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Influence of Lightning Phenomena on Electric Power Systems

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تأثير تفريغات الصواعق على أنظمة الطاقة الكهربائية

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Abstract:
This paper examines the influence of lightning discharges on electric power systems, analyzing the resulting overvoltage's on overhead transmission lines and substation insulation. By evaluating the withstand characteristics of air gaps and insulator materials through computer simulations, the work outlines insulation coordination principles, including a suitable coordination margin to minimize damage and improve system reliability.

Keywords: influence of lightning discharges, electric power systems, overvoltage's, transmission lines, substation insulation,

الملخص
تتناول هذه الورقة البحثية تأثير تفريغات الصواعق على أنظمة الطاقة الكهربائية، حيث تحلل الجهد الزائد الناجم عنها في خطوط النقل الهوائية وعوازل المحطات الفرعية. ومن خلال تقييم خصائص تحمل الفجوات الهوائية ومواد العزل عبر المحاكاة الحاسوبية، يحدد البحث مبادئ تنسيق العزل، بما في ذلك هامش التنسيق المناسب ومواد العزل، وذلك بهدف الحد من الأضرار وتعزيز موثوقية النظام.

الكلمات المفتاحية: تفريغات الصواعق، أنظمة الطاقة الكهربائية، الجهد الزائد، خطوط النقل، المحطات الفرعية.

Introduction

Energy, a fundamental factor to support current society and economy, is needed to run industries, transport, communication, health care, agriculture and human domestic activities. With the rapid growth of population, urbanization, industries and technologies all over the world, the global energy demand has substantially increased [1]. To meet such demand for energy, and to ensure a supply of energy that is reliable, secure, affordable and sustainable, is the great challenge to all countries in the world [2].

The electric power system is made up of generation, transmission, distribution, and utilization components. As the complexity and size of these systems increase, new technical challenges arise that could endanger the proper functioning of these systems. These challenges, in addition to load and generation variations, can be caused by external disturbance and environmental phenomena that create high electrical stresses on power system components. These stresses can cause damage to the equipment, power outages, decreased system reliability, and increased operation and maintenance costs.

The reliability of an electric power system depends not only on the amount of power available and an effective transmission and distribution system, but also on the ability of the individual pieces of equipment to withstand unusual operating conditions and transient disturbances. Overvoltage's are one of the most important stresses on the insulation of the electrical power system. These overvoltage's can be caused by a variety of situations including switching, faults, and atmospheric conditions. Of these conditions, lightning is perhaps the most important because of the high current and very rapid change in voltage that it can cause.

OVL caused by lightning is transmitted through overhead lines and reaches substations and other electrical apparatus. The study on the relationship between occurrence of lightning and power systems is very important for improving the protection, insulation coordination and reliability of operation of power systems as well as for increasing the robustness of power grid.

1. Lightning Discharge Phenomenon

Lightning phenomenon is caused by a peak discharge during which the charge accumulated in the clouds discharges into the neighbouring cloud or to the ground. The description of the lightning mechanism is given here in a very simplified form, only to present the background of these phenomena. More about lightning phenomena is presented in specialist books and papers [3, 4, 5, 6]. The mechanism of charge formation in the cloud and their discharge, as well as the numerous the factors which help the formation or accumulation of charge in the clouds are complex, and unpredictable. But during thunder storms, positive and negative charges become separated by heavy air currents with ice crystals in the upper parts and rain in the lower parts of the clouds, and this cloud separation depends on the height of the clouds. The probable electric field strength near the ground during thunderstorm is presented in Figure 1.

