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EXPERIMENTAL STUDY OF ENVIRONMENTAL FACTORS' IMPACT ON SURFACE LEAKAGE CURRENTS OF HIGH-VOLTAGE SUPPORT INSULATORS

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Abstract. *Ensuring the reliability of high-voltage insulation systems is critical for the safe and efficient operation of power equipment. Surface leakage currents, formed under the influence of atmospheric and anthropogenic factors, accelerate the aging of insulation materials, reduce their dielectric strength, and increase the risk of emergency failures. Particular attention is given to the combined impact of relative humidity, temperature fluctuations, surface contamination, and wind speed, which together create highly unfavorable conditions for the operation of insulation systems and necessitate the implementation of automated approaches to monitoring and managing their condition.*

The aim of this work is to experimentally determine the influence of key climatic and anthropogenic factors on the leakage currents of support insulators, to assess the relative contribution of these factors, and to construct generalized graphical dependencies. The results obtained can be used to predict the performance of insulation systems and to develop automated methods for optimizing the operating modes of power equipment.

The research was conducted on IOS-35-1000 UHL insulators operated at substations in the central region of Ukraine.

It was found that the dominant influencing factors are relative humidity (30%), negative temperature difference (25%), and surface contamination (20%). Absolute humidity, duration of moisture exposure, and wind speed have a secondary effect on leakage current, with wind partially reducing surface conductivity. The experimental *graphical dependencies reflect the dynamics of conductive layer formation under various moistening conditions.*

Critical operating conditions for insulation systems arise when high humidity, negative temperature differences, and the presence of a hygroscopic contamination layer are combined. The results obtained can be used to predict the reliability of insulation structures and to improve automated insulation condition monitoring systems.
Key words: *high-voltage insulator, leakage current, surface contamination, atmospheric factor, experimental study*.

Topicality. Ensuring the reliability of high-voltage insulation systems is among the key challenges of modern industrial power engineering. The formation and development of surface leakage currents on insulation materials under the influence of atmospheric and anthropogenic factors significantly affect the operational safety of power equipment. It is well established that prolonged exposure to factors such as relative and absolute air humidity, temperature fluctuations, wind speed, and the presence of surface contamination substantially increases the level of surface leakage currents. The growth of these currents accelerates localized material aging, reduces dielectric strength, and may ultimately result in emergency failures of high-voltage equipment.

Given the complexity and multifactorial nature of this phenomenon, it is critically important to conduct experimental studies to identify the mechanisms and relative contributions of individual factors in the formation of leakage currents. Particular attention should be paid to the combined influence of these factors, since their synergy (for example, elevated humidity and the presence of hygroscopic contaminants under condensation conditions) creates critically unfavorable conditions for the operation of insulation systems and necessitates the optimization of industrial power supply operating modes.

Analysis of recent research and publications. Modern scientific research highlights the development of methods for diagnosing and predicting the condition of insulation using both experimental and analytical approaches. For instance, the authors [1] demonstrated that integrating traditional leakage current measurements with machine learning algorithms enables the classification of high-voltage insulator contamination levels with an accuracy exceeding 98%. Similarly, the study in [2] confirmed that the analysis of higher-order current harmonics and phase characteristics serves as an effective indicator of moisture and contamination levels on insulating surfaces. Time series-based degradation prediction methods allow for the assessment of defect risks in distribution networks [3][5], while combined temperature and electrical measurements facilitate the tracking of aging processes and the early stages of dielectric strength degradation [4].

