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Rational Approach to Assessment of Risk Due to Lightning for Nuclear Power Plants

Abstract. A nuclear power plant (NPP) contains structures, systems, and components that are sensitive to lightning influences. Dangerous effects of such influences can include reactor trips, actuation of safety systems, loss of fire protection and so on. A damage type within a plant depends both on lightning activity at different its location and on features of involved systems. Due to expected serious consequences of lightning damages to NPPs there is no doubt that they should be protected. The problem consists in rational selection and application of adequate protection measures.

Streszczenie. Elektrownie nuklearne mają liczne struktury, systemy i komponenty narażone na szkodliwe oddziaływania wyładowań piorunowych. Wyładowania te mogą powodować zaburzenie pracy reaktora, uruchomienie systemów bezpieczeństwa, utratę ochrony przeciwpożarowej, itd. W zaistniałej sytuacji racjonalna ocena zagrożenia piorunowego i dobór odpowiednich środków ochronnych jest konieczny. (Racjonalna ocena zagrożenia piorunowego elektrowni nuklearnych).

Keywords: Lightning protection, risk management, lightning risk, nuclear power plant.
Słowa kluczowe: Ochrona odgromowa, zarządzanie ryzykiem, ryzyko piorunowe, elektrownia nuklearna.

Introduction

Lightning discharges belong to natural weather phenomena, which cannot be prevented. In the case of nuclear power plants (NPPs) the sensitive digital and low-voltage analogue electronic systems are very widespread and important for their different benefits [2]. However, because of their increasingly lower internal operating voltages and higher internal operating frequencies, they become more vulnerable to lightning induced transients than the older analogue systems [7, 15, 16, 17]. Direct and nearby cloud-to-ground discharges are hazardous not only to such sensitive systems but also to the structure itself and to persons and installations within or on the structure. The application of lightning protection measures in NPP is needed, but it should be confirmed in terms of risk. Also the selection of protection measures should be considered in the same way, because it allows to confirm that the risk has been reduced to a tolerable level by means of most adequate protection measures. In the risk management approach, the lightning threats that create risk are identified, the frequencies of all risk events are estimated, the consequences of the risk events are determined and - if they are above a tolerable level - protection measures are applied to reduce the risk (R) to below its tolerable level (R_T). The approach to the risk management depends - of course - on the features of the structure to be protected. Nuclear power plants belong to special structures and their features are also specific and in special way may influence this approach, what should be recognized.

NPP from lightning hazard point of view

Nuclear power plants belong to structures, which – due to their location and spatial configuration – are especially exposed to the lightning flashes with very heavy consequential effects. From this point of view, NPP may be classified as "critical structure", which may be damage itself, but much important may be damages to its contents and to its surroundings, for instance, due to radioactive emissions.

The nuclear technology may be different, so that the equipment of such critical structure may be also diversified, but in general it may consists, for instance as shown in Figure 1.

As it has been shown in Fig. 2, appliances and systems involved into NPP technology create four following groups: internal systems located within a plant, services passing through the entrance, equipment of MV/HV power station, equipment belonging to off-site power. The group of safety related systems, i.e. the systems of instrumentation and control (I & C) are most important from lightning hazard point of view. They may be further subdivided into following groups like [13]: reactor protection system, safety actuation system and safety system support features; automatic control systems, preventive protection systems and control room data processing systems; emergency communication systems and radiation monitoring systems. Considered systems are progressively developed into computer systems, which create now well integrated computer networks. For this reason it seems to be evident that NPP systems are very sensitive to external electromagnetic influences and under these influences may be easily disturbed or even damaged.
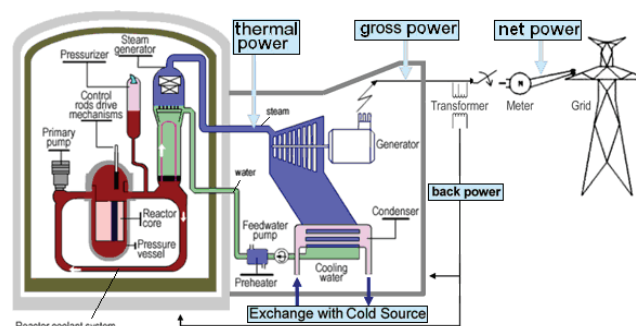

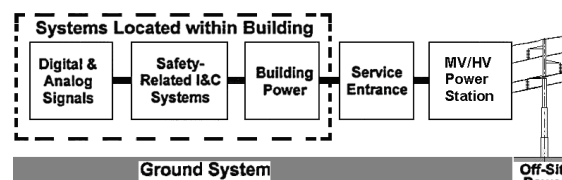Fig.1. An example of basic nuclear power plant equipment and technology (taken from [18])

Fig.2. Example of power plant systems (adapted from [2])

Lightning events and parameters

Lightning flashes are described by frequency of their occurrence in the region under consideration and by parameters of their currents.

