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RISK EVALUATION IN LIGHTNING AND OVERVOLTAGE PROTECTION

Dénes TATÁR

Department of High Voltage Engineering and Equipment
Budapest University of Technology and Economics
H–1521 Budapest, Hungary
E-mail: tatar@mail.matav.hu

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Abstract

With the development of electronics several tendencies whose joint emergence redoubles the significance of damages to electronic parts is visible simultaneously today. The complexity of systems of electronic devices is increasing continuously, and there are large arborescent networks that allow various electromagnetic effects threatening to harm the equipment to spread easily, while society is more and more dependent on the operation of complicated systems.

The present paper summarises and classifies the electromagnetic phenomena representing actual danger to electronic equipment. By extending the idea of 'strokeless period', which is widely used in lightning protection, a general mathematical method is introduced for defining the probability of damage. This method will then serve as a basis for a concept for overvoltage protection and it will allow to make decisions on the necessity and economic efficiency of protection. It presents a detailed calculation for the probability of the occurrence of overvoltage waves entering buildings through electric conduction as a result of a stroke of lightning, which is one of the most uncomfortable effects coming from our environment.

Keywords: electromagnetic phenomena, overvoltage protection.

1. Introduction

Historians are already talking about the third industrial revolution nowadays. Although we have barely realised it, information society has been born. The channels that forward information at a speed surpassing every previous anticipation and prediction permeate our life and existence. The indispensable means of transferring information are electronic devices that transform physical signals and phenomena forwarded in networks into data, which they usually process as well.

Since the operation of electronic equipment is based on electricity, the electromagnetic effects disturbing their operation deserve particular attention. In practice such electromagnetic noises may be caused by natural phenomena, but they may also be created by other electric devices and equipment. Information systems usually communicate through networks consisting of electrically conductive materials, and their communication takes place by electric signals. Along with the electric signals noises always occur in the networks as well, and they spread just as easily as data. This is the way how electromagnetic phenomena that stand out both in importance and frequency of occurrence from among physical disturbing effects get to the devices connected to the network. Network elements and equipment are made up of electronic circuits, which due to industrial development, and better and better micro-electronic solutions are getting smaller and smaller, their sizes are decreasing rapidly. In proportion with the decrease in size the sensitivity of parts is increasing and the amount of energy that is capable of causing harm to their electronic systems is getting smaller. The dangerous amount of energy appears in the form of voltage pulses in the network. Usually these effects are called overvoltage, and their temporal progress depends on the mechanisms that have caused them. Although dangerousness also depends on the parameters of the form of the wave, in practice such voltage waves are characterised by their peak values [11]. Therefore, the tolerance of parts is also indicated by a so-called critical voltage, which is the peak value of the voltage wave whose occurrence the electronic equipment is able to endure without any damage.

2. The Origins of Overvoltages

2.1. Model for the Analysis

For a general analysis a model is needed, that is found in many places in practice and is made up of electronic elements connected to a communications network, and at the same time it can serve as a good model for dangers threatening other similar systems. A building management system encompasses the various networks in a building such as building management, telephone, computer systems etc., and in an ideal case it operates all these together ('intelligent building') as well. On the other hand it bears a great responsibility, because it has to guarantee safe operation as well as the safety of people, possession and information in the building. The electronic devices that are connected to communication networks and face the greatest danger by overvoltages usually operate in different buildings. For such a model building management systems have been selected.

2.2. The Most Common Sources of Overvoltages

Now let us have a closer look at the physical processes that represent such dangers to systems. Overvoltages are created as a result of the following events:

- Switching taking place in electricity supply systems (SEMP – Switching Electromagnetic Pulse)
- Electromagnetic effects of nuclear explosions (NEMP – Nuclear Electromagnetic Pulse)
- Electrostatic discharges (ESD Electrostatic Discharge)
- Direct stroke of lightning and/or its secondary effects (LEMP – Lightning Electromagnetic Pulse) [9].