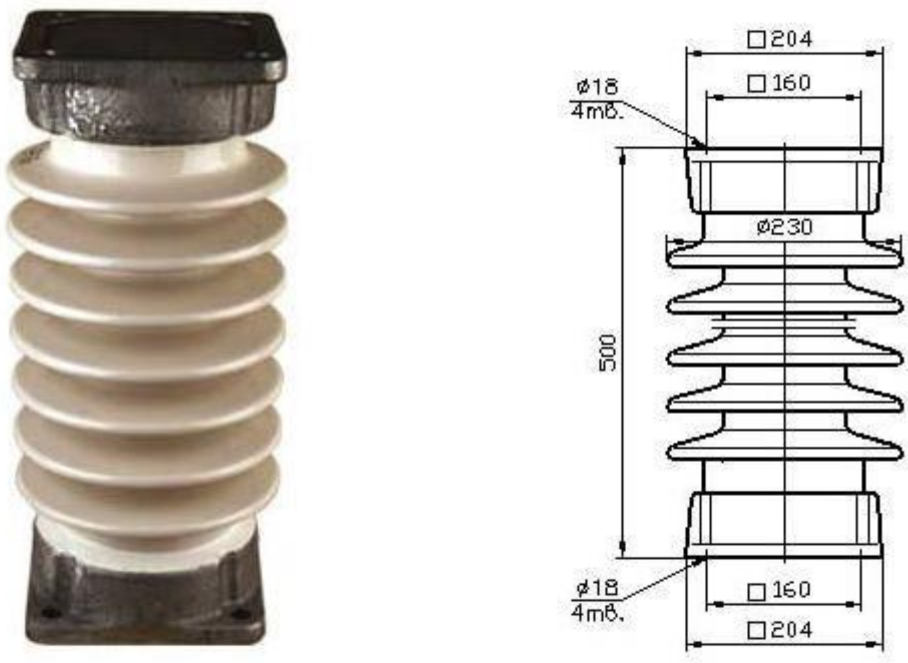
Despite significant progress in algorithmic signal processing, the literature still lacks a systematic presentation of quantitative dependencies of leakage current on specific climatic parameters. Therefore, comprehensive experimental investigations into the influence of humidity, temperature fluctuations, wind speed, and contamination levels on leakage current remain highly relevant. This study presents generalized graphical dependencies that not only enable the comparison of individual factors but also provide an assessment of their relative contributions to the formation of surface electrical conductivity in high-voltage support insulators. Such findings are of considerable practical significance for predicting performance and optimizing the operating modes of insulation systems under real climatic conditions.

The aim of this work is to experimentally determine the influence of key climatic and anthropogenic factors on the leakage currents of support insulators, to assess the relative contribution of these factors, and to construct generalized graphical dependencies.

Materials and methods of research. An analysis of the current literature indicates that leakage current is regarded as a sensitive indicator of the condition of insulation systems, with its variations being directly linked to the effects of moisture, temperature gradients, and surface contamination. Although a considerable body of research exists, the primary emphasis has predominantly been placed on diagnostic methods employing spectral analysis or machine learning algorithms [1–5]. At the same time, the systematic presentation of quantitative dependencies of leakage current on individual atmospheric and anthropogenic factors remains insufficiently addressed in the literature.

This underscores the need for targeted experimental investigations that would enable the isolation of each factor’s influence and facilitate a comparative assessment. The present work reports the results of such investigations, examining the dependence of leakage current on absolute and relative humidity, temperature differences, wind speed, and surface contamination. The obtained data are presented as graphical dependencies, followed by an integral assessment of the relative influence of these factors.

Research results and their discussion. To assess the degree of contamination of support insulators and to conduct experimental studies, electrical network companies in the central region of Ukraine were selected, where more than 150 substations operating at voltage levels of 150/35/10 kV and 35/10 kV are in service. For 35 kV overhead lines, such substations predominantly use IOS-35-1000 UHL support insulators (Fig. 1).



a *b*

Fig. 1. IOS-35-1000 UHL-type insulators:
a – external view; *b* – drawing

Studies on the moisture content of insulators in complete switchgear assemblies are widely represented in the literature [6–10], including both quantitative and qualitative assessments of the impact of environmental factors on leakage current. Insulators in complete switchgear are usually protected by cabinet enclosures; therefore, the main sources of moisture are condensation and dew, while external insulators are additionally exposed to atmospheric precipitation. The most hazardous factors are fog, drizzle, and dew, which can be reproduced under laboratory conditions by applying controlled contaminant layers. Surface wetting may occur as a result of condensation, droplet deposition, the hygroscopicity of contaminants, and molecular diffusion between the salt solution and water vapor. Condensation arises from temperature differences between the surrounding air and the insulator surface, with the rate of the process determined by the ratio of saturated vapor near and directly on the surface.

These processes can be reproduced in laboratory conditions by artificially applying contaminants with quantitative and qualitative characteristics approximating those of the natural surface layer to the insulator. Therefore, in accordance with [11], the wetting of insulator surfaces may occur through: (i) condensation; (ii) droplet deposition on the insulator surface; (iii) hygroscopic behavior of contaminants; and (iv) molecular diffusion between the salt solution on the surface and water molecules in the air.

Moisturization of insulator surfaces by condensation occurs as a result of temperature differences between the ambient air and the insulator surface. The driving force of this process is the difference in saturated vapor density at the insulator surface and at some distance from it. The rate of condensation is determined by the following equation:

$$V_k = h_a\left(P_n - P_1\right), \tag{1}$$

where V_k is the condensation rate per unit surface area; h_a is the diffusion coefficient; P_n is the saturation vapor density at a distance from the insulator surface; and P is the saturation vapor density at the insulator surface.