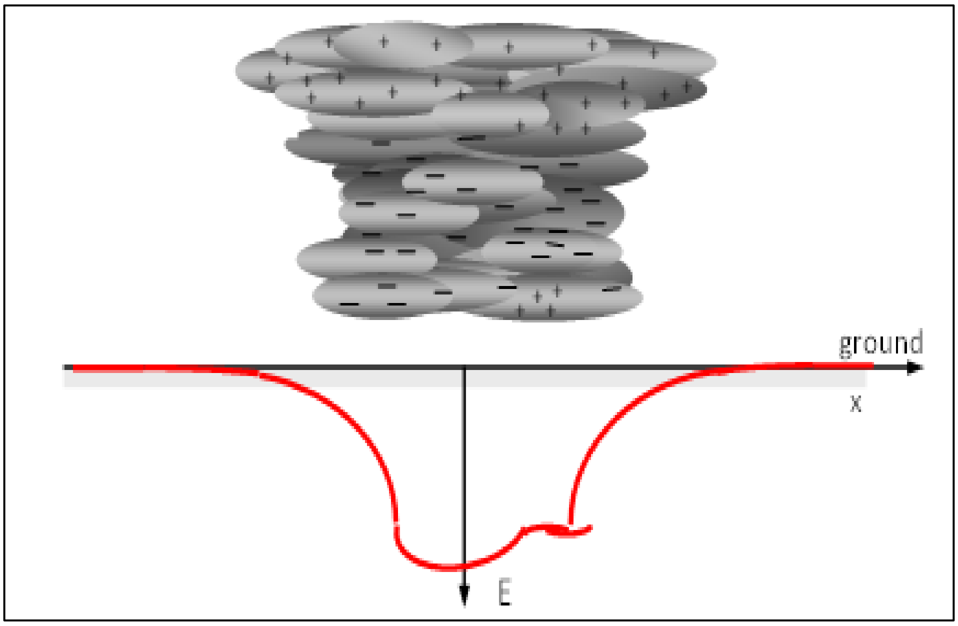

Figure 1: Probable electric field strength during thunderstorm

The volume of the charge that participates in the lightning flashover is uncertain. The charge inside the cloud may be 1-100 C, and potential 107-108 V, with field gradients ranging from 100 Vm within the cloud to 105 Vm-1 at the initial discharge point. The lightning discharge to an open ground starts invariably in the cloud. It becomes visible when penetrating its lower boundary, then progresses towards the earth as a faintly luminous discharge, called the leader stroke. The temporal development of a multiple earth flash is presented in Figure 2.

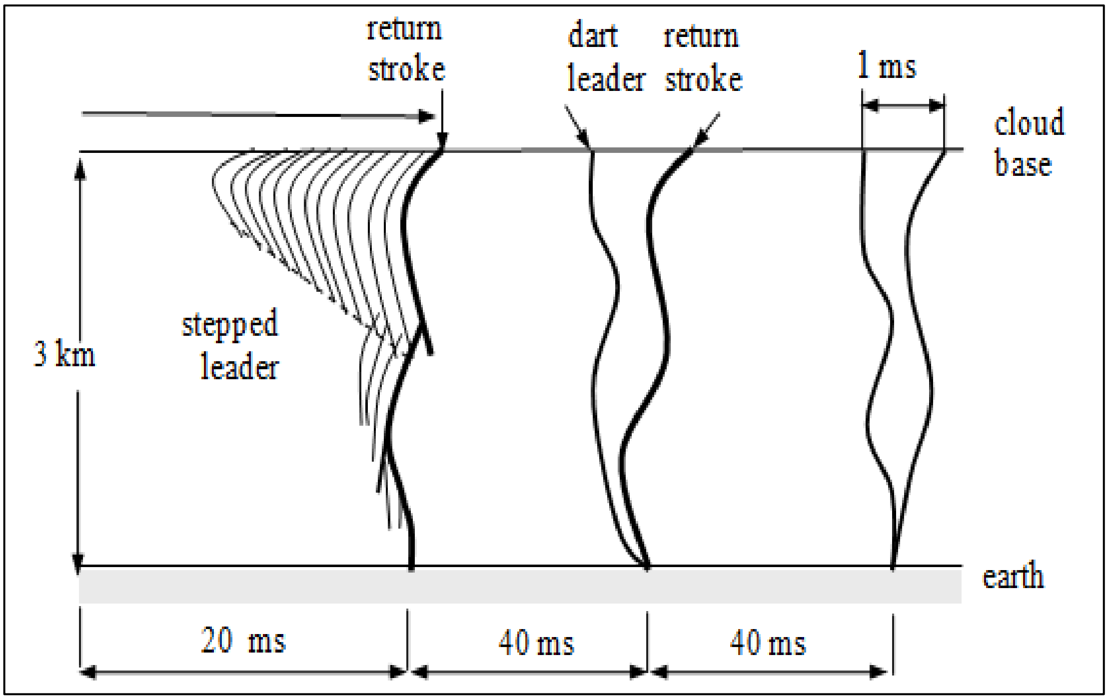

Figure 2: Temporal development of multiple earth flash.

It is usually heavily branched and, as the great majority of leaders, originates from negatively charged cloud centres; and are thus negatively charged, these branches are attracted by positive charge pockets floating in the air. The leader channel and its branches are extended towards the earth in discrete steps of about 20 m length but there is some evidence that these lengthen as the leader approaches the ground. Such discharges are called stepped leaders. The most frequent velocity of movement of the leader tip is between 105 and 2*105 ms-1, being less than one thousandth of the speed of light. The current in the leader is estimated at several hundred amperes. When the faint lightning leader channel reaches the ground, an intense luminosity is seen to travel upwards along its path towards the cloud and along its branches. This is the so-called return stroke. In effect, this constitutes an electric short circuit between the negative charge deposited along the leader and the electrostatically induced positive charge in the ground. The velocity of the return stroke decreases from the ground to the cloud but initially amounts to 108 ms-1, the most frequent average value over its full length being 3.5*107 ms-1, which is about one tenth the speed of light or a hundred times faster than that of the leader. The leader and return stroke process as described may complete the visible part of the lightning discharge. However, after a certain time interval, a second leader stroke, followed along a return stroke, may occur. This subsequent stroke usually follows by the path taken by the first stroke with the exception that it is not stepped and is much faster; therefore, it is called a dart leader. The process of dart leader and return stroke formation can be repeated several times. Each such component is termed a stroke while the complete process of successive strokes is termed a multi-stroke flash, or briefly a lightning flash. A lightning flash can thus consist of a single stroke or a sequence of several discrete strokes. As a rule, all subsequent strokes follow the path blazed by the first stroke but in a high wind the entire channel can be blown sideways. The account given so far is concerned with negative lightning flashes that are flashes conveying negative charge from cloud to ground. This comprises some 95% of all earth flashes and even more in tropical storms. Only scanty information is available about the characteristics of positive lightning discharges. Despite differences in the development of the initial leader stroke, the leader-return process is the same in positive and negative charges to open ground, with the one important difference that positive flashes usually consist of a single stroke and seem to occur towards the end of a storm, when the upper positive cloud charge may be discharged to earth in one stroke which is often of exceptional severity [4, 5].