It is true for each of the processes listed above that under certain circumstances they might damage electronic parts. The purpose of protection against overvoltages is to protect equipment against effects resulting from these physical mechanisms. However, protection always costs money, so during planning it is very important to map the risks as well as to carry out cost-benefit analyses for protection. In other words, it is not worth spending more money on the protection of a device than the amount we would have to pay for the reparations of the damage caused by failures. On the one hand, during protection planning one must be aware of what they want to protect, i.e. all the costs that might incur need to be surveyed. Calculating the expenses the costs of discontinuation of services and any loss of information need to be considered in addition to the costs of reparation or replacement of the equipment. On the other hand, it has to be surveyed how often each of the physical processes causing damage occur and in what percentage of these occurrences damaging effects are to be expected.

2.3. Coupling Mechanisms

The term coupling mechanisms refers to those electromagnetic phenomena, channels, which take overvoltages from the originating physical event to the devices that suffer damage. Coupling mechanisms have three types:

- Conductive coupling
- Inductive coupling
- Capacitive coupling

In the case of conductive coupling the overvoltage wave occurs in the form of voltage difference in an electrically conductive network, and from there it travels by electric wires to the elements of the building management system. The most typical example for conductive coupling is switching overvoltage. The pulse is created directly in the electricity supply network, in which it also spreads, so it reaches every connected device [7, 10].

Electromagnetic fields generated as a result of physical processes (in practice mostly strokes of lightning, but they might be nuclear explosions or switching mechanisms as well) induce voltage in conductors and loops while spreading in space. It is, unfortunately, also true for the conductors and loops of the network of a building management system. Pulse is created directly in the protected networks before the devices to be protected [2, 3].

In the case of capacitive coupling voltage pulses are created through diffuse capacitance between conductors and other metallic objects under high voltage. The most common example for this phenomenon is when lightning striking into the primary lightning protection system of a building produces high voltage in the lightning rod. As a result of the diffuse capacitance between the lightning rod and other electrically conductive parts of the network voltage pulses are created in the conductors as well [1].

2.4. Calculating Risks

For every physical process due to which overvoltages affect electronic systems a probability value can be defined. This parameter informs about the probability of the given event taking place within a certain period of time. For example, according to the statistics of electricity supply companies, it can be determined how many switching mechanisms are carried out in a given part of the energy supply network in a year on the average. Of course, it is not certain either that in each case the consequences are so serious that they may cause damages, i.e. as in the previous example a voltage pulse is created that damages an electronic device. It has to be established what percentage of the events resulting in overvoltages is able to cause dangerous pulses. In order to do so one needs to know exactly the route through which overvoltages travel from the place of the event causing overvoltage to the device that suffers damage. This route, or it could rather be called a process, is called a coupling mechanism.

Of course, appliances are not damaged as a result of every event of overvoltage, but waves whose peak values reach the critical voltage value characteristic of the given device represent potential danger. The objective of the analyses is to determine the probability of reaching the critical voltage. Harmonising all these, the probability can be established that describes the damaging effect of a given physical process:

$$P = P_A * P_B * P_C \,, \tag{1}$$

where P_A is the probability of the occurrence of the physical process that causes overvoltages, P_B refers to the probability that the coupling mechanism is able to forward the voltage wave to the equipment, and P_C shows the average probability of overvoltage waves resulting in overvoltage pulses exceeding the critical voltage.

2.5. Stroke Frequency

The concept of stroke frequency comes from primary lightning protection, and it refers to the probability that a certain building is struck by lightning. In the case of lightning the expected length of the period between two strokes is called average strokeless period [12, 13].

The objective of lightning protection is to reduce the probability of damages caused by strokes of lightning to an acceptable level. On the average a protected building suffers lightning strokes at the same frequency as if it were not equipped with protection, but the protection ensures that most of the strokes do not cause any harm. Unfortunately there is no perfect protection, and at a little frequency, strokes of lightning may cause damages even in protected buildings. These are also characterised by strokeless period, which here refers to the average period between two cases of damage. Therefore, the purpose of lightning protection is to increase the average strokeless period characteristic of a building.

The concept of the average strokeless period can be extended to include overvoltages:

In overvoltage protection the average period of time between two cases of damage caused by overvoltages is called a strokeless period.

The purpose of protection is defined by determining the minimum period of time that needs to be exceeded by the average strokeless period.

Considering the above mentioned overvoltage sources based on (1), we may conclude that except the lightning stroke, they do not present a serious threat to building management systems because their stroke frequency is rather small. Although these effects are not to be disregarded while developing concepts for protection, the secondary effects of the lightning are really crucial to consider.