The lightning occurrence frequency is measured by ground flash density N_g - the number of lightning flashes per km^2 per year. This value may be available directly from ground flash location network for the considered region or it

may be estimated on the base of the number T_D of thunderstorm days per year, taken from isokeraunic map. Other parameters were investigated from the middle of the last century. A reliable synthesis of collected data were published within CIGRE activities. Statistical log-normal type distributions of these parameters, are given in the IEC 62305 standards and are used for the aim of lightning protection of each structure.

Most important parameters for the purpose of protection system designing are following [1, 3, 9]:
- current peak value I of the first stroke;
- maximum rate of rise S or steepness of the front of impulse current of subsequent stroke;
- total charge Q in a flash;
- specific energy W/R transferred by a flash;
- standardized front time T_1 of impulse current;
- standardized time T_2 to half value on the tail of impulse current.

NPP in lightning environment

The main characteristics of NPPs with relevance to lightning effects include their: construction and functions; occupants and contents; entering installations; measures to limit consequential effects of damages; scale of the extension of danger.

The lightning flashes striking directly a structure can cause: immediate mechanical damage; fire and/or explosion; injuries to people; failure or malfunction of electrical and electronic systems.

The flashes to ground near the structure can cause failures or malfunction of electrical and electronic systems.

The flashes striking directly the connected lines (mains, telecommunication and data lines) or other services can cause: fire and/or explosion; injuries to people; failures or malfunction of electrical and electronic systems.

The flashes to ground near the incoming lines and services can cause failures or malfunction of electrical and electronic systems.

In the case of NPP structure all these events can extremely correspond with contamination of natural environment by radioactive fuel and it is possible to distinguished following typical damages [2]: physical damage of outdoor equipment due to direct strike; failure of data system due to inductive overvoltage; reactor trip without equipment damage; reactor trip accompanied by equipment damage; loss of offsite power, without equipment damage; loss of offsite power, accompanied by equipment damage.

Each type of damage, alone or in combination with others, may produce different consequential loss in a NPP like: loss of human life; loss of service to the public with consequences for environment; loss of economical value (structure, content and loss of activity).

More than one loss may appear in a NPP. Loss of economical value always appears.

Lightning risk and basic criteria for its assessment

The lightning hazard impending over a NPP is a random process composed of a set of effects, which are correlated with the parameters of lightning discharge, the characteristics of the NPP, its content, the installation internal to the structure, the lines and other services entering the structure.

If the time of observation is fixed (usually t = 1 year), it is possible to demonstrate [4, 5] that the risk, defined as the probability to have an annual loss in a NPP due to lightning, may be calculated according to the following expression:

$$(1) \qquad R = 1 - e^{(-NPL)}$$

where: N - the average yearly number of flashes influencing the NPP and its content; P - the damage probability of the NPP due to single flash and L - the average amount of loss, with consequential effects, due to single flash.

The product NPL is the level of risk or the number (or frequency) of annual loss in a NPP due to lightning. It is evident that if $NPL \ll 1$ (in practice $NPL < 0.1$), the risk (as a probability) and the level of risk are coincident. The International Standard [9] defines this risk as the probable annual loss in a structure due to lightning, and suggests to evaluate it by the following three-factor formula

$$(2) \qquad R = N P L$$

The following three categories of the risk R, corresponding to the types of loss L, are to be taken in account: R_1 - risk of loss of human life; R_2 - risk of loss of services to the public; R_4 - risk of loss of economic value.

It would be noted that in accordance with IEC 62305-2 standard the category R_3 of the risk of cultural heritage loss exists, but is not applicable in this case.