The amount of condensate accumulated per unit surface area over a time period T is given by:

$$W = \int_0^T V_k d\tau, \tag{2}$$

where τ is the time interval.

When relative humidity reaches 100%, excess moisture forms droplets that fall onto the insulator surface, producing a fog effect. The deposited layer consists of both active and inert particles (e.g., NaCl, KCl), which absorb and retain moisture, thereby creating favorable conditions for the dissolution of salts. Since the vapor pressure of water in solution is always lower than that of pure water, molecular diffusion occurs, contributing to the accumulation of moisture on the contaminated surface. All of these processes alter the leakage current, which serves as a key parameter for automating insulation condition monitoring. To assess the risk of flashover and to determine threshold values for the operation of protective devices, it is necessary to establish the dependence of leakage current and discharge voltages on environmental factors.

Accordingly, studying the effect of moisture-related processes on leakage current is particularly important for insulators installed outdoors. For this purpose, it is essential to select and justify the factors governing changes in leakage current and to evaluate the contribution of each. This is possible only through the construction of a mathematical model describing the dependence of leakage current on influencing factors, based on experimental data. To determine the risk of insulator bridging and to justify the operational settings of automatic devices for monitoring contamination of 35 kV overhead line insulators, it is also necessary to establish the dependence of discharge voltages on insulator leakage current under operating voltage.

The research was conducted in a dedicated chamber (Fig. 2) using a device for applying artificial contamination to the insulator surface (Fig. 3). Direct measurement of leakage currents was carried out using the circuit shown in Fig. 4. After installing and calibrating the measuring circuit for the reference insulator under study, a series of experiments was performed to evaluate the influence of major atmospheric and anthropogenic factors on leakage currents. During these investigations, changes in surface conductivity were recorded under the influence of absolute and relative humidity, the temperature difference between air and insulator surface, wind speed, surface contamination, and wetting duration. The analysis of these factors made it possible to determine their relative contributions to conductive layer formation, to assess critical operating conditions, and to establish the foundation for developing an integrated model for predicting the reliability of insulation systems.

Fig. 2. High-voltage test chamber with the experimental setup.

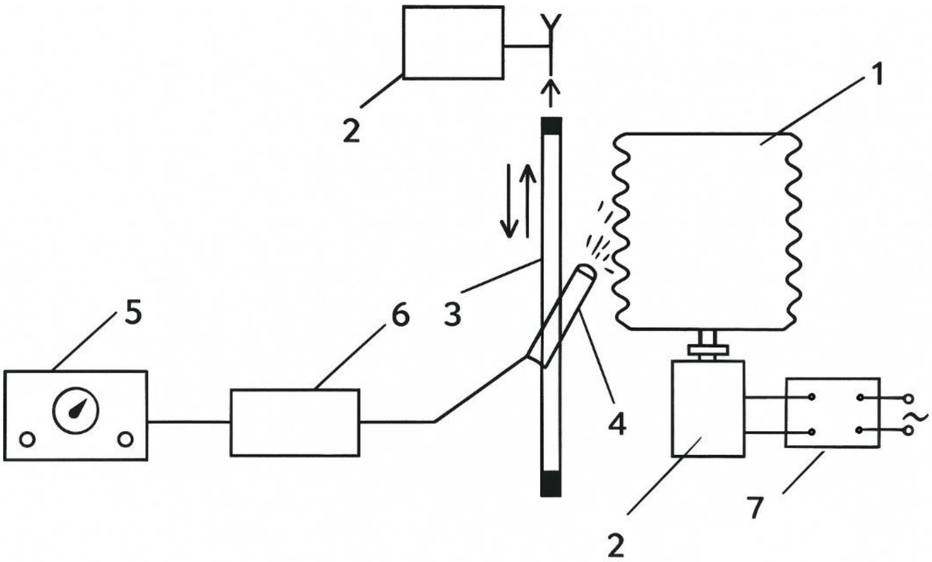


Fig. 3. Device for applying artificial contaminants to the surface of an insulator: 1 – insulator; 2 – electric motor; 3 – reciprocating motion guides; 4 – airbrush; 5 – compressor; 6 – receiver; 7 – voltage regulator**.**