3. Overvoltages Caused by Strokes of Lightning

The secondary electric effects of strokes of lightning create overvoltage pulses in the environment through various coupling mechanisms.

3.1. Overvoltage Created by Capacitive Coupling

Capacitive coupling occurs in the capacity between the lightning protection system and an ungrounded metallic object of a building. The practical effect of overvoltages caused by capacitive coupling can be neglected, because the capacity between the ground and the metal object is very small, so the voltage appearing in this manner may be disregarded [1].

3.2. Overvoltage Produced by Inductive Coupling

In the case of overvoltages produced by inductive coupling the lightning current running down induces overvoltage in the conductors in the network of the building management system.

$$u_i = \frac{\mathrm{d}}{\mathrm{d}t} \int_A B * \mathrm{d}A \,. \qquad (2)$$

The magnetic field is inversely proportional to the distance, so the nearer the lightning channel where the processes of the lightning with a high current gradient take place, the greater the inductive effect. In the original formula probability P_B that describes the effectiveness of the coupling mechanism is higher for nearer strokes of lightning than for distant ones. Knowing the topology of the network in the building and the probability of occurrence of strokes of lightning, summarising the effects of the strokes of lightning affecting the environment of the building the stroke frequency can be calculated.

Most of the actual damages take place in this manner. The detailed calculation referring to this is not included in the present paper due to reasons of size [2, 3].

3.3. Overvoltages Generated by Conductive Coupling

Pulses that reach a building by electric conduction in some electric network are called overvoltages caused by conductive coupling. On the basis of stroke points this can be classified in two big groups:

overvoltages produced by

- strokes of lightning hitting the building,
- strokes of lightning hitting the environment of the building.

Overvoltages in the first group are caused by strokes of lightning reaching the building directly. If the primary lightning protection system has been properly designed and built, the strokes of lightning that reach the building hit the lightning rod of the protection system. Current travels towards the ground distributed on the conductors, then it reaches the ground through the grounding resistance.

The current pulse of the stroke of lightning running down generates voltage drop on the grounding resistance and it produces a voltage pulse in the equipotential bonding systems (EBS) compared to the grounded point.

The equipotential bonding systems (EBS) of buildings are connected to the lightning protection systems before the grounding, therefore the overvoltage appears on every electrically conductive object (e.g. metallic cases of devices) that is connected to the EBS. The peak value of the pulse can be approximately calculated according to the Ohm law:

$$\hat{U} = \hat{i} * R_f \, , \tag{3}$$

where $\hat{U}$ is the peak value of the generated voltage pulse, $\hat{i}$ is the peak value of the lightning current and R_f refers to the grounding resistance.

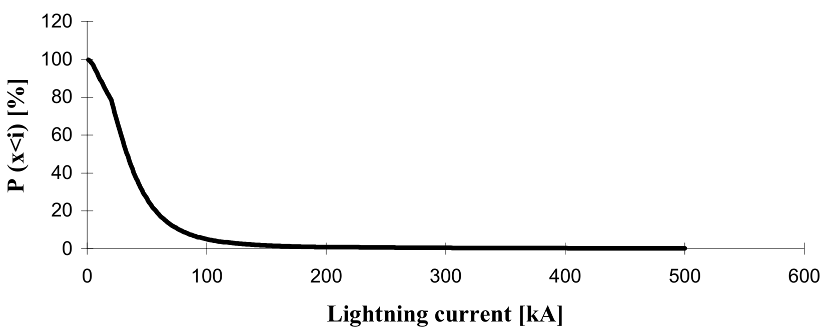

Fig. 1. Lightning current distribution

In statistics of lightning currents (represented in *Fig.1*) the 50% value is associated with a pulse with a peak value of 50 kA. In practice that means that every second stroke of lightning produces a voltage pulse greater than 100 kV on an average 2-Ohm grounding resistance [5, 6].