Each risk category should be evaluated as the sum of different risk components $R_{X = A, B, C, M, U, V, W, Z}$, each assessed in the way analogous to formula (2), depending on each damage source, as follows:
- source 1 (lightning flashes direct to the structure) may generate: component R_A related to shock of living beings due to touch and step voltages; component R_B related to fire, explosion, mechanical and chemical effects and in particular radioactive pollution inside and outside the structure; component R_C related to the failure of electrical and electronic NPP safety systems related due to overvoltages on internal installations and incoming services.
- source 2 (lightning flashes to ground near the structure) may generate component R_M related to the failure of electrical and electronic NPP safety systems related due to overvoltages on internal installations mainly caused by magnetic field generated by the lightning current.
- source 3 (lightning flashes direct to the incoming lines) may generate: component R_U related to shock of living beings due to touch and step voltages; component R_V related to fire, explosion, mechanical and chemical effects and in particular radioactive pollution inside and outside the structure; component R_W related to the failure of electrical and electronic NPP safety systems due to overcurrents and overvoltages, transmitted by external lines to the structure.
- source 4 (lightning flashes to ground near the incoming lines) may generate component R_Z related to the failure of electrical and electronic NPP safety systems due to induced overvoltages, transmitted through the incoming lines.

For each distinguished category of the risk $R_{i = 1, 2, 4}$, corresponding with adequate type of loss $L_{i = 1, 2, 4}$, the values are then given by the sum of relevant components, as follows:

$$(3) \qquad R_1 = R_A + R_B + R_C + R_M + R_U + R_V + R_W + R_Z$$

$$(4) \qquad R_2 = R_B + R_C + R_M + R_V + R_W + R_Z$$

$$(5) \qquad R_4 = R_B + R_C + R_M + R_V + R_W + R_Z$$

The sum of relevant components may be created also with reference to the point of lightning strike. In the case of the risk R_D due to direct flashes to the structure one obtains a following group of components:

$$(6) \qquad R_D = R_A + R_B + R_C$$

In the case of the risk R_I due to indirect flashes to the structure one obtains a following group of components:

$$(7) \qquad R_I = R_M + R_U + R_V + R_W + R_Z$$

Taking in account both cases one obtains the total value R of the risk as follows.

$$(8) \qquad R = R_D + R_I$$

The aim of a lightning protection is to reduce the value of the risk R to the level lower than the maximum one R_T which can be tolerated for the structure to be protected. Hence the following condition:

$$(9) \qquad R \leq R_T$$

If more than one type of damage could appear in the structure, the condition $R \leq R_T$ shall be satisfied for each type of the damage. In the case of NPP, where lightning causes the loss of a social value the level R_T of tolerable risk shell be established under the responsibility of concerned national body.

Protection measure's selection procedure

For the NPP to be protected, the lightning protection system is always required. Suitable protection measures are specified in the topical standards [11, 12, 14] and professional guidance [2]. The group of most important of them is created by: external and internal LPS, equipotential bonding (EB) or satisfactory separation distances, earthing and bonding measures, magnetic shielding, line routing, isolating interfaces and coordinated SPD systems. These measures shall be selected with appropriate attention with regard to results of risk monitoring. For this aim the main steps to be follow are following:
a) identify the NPP structure to be protected with its equipment and its characteristics;
b) identify the types of damage (and relevant risks) due to lightning in the structure;
c) for each type of damage evaluate the risk R taking in account selected protection measures,
d) select the tolerable level of the risk R_T;
e) compare the calculated value R with R_T and, if $R > R_T$, select the protection measure, which allow to reduce most effectively the greatest risk components with respect to the condition: $R \leq R_T$;
f) select, if needed $(R > R_T)$, step by step the successive protection measures monitoring the risk level and taking in account the technical and economical aspects.

Conclusions

Topical standards on the lightning protection of structures don't cover full requirements needed for an effective NPP protection, but the rules included in these standards are a good base of practice to assure suitable protection efficiency. Considerations of this paper aim to adequate for NPP regulations. On the background of these considerations the following conclusion can be formulated:
- it is possible to introduce the lightning risk assessment of NPPs in the frame of reliability theory, mathematical statistics and probability theory;
- the rational risk assessment should be based on the evaluation of the numbers of dangerous events, the probability of damage, and the amount of consequential loss;
- important element of the calculation of risk is lightning current distribution issues characteristic for each location of NPP;
- detailed data on NPP location, structure and system are essential to perform risk evaluation.

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