p_1)\ (1 - p_2)$$

in the case of damage resulting from one of two parallel events at one strike, e.g. failure of electronic system which may be caused by an overvolvoltage due to resistive coupling or to inductive coupling, at the same lightning strike to the structure; in this case - as it is shown - the probability of failure of the system is a parallel combination of probability p_1 of appearing a dangerous overvolvoltage by resistive coupling and probability p_2 of appearing an overvoltage by inductive coupling.

- Formulas and tables are given in IEC 62305-2 for each resulting probability $\mathbf{P_x}$ either as direct function of design data of the protection measure or as function of factors **K** directly related to the protection measure features. This is the case of protection measures enabling to reduce the level of the overvoltages such as e.g. screening of the structure and of its room, screening of wirings, circuits routing [8,9]. In such way the formulas and tables allow to evaluate the effect of any combination of separate protection measures on the reduction of the probability of damage. In other words: each relevant separate protection measure is represented and the effect on the reduction of the resulting probability $\mathbf{P_x}$ is evaluated.

- The input data required to determine $\mathbf{P_x}$ are the design data of each separate protection measure (e.g. cross section of conductors, mesh width, characteristics of SPD) and design data of the object to be protected (e.g. structure and equipment).
- The output data for $\mathbf{P_x}$ evaluation come from an expert system: first approach can only be estimations by using approximate relations (e.g. magnetic field attenuation by grid like spatial shield with different mesh width). Therefore only rounded values, preferably in logarithmic scales (1 - 0,5 - 0,2 - 0,1 or 1 - 10^{-1} - 10^{-2} - 10^{-3}), should be used. These values may be amended later taking into account the experience of users of the risk standard IEC 62305-2 (e.g. insurance statistics).

6.4. Relative damage $\mathbf{D_x}$

The consequent damage due to lightning strikes is given in relative values: $\mathbf{D_x}$ = 1 means the total loss of the object to be protected within one year. For each type of loss the relevant values of $\mathbf{D_x}$ are given in IEC 62305-2:

- The input data required to determine $\mathbf{D_x}$ are: expected amount of annual loss in front of the total value of good (people, public service, cultural heritage, economic values) relevant to the structure (e.g. number of persons, the time of danger, the value of goods in currency); **Reducing factors** due to protection measures (e.g. fire protection, alarm systems); **Increasing factors** due to special hazard (e.g. panic, immobilised persons, contamination or hazard to surroundings or environment).
- The output data $\mathbf{D_x}$ come from an expert system: first approach can only be rough estimations from the experts. Therefore only rounded values, preferably in logarithmic scales (1-0,5-0,2-0,1 or 1 – 10^{-1} - 10^{-2} - 10^{-3}), should be used. These values may be amended later taking into account the experience of users of the risk standard IEC 62305-2 (e.g. insurance statistics).

7. RISK MANAGEMENT FOR STRUCTURES AS IN IEC 62305-3 AND IEC 62305–4

The object to be protected is a structure with content inside, persons inside and outside (IEC 62305-3) and electrical and electronic systems inside (IEC 62305-4). Incoming services are not considered as object to be protected, but only as source of danger for the structure (injected surges). The risk analysis therefore has to consider:

annual number of flashes relevant to structure:
direct: $\mathbf{N_1}$ **-** direct flashes to structure,
indirect: $\mathbf{N_2}$ - flashes nearby to structure,
indirect: $\mathbf{N_3}$ **-** direct flashes to service,
indirect: $\mathbf{N_4}$ – flashes nearby to service;
resulting probability of damage:
protection measures and conditions relevant for a structure (with content inside, persons inside and outside and electrical and electronic systems inside) are to consider;
relative damage:
possible damages, reducing and increasing factors relevant for a structure (with content inside, persons inside and outside and electrical and electronic systems inside) are to consider.

8. RISK MANAGEMENT FOR SERVICES AS IN IEC 62305-5

The object to be protected is a service (IEC 62305-5) like telecommunication lines, power lines or pipelines. Structures connected to the service are not considered as object to be protected, but only as source of danger for the service (injected surges). The risk analysis therefore has to consider:

annual number of flashes relevant to service:
direct: $\mathbf{N_3}$ - direct flashes to service,
indirect: $\mathbf{N_4}$ - flashes nearby to service,
indirect: $\mathbf{N_1}$ **-** direct flashes to structure;

resulting probability of damage:
protection measures and conditions relevant for a service are to consider;
relative damage:
possible damages, reducing and increasing factors relevant for a service are to consider.

9. CRITERIA OF PROTECTION

The criteria of protection of structures against physical damages and life hazard are finalized to:

- intercept, conduct and disperse the lightning current into the earth by LPS; bonding measures to minimise potential differences and to limit surges using a meshed bonding network and bonding all metal parts or conductive services directly or by suitable surge protective devices (SPDs) are included in internal LPS;
- avoid dangerous step and touch voltage in the area up to 3 m outside the structure by increasing the contact resistance (related to the surface resistivity of the soil) or by electrical insulation of exposed conductor or by physical restrictions or warning notices, where necessary.

The criteria of protection of electrical and electronic systems within the structure are directed to:

- limit overvoltages between the services incoming the structure and the earth termination system of the structure. **Protection measures**: shielding of incoming lines, equipotential bonding at the entry point direct or via SPD.

- limit potential differences between apparatus connected to the same earth termination system. **Protection measures**: bonding network, circuit screening, SPD;
- limit overvoltages induced on internal circuits by lightning current. **Protection measures**: circuit shielding, rooms shielding, internal wiring routing, SPD;
- limit overvoltages transmitted from the services incoming the structure. **Protection measures**: underground shield cables, SPD, special devices (transformers, and filters, optoelectronic decouplers, only for telecom or signal lines).

To be effective each protection measure should be dimensioned and installed according to the relevant rules and should satisfy the general condition to be suitable for the place of its installation: it means that the measure should withstand the stress expected in the place of its installation.

In particular, protection measures between protection zone 0 and zone 1 (SPD, conductors of grid like spatial shield) in order to be effective, should be dimensioned to withstand the expected direct lightning currents in this place.

It follows that SPD of class I test could be installed, without restrictions, in the environments exposed to direct lightning current, while SPDs of class II or III test may be installed only in the zone protected against direct flashes [8,9].

The coordination of SPD should enable to avoid the overstress of SPD and to ensure protection level compatible with the the impulse withstand level of equipment to be protected. Details on the coordination and the correct installations of SPD are reported in [8-13].

10. FINAL STATEMENTS AND CONCLUSION

- The former IEC 61024 provided protection for structures and contents only. Only bundled protection measures by predefined LPS type I to IV, each defined by a set of construction rules, were used. Therefore it was sufficient to have a selection procedure for the required LPS type as given in IEC 61024-1-1.
- The new IEC 62305 provides protection for structures and contents, electrical and electronic systems and for services. A wide range of separate protection measures can be used: in IEC 62305-3 e.g. the LPS type I to IV, upgraded LPS by integrating natural components, protection against touch and step voltage and in IEC 62305-4 e.g. spatial shielding, line routing and shielding, bonding network, bonding at each LPZ entry direct or by suitable SPDs, cascaded LPZs. All these separate protection measures can be combined arbitrarily to complex solutions.
- To reach tailored protection systems (optimum protection at minimum cost) the object to be protected can be subdivided into several lightning protection zones (LPZ). The risk management method in IEC 62305-2 is used to find the need of protection, to select optimised protection measures and to check the residual risk after the installation of the final lightning protection system.

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