If the equipotential bonding systems and the primary lightning protection system are designed and built according to the standard, every metallic object that is connected to the EBS receives high voltage. But although the case of a device may be under high voltage compared to the ground, no voltage differences are generated inside it, thus the device does not suffer any damage. A damage can occur when the overvoltage appearing at a device reaches the insulation voltage level of the device and a sparkover takes place between the box and some electronic part of the equipment. This voltage level can be approached as the critical voltage level for the equipment. The probability of this event can be calculated in the following way:

$$P_{\text{damage}} = P_{\text{stroke}} * P_{\left[i_v \geq \frac{U_{sz}}{R_f}\right]}, \tag{4}$$

where P_{stroke} is the strokeless period referring to the building, i_v is the peak value of the lightning current, U_{sz} is the voltage at which the device might suffer damage (critical voltage level) and R_f is the grounding resistance.

In the second case the stroke of lightning does not hit the building itself but another object, usually another building in the environment. An overvoltage wave only reaches the given building by conductive coupling if it is in metallic connection with the other object. For that to happen the two buildings have to be connected by some conductors.

A typical example for that sort of connection is, when there is one building management system operating jointly in two separate buildings. In such cases the systems are controlled from a single common place, probably from one of the buildings. In other cases conductive coupling occurs through telephone or computer networks but the EPH systems of buildings may also be connected to each other. Now presume that sparkover has occurred in some equipment of a building struck by lightning. As a consequence, the information line is under voltage, so the overvoltage reached a device in the other building, and it is exposed to a voltage strain similar to that of the equipment damaged in the first building. Thus, probably it will also be damaged. In this case a part of the lightning current flows through the information line, then it goes on towards the ground through the grounding resistance of building number two. Currents are distributed approximately in proportion to the grounding resistance; roughly in the ratio of fifty to fifty. The case is shown in the model in *Fig. 2*.

The more buildings and/or objects a given building is in metallic connection with, the greater the danger it faces because of strokes of lightning hitting its surroundings. In this respect densely built-up areas are the least favourable, since presuming that the buildings are in metallic connection, overvoltages may come from every side. Therefore the more densely an area is filled with buildings, the higher the stroke frequency is. According to practical experience, provided

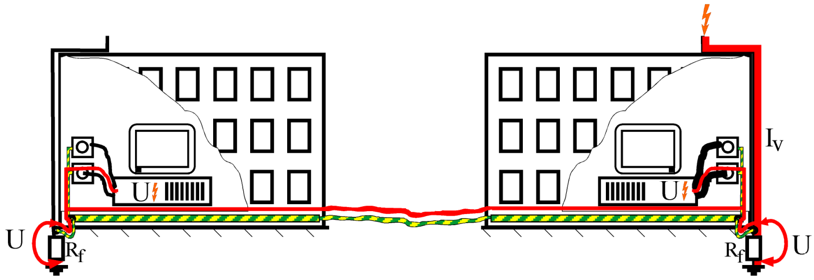

Fig. 2. Lightning stroke to the neighbour building

buildings are in metallic connection with one another, half of the lightning current entering the building flows towards the ground while the other half spreads on towards the neighbouring buildings [10]. The schematic model of this phenomenon is shown in *Fig. 3*, where each building has only two neighbours.

3.4. Calculating Stroke Frequency

The purpose of the calculation is to determine the occurrence frequency of a given critical voltage depending on the size of the building in the case of a completely built-up area. Although the calculations pertain to the ideal conditions below, they approximate reality well:

- The buildings are square and they are grounded in their centres. (In general, buildings tend to be square since streets usually meet at right angles as well. Central grounding has no physical significance; it is just more descriptive that way.)
- In the case of a densely built-up area each building has got four neighbours. (This condition is a direct consequence of the square buildings and the densely built-up neighbourhood.)
- Half of the lightning current entering the house flows through the grounding towards the ground, while the rest flows towards the neighbours and spreads on among them distributed in an equal ratio. (This mode of calculation is recommended by the standard.)
- The grounding resistance of the buildings is 2 ohms.
- The number of strokes of lightning per 1 km^2 is 2.5 a year. (This is a statistical fact valid for Hungary in general.)
- In the vicinity there are buildings of equal areas, e.g. an office building is surrounded by other office buildings or a detached house is neighboured by further detached houses. (In reality there are innumerable exceptions from this condition but industrial parks, complexes of residential buildings and housing estates, where buildings of similar functions and sizes stand together, are developing dynamically and are becoming more and more common).