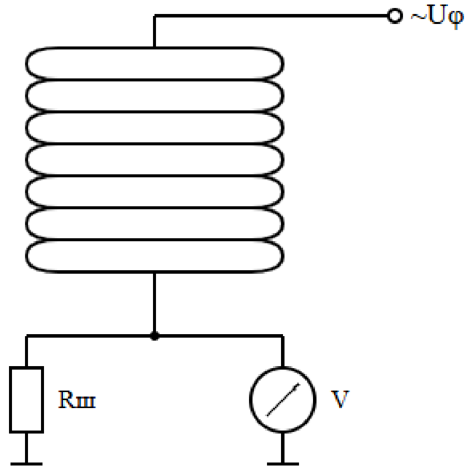
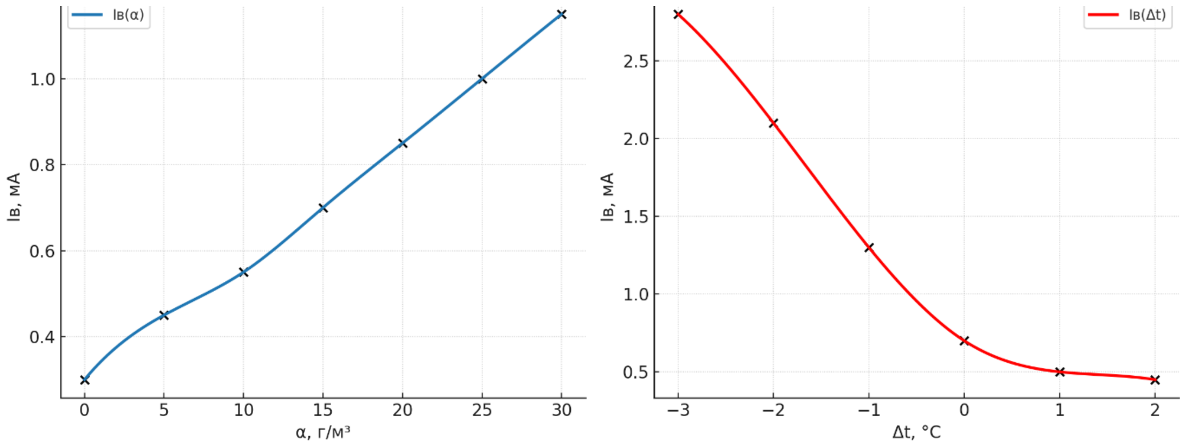


Fig. 4. Diagram of leakage current measurement for support insulators

Therefore, the influence of humidity was investigated first. As shown in the graphs in Fig. 5, humidity parameters (both absolute and relative) together with thermal conditions significantly affect the level of leakage current.

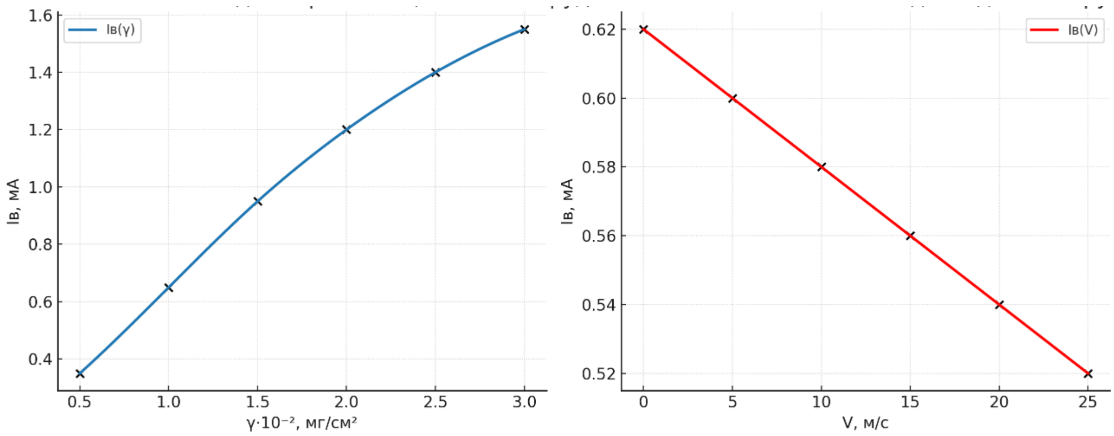


a) b)

Fig. 5. Dependence of leakage current on (a) absolute air humidity α and (b) temperature difference Δt.

An increase in absolute humidity from 0 to 30 g/m³ is accompanied by an almost exponential rise in *Iв*, indicating the dominance of adsorption mechanisms in the formation of the conductive layer. At the same time, negative values of Δt intensify moisture condensation and cause a sharp increase in *Iв*, whereas positive values of Δt maintain conductivity at a low level in the absence of condensation.