2. Overvoltage's in Electric Power systems due to Lightning

Lightning overvoltage's are caused either by direct strokes to the phase conductor or as a result of strokes to earth very close to the line which produces induced lightning surges. The overvoltage, by which substation insulation is stressed, is a function of the line construction and the system configuration. Overvoltage induced by indirect lightning on overhead lines can cause damage to the power system.

The scheme of an influence of lightning strokes on overhead transmissions lines in power systems is presented in Figure 3.

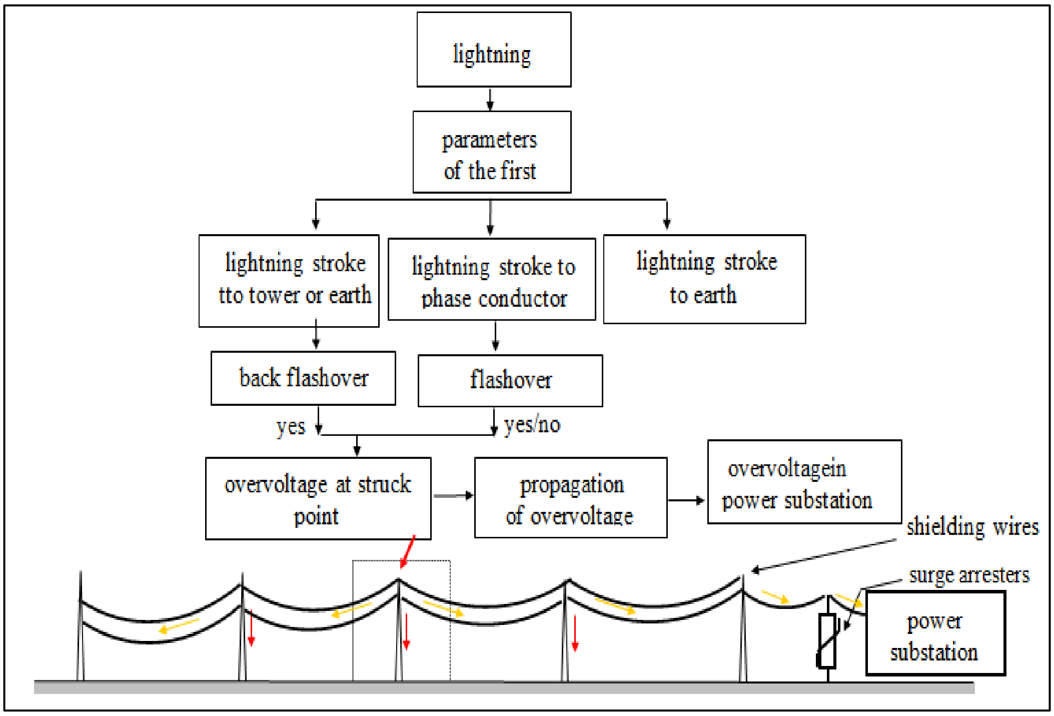

Figure 3: General scheme of lightning overvoltage's in power systems.

Moreover, due to its more frequent occurrence, indirect lightning constitutes a more important cause of micro-interruptions than the direct strike. Their estimation is therefore crucial for the correct operation coordination of overhead lines and, as a consequence, has been the object of various studies since many years. The majority of lightning strokes takes place from clouds which have positively charge upper regions with the rest negatively-charge except for some localized positive charge in part of the cloud base. The lightning stroke consists basically of two components, a leader stroke from the cloud which initiates an upward streamer from some irregularity on the earth and a conducting channel along which a return stroke then passes. In many cases the stroke is multiple with a number of leaders and return strokes.

The return stroke, in the course of which the current reaches its peak, may have a current as low as hundreds of amperes, but is more frequently between a few, kiloamperes and about

100 kA. The current waveform is generally a unidirectional pulse rising to a peak value in about 3s and falling to small values in several tens' microseconds.
When the lightning current stroke contacts the line, the voltage wave starts to be formed as shown in Figure 4.