According to the presumptions the buildings form a chess-board pattern. The stroke frequency for the building located in the middle has to be determined, that means it is to be established how many times a year the overvoltages entering the building by conductive coupling reach the critical voltage value.

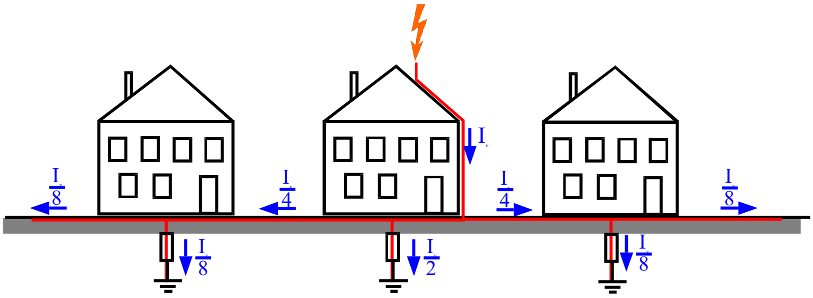

Fig. 3. Overvoltage spreading by conductive coupling

It can be defined for each neighbour of a building in the central position, what this lightning current peak value is that spreading on among the buildings causes a voltage drop that exceeds the critical value on the grounding resistance of it.

$$i_{\text{critical}} = f(i;\ j)\,, \tag{5}$$

where parameters 'i' and 'j' define the co-ordinates of the buildings.

Locating the building in a $9 * 9$ square grid, the formulas of *Table 1* are to calculate the critical current peak value for the building located in the central position:

If the lightning stroke hits, for example, the building (1;2), the critical lightning current for the central building is 144 times higher than the critical current for the struck building.

Table 2 shows for the neighbouring buildings the lightning current peak values that are necessary for reaching the critical voltage (in this case 400 V). The building is situated in field [0;0].

It can be determined on the basis of lightning statistics what percentage of strokes of lightning reaches the current peak value in question.

$$P(I_{\text{cr}})_{(i,j)} = P(I > I_{\text{cr}(i,j)})\,. \tag{6}$$

From the area of the buildings (ΔT) and the frequency of thunder strokes concerning the given environment (b) a frequency for each building can be calculated, determining how many times a year overvoltage pulses exceeding the critical voltage arrive from that building on the average.

$$\Delta P_{\text{stroke}}[i;\ j] = P(I_{\text{cr}})_{(i,j)} * b * \Delta T\,, \tag{7}$$

Table 1. Current peak value functions

If: $i = 0 : i = 0$:	$I_{\mathrm{cr}(i;j)} = \dfrac{I_0}{2}$
If: $abs(i) = 1 : i = 0$ or $i = 0$:	$I_{\mathrm{cr}(i;j)} = \dfrac{I_0}{8}$
If: $abs(i) = 1 : abs(i) = 1$:	$I_{\mathrm{cr}(i;j)} = \dfrac{I_0}{48}$
If: $abs(i) > 1 : i = 0$:	$I_{\mathrm{cr}(i;j)} = \dfrac{I_0}{16}$
If: $i = 0 : abs(i) > 1$:	$I_{\mathrm{cr}(i;j)} = \dfrac{I_0}{16}$
If: $abs(i) > 1 : abs(i) = 1$:	$I_{\mathrm{cr}(i;j)} = \dfrac{\dfrac{I_{\mathrm{cr}(i-1,j)}}{2} + \dfrac{I_{\mathrm{cr}(i,j-1)}}{3}}{2}$
If: $abs(i) = 1 : abs(i) > 1$:	$I_{\mathrm{cr}(i;j)} = \dfrac{\dfrac{I_{\mathrm{cr}(i-1,j)}}{3} + \dfrac{I_{\mathrm{cr}(i,j-1)}}{2}}{2}$
Any other cases:	$I_{\mathrm{cr}(i;j)} = \dfrac{\dfrac{I_{\mathrm{cr}(i-1,j)}}{2} + \dfrac{I_{\mathrm{cr}(i,j-1)}}{2}}{2}$