Experimental studies of pollution and wind influence have shown that surface contamination enhances conductivity, while wind partially reduces it (see Fig. 6). A 4–5-fold increase in γ results in a 3–4-fold increase in *Iв*, due to the hygroscopic properties of salt deposits and the formation of a continuous conductive layer. An increase in wind speed from 0 to 25 m/s reduces *Iв* by 10–15% as a result of surface drying and partial removal of condensate.



a) b)

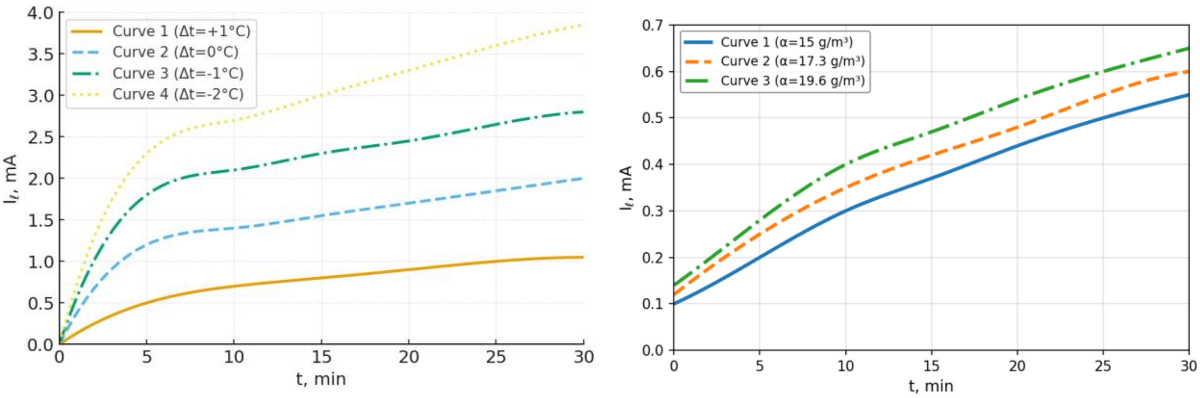
Fig. 6. Dependence of leakage current on (a) surface density of the contamination layer γ and (b) wind speed V.

The study of moisture duration and temperature effects (Fig. 7a) showed that the initial 5–10 minutes of moisture exposure account for the primary increase in conductivity. During the first few minutes, a conductive layer is formed, after which the curve approaches a quasi-steady state. Negative values of Δt result in significantly higher *Iв* values due to condensation. At the same time, the analysis of absolute humidity effects at different temperature regimes (Fig. 7b) demonstrated that even in the absence of condensation (Δt=+1°C), an increase in α leads to higher *Iв*. This increase is associated with moisture adsorption and higher surface conductivity; however, the effect remains moderate without condensation.

The investigation of condensation effects at negative Δt (Fig. 8a) showed that at Δt=−2°C, condensation produces high initial values of *Iв* and rapid growth. The condensation film sharply reduces surface resistance, and an increase in α further intensifies this effect.

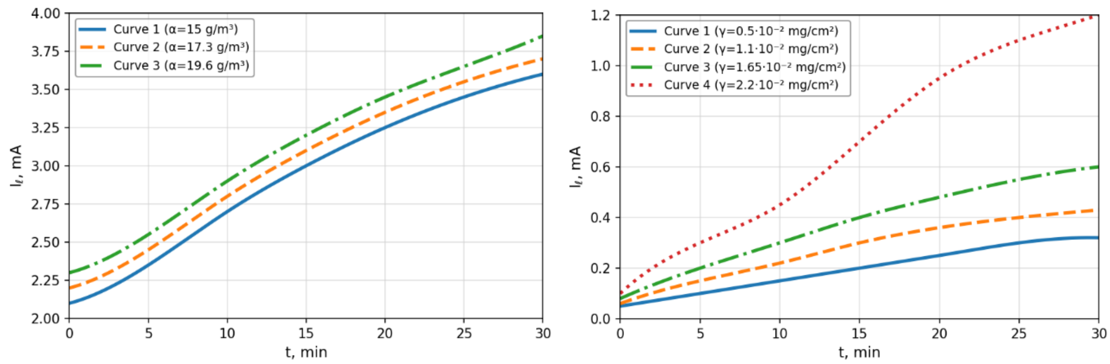
The analysis of contamination effects at Δt=+1°C (Fig. 8b) demonstrated that in the absence of condensation, contamination significantly increases *Iв*, although the absolute values remain relatively small. Hygroscopic salts enhance moisture retention and increase conductivity, with the effect becoming more pronounced as γ increases.

Finally, the evaluation of contamination effects at Δt=−1°C (Fig. 9a) revealed that the