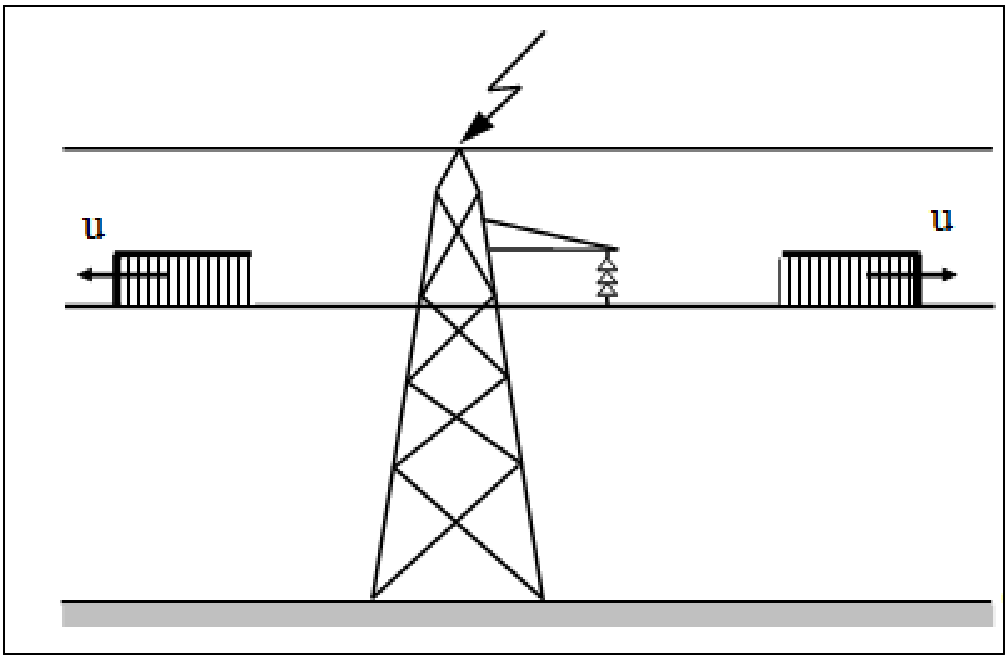

Figure 4: The voltage wave formed as a sequence of a lightning stroke.

The scheme, which is presented in Figure 4, can be represented by an electrical equivalent circuit, considering the lumped parameters, as shown in Figure 5.

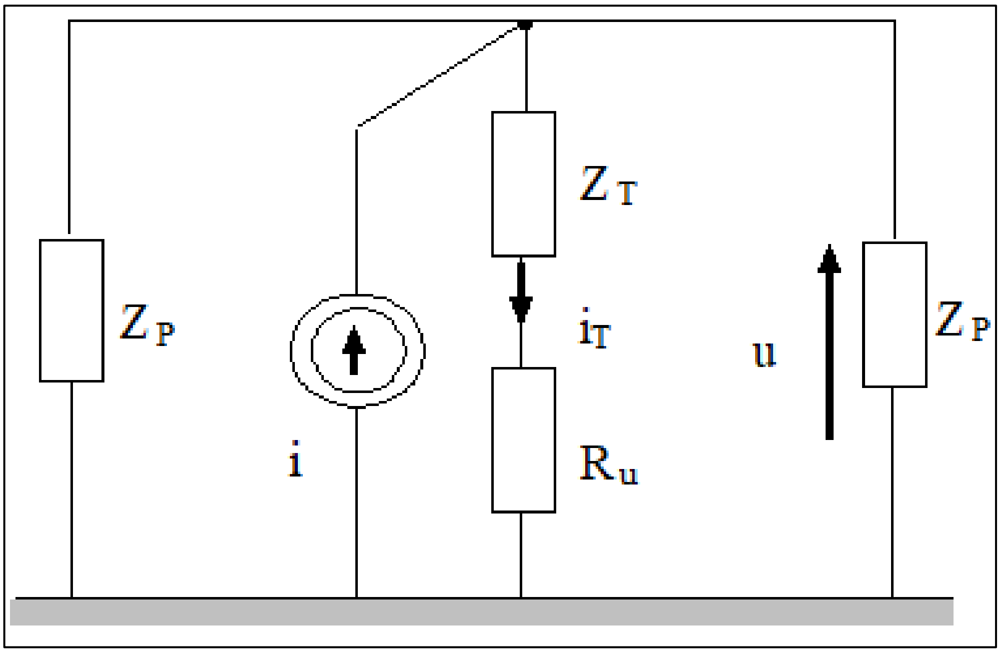

Figure 5: The electrical equivalent circuit of formed voltage wave in the transmission line.

In Figure 5 the line conductor is represented by two impedances Z_p, the transmission line tower is represented by impedance Z_T and earth resistance by the resistor R_u.

3.Properties of Withstand Voltages of Insulation Systems

Basic problems presented in this dissertation concentration on overvoltage risks of insulation systems of overhead transmission lines and electric power devices in power substations. Special emphasis lightning overvoltage's, which have been analyzed on the basis of the results of computer simulations. An insulation system of overhead transmission lines has a form of air distances and electric line insulators. Withstand insulators of high voltage overhead lines are usually made of ceramic or glass. Sometimes they are based not only on maximum values of overvoltage's but also on their courses. The electric withstand of air distances is presented in a simplified form in Figure 6 in comparison to the withstand voltage of internal solid insulation. Withstand voltage of large air gaps is presented in curve II, Figure 6. It has large electric withstand for short strokes and overvoltage's over long spans of time.