Table 2. Lightning current peak values necessary for a critical voltage of 400 V

	−4	−3	−2	−1	0	1	2	3	4
−4	1368	684	414	360	691	414	360	684	1368
−3	684	291	145	98	115	98	145	291	684
−2	414	145	57	28	19	28	57	145	414
−1	360	98	28	9.6	3.2	9.6	28	98	360
0	691	115	19	3.2	0.4	3.2	19	115	691
1	360	98	28	9.6	3.2	9.6	28	98	360
2	414	145	57	28	19	28	57	145	414
3	684	291	145	98	115	98	145	291	684
4	1368	684	414	360	691	414	360	684	1368

where $\Delta P_{\mathrm{stroke[i;j]}}$ determines for a given building of the environment at what frequency overvoltage waves bigger than the critical one come from it.

Taking all the buildings of the environment into account the probabilities are summarised, so the stroke frequency is:

$$P_{\text{stroke}} = \sum_{\text{environment}} \Delta P_{\text{stroke}}[i;\ j]\,. \tag{8}$$

It should be noted that this formula contains overvoltages coming from the environment, on the one hand, and overvoltages caused by lightning striking the building, on the other hand as well, because in *Table 2* the necessary lightning current is also shown for the building located in field [0; 0]; i.e. the building that is being examined.

Fig. 4 presents the stroke frequency for critical voltage values of 400, 900, 1500 V:

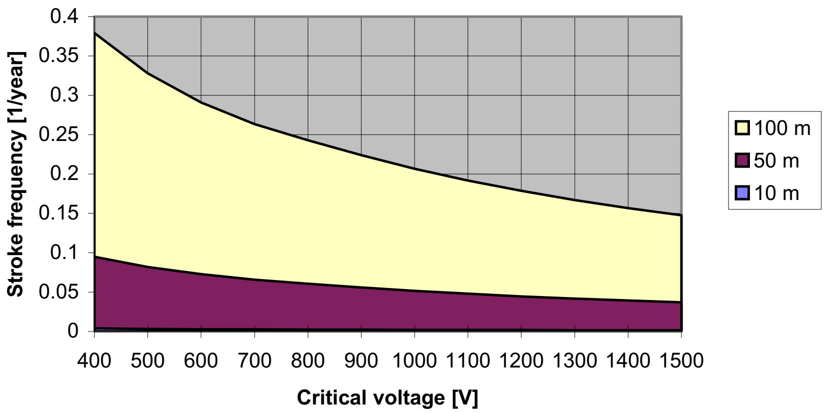

Fig. 4. Overvoltages in the case of conductive coupling as a function of the building size

Of course, the frequency increases as a function of the size of the buildings since the frequency of strokes of lightning is higher for larger buildings.

4. Conclusion

From the above results (*Fig. 5*) it may be concluded that the average strokeless period, which is the converse of stroke frequency, for large office buildings is within the range of 2–5 years in the case of small critical voltages. The danger threatening medium-sized buildings or blocks of flats is far less; pulses exceeding the critical voltage are to be expected every 10–20 years, while this value is 40–50 years in the case of detached houses. In planning and sizing overvoltage protection systems these values need to be taken into consideration.

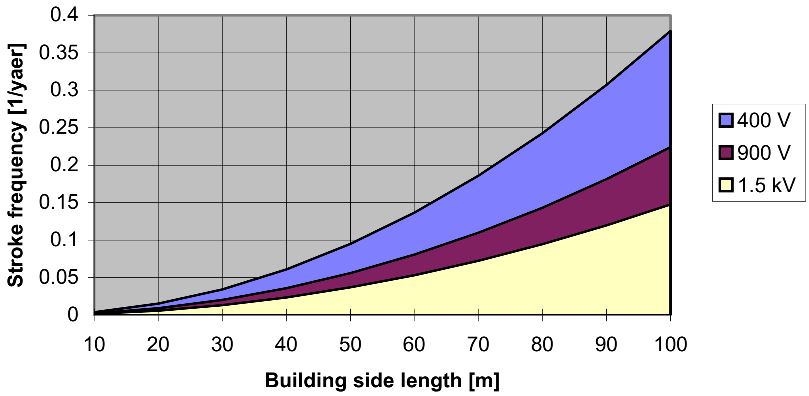

Fig. 5. Overvoltages in the case of conductive coupling as a function of the critical voltage

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