Generally for all insulation systems electrical withstand for lightning overvoltage's is greater than for switching and temporary overvoltage's. Therefore lightning overvoltage's which are generated in power systems have large maximum values and they create large risk of insulation systems, and they should be taken into account as basic risks of power systems. For this reason the time-voltages characteristics for lightning overvoltage's should be known because they have basic means in insulation coordination [5, 7, 10].

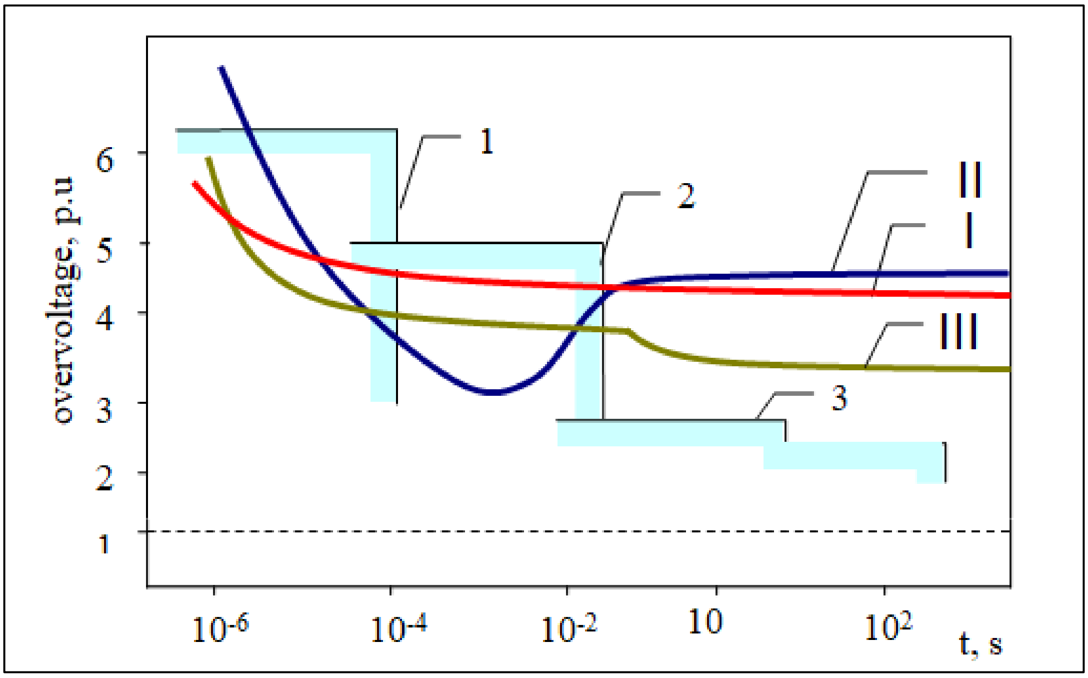

Figure 6: The electric withstands voltages of selected insulation systems for typical overvoltage's:

1 - lightning overvoltage's,
2 - switching overvoltage's,
3 - temporary overvoltage's: I - air insulation of medium voltages,
II - large air distances, III - solid internal insulation

Withstand voltage of air insulation systems is the smallest for switching overvoltage's with positive polarity. The minimum value of flashover voltage depends on value distance between electrodes and time to the crest of the switching stroke. This minimum (critical) electric withstand should be taken into account in co-ordination of the highest voltage insulation systems. Electric withstand of insulation systems of power devices is determined in the form of limiting values of voltages. When voltage is greater than this value then air insulation systems can lose their properties by a flashover.

The phenomenon of electrical flashover has a statistical nature. If an impulse voltage of a certain shape is applied repeatedly to the self-restoring insulation system, the outcome of all applications may not be the same. Some impulse applications may cause a flashover, while other still with the same maximum value, may be withstand by the insulation. This phenomenon is particularly true for sufficiently large gaps (larger than about a 0.5 m rod-plan gap in air at atmospheric pressure). It also occurs over a finite range of impulse voltage maximum values, above which all shots cause breakdowns and below which all shots would not cause breakdown. This probabilistic property is very essential for insulation dimensioning. In fact, at very high transmission voltages this property is used for setting an economical compromise between the insulation cost and the risk of insulation failure. The probability of a breakdown (i.e., the number of breakdowns relative to the total number of applied shots) may be plotted against the applied voltage as shown in Figure 7.

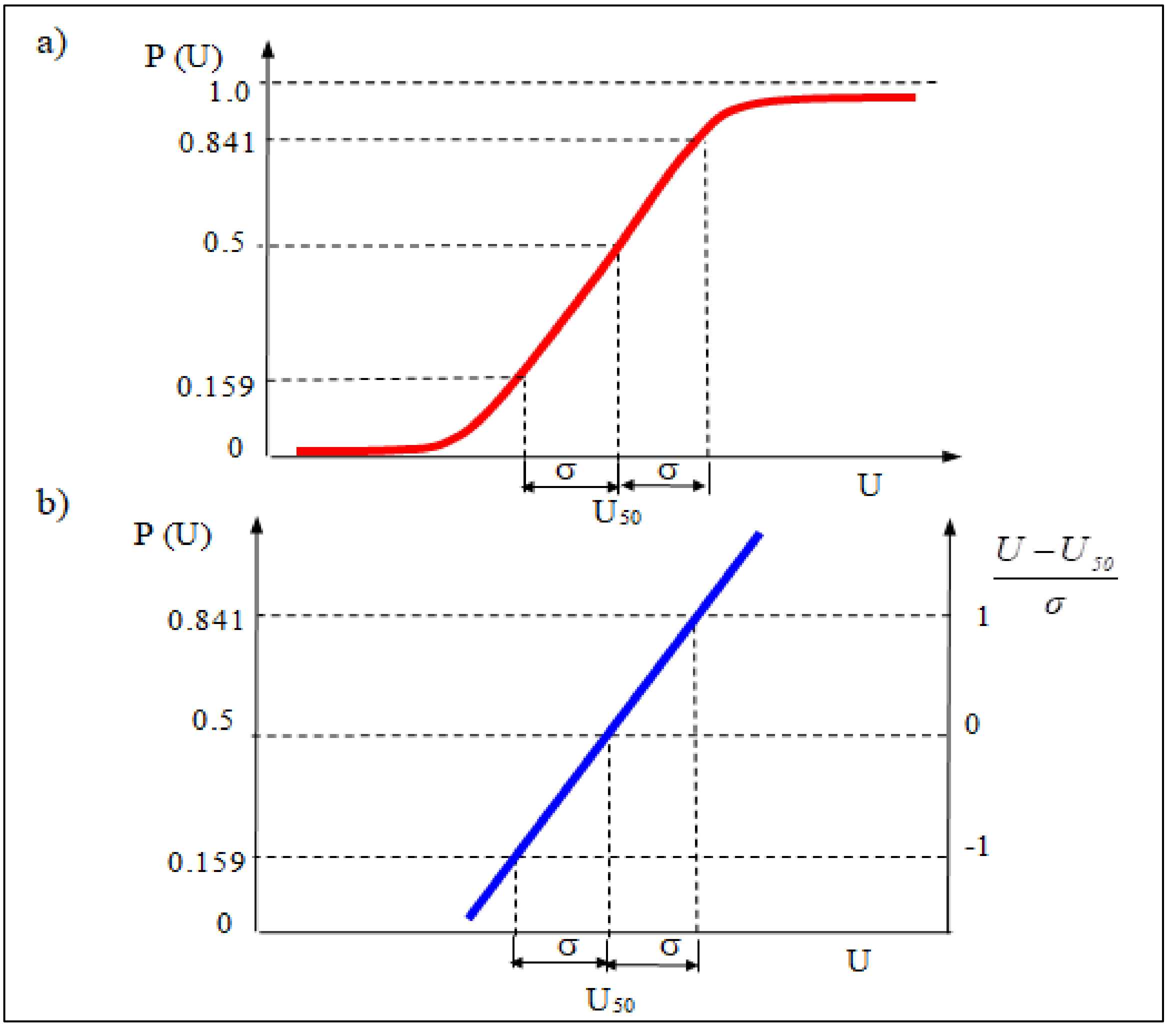

Figure 7. Breakdown probability of external insulation system: a - on linear coordinates, b - on Gaussian scale

Experimental investigations have revealed that for most external insulation systems the breakdown probability function may be expressed by the well-known cumulative Gaussian distribution function: [5, 11].

$$P(u) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{u} \exp(-\frac{1}{2}(\frac{u - U_{50}}{\sigma})^2 du \quad (1)$$

where: U_{50} - 50% breakdown voltage of the representative, also called the critical flashover voltage (CFO), V

σ - standard deviation of the representative Gaussian distribution (σ describes the degree of scatter in breakdown voltages about their mean value U_{50}).

If the postulate of equation (1) - that the breakdown probability fits a Gaussian cumulative function - is accepted, *P(U)* can alternatively be plotted on a normal probability ordinate scale as seen in Figure 7, in which case *P(U)* appears linear.

The linear units on the ordinate in this case are those of the quality $\frac{U - U_{50}}{\sigma}$ rather than *P(U).*

4. Principles of Insulation Coordination and its Methods

The basic aim of insulation coordination is designing the appropriate insulation systems of electrical devices to minimize damage and financial costs. Insulation coordination account for electric strength values of electrical devices in relation to the voltage which can appear on the power systems [5, 8, 12]. It takes relative coordination of the basic components in relevance to the exploitation of power systems:

- voltage and overvoltage risks of insulation systems,
- withstand voltage of insulation systems,
- methods of overvoltage protection.

When formulating of the process of insulation coordination, the required operating reliability of electrical power systems - with consideration to the unfailing work of insulation system – is obtained after assuming a suitable coordination margin U_M:

$$U_M = U_w - U_p \tag{2}$$

It is equal to the difference between the electric withstand U_w of the insulation system and the protection level U_p, which is equal to the reduced level of overvoltage protection systems, for example shielding wires and surge arresters.

The value of the margin U_M influences not only the reliability of the electrical power system, but also its costs (Fig. 8).

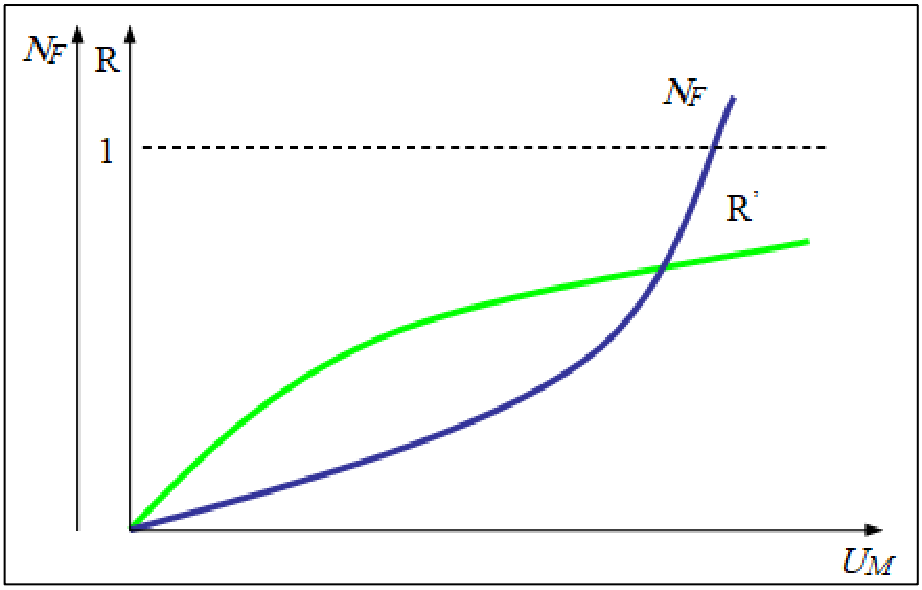

Figure 8: Influence of the margins coordination U_M on reliability R' and financial expenditures N_F of insulating system

The operating reliability R' of insulating systems increases with the increasing width of the margin coordination U_M. Also, the financial expenditures are increased in this case. Moreover, environmental and system operation conditions of electrical power system, the change of characteristics and parameters as well as the technological dispersion of devices have influence on the width of the coordination margin.

In reality the coordination margin is a random variable. It is determined by the random character of electric withstand and overvoltage risks as well as by random character of protection characteristics of overvoltage protection devices. In this concept the dimensioning of insulation systems is determined on the basis of the failure probability R' which is expressed by the following formula:

$$R' = \int_0^\infty P_o(U)\ P_d(U)\ dU \tag{3}$$

where: $P_o\,(U)$ - overvoltage probability distribution in the insulation system,
$P_d(U)$ - insulation failure cumulative distribution [24, 35, 52, 65].

The overvoltage probability distribution and insulation failure cumulative distribution are shown in Figure 9.

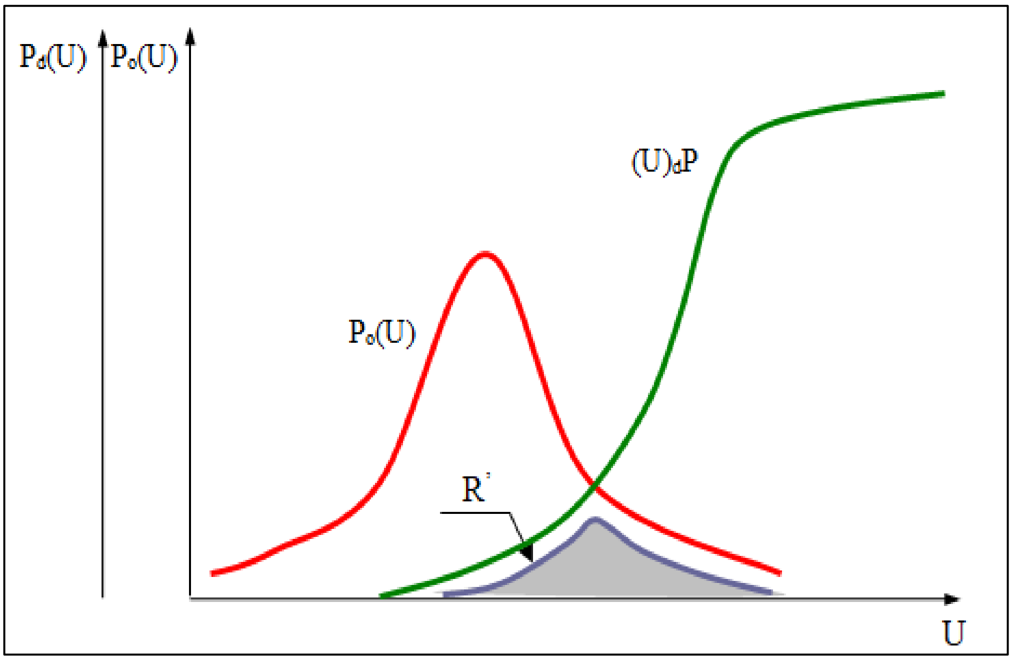

Figure 9: Overvoltage probability distribution, insulation failure cumulative distribution and risk of failure probability distribution.

Insulation coordination which is determined with the use of this method has form of an optimization work.

Simulation for Lightning waveform

Front time: The wave rises very sharply from zero to reach its peak—approaching 10^3 A in a very short time in a very short time (approximately 1.2 μs). figure 10

Tail Time: After reaching the peak, the wave begins to decay slowly due to After the effect of the reaching half its maximum value (5,000 amperes) at approximately 50 μs.

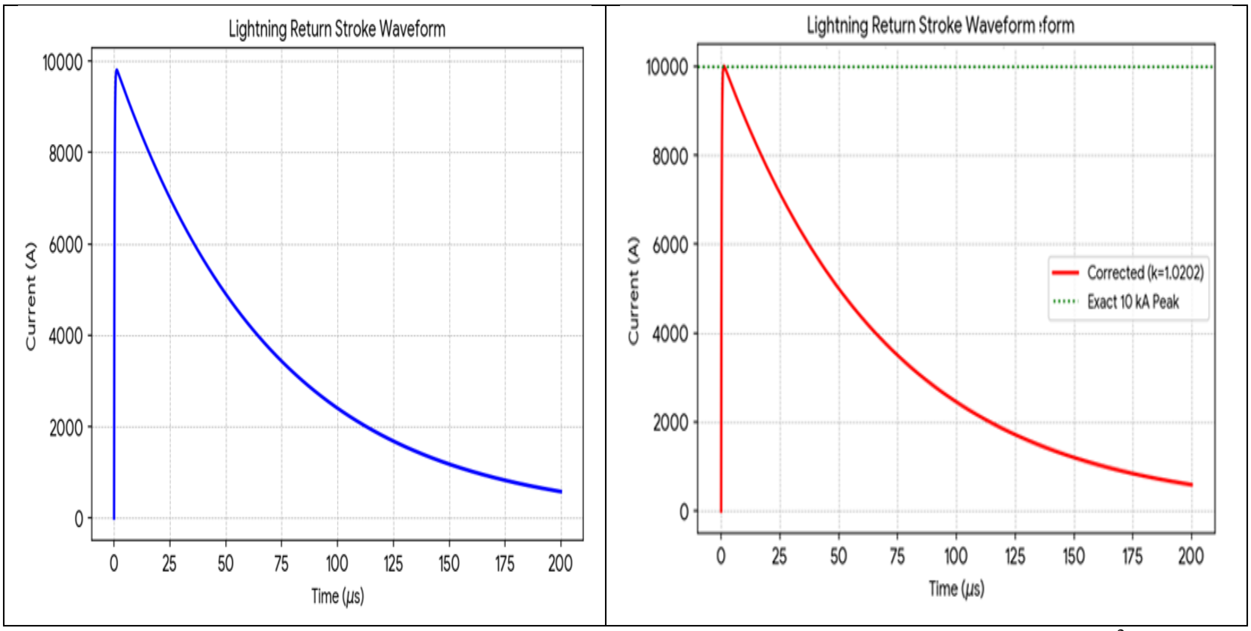

Figure 10: The wave rises very sharply from zero to reach its peak—approaching 10^3 A in a very short time in a very short time (approximately 1.2 µs)

Conclusion

This paper evaluated the profound influence of lightning-induced overvoltage's on electric power systems, contrasting the distinct mechanisms of direct strokes and the highly frequent indirect discharges that cause system micro-interruptions. The research demonstrates that while power system insulation natively exhibits higher dielectric strength against lightning impulses than switching or temporary overvoltage's, the strength against lightning impulses than switching or temporary overvoltage's, the extreme peak currents (frequently ranging up to 100 kA) and rapid front times create severe operational risks that demand systematic insulation design. Through analysis of external insulation configurations, it is established that air gap flashover phenomena possess an inherently statistical nature conforming to a cumulative Gaussian distribution. Consequently, effective insulation coordination cannot rely solely on deterministic maximum values. By optimizing the coordination margin (UM) between the insulation's statistical breakdown threshold (U50) and the protective level (Up) offered by surge arresters or shielding wires, a balanced compromise can be engineered. Ultimately, integrating probabilistic failure risk evaluations into computer simulations provides a reliable framework for minimizing structural damage and optimizing financial expenditures while maximizing power grid resilience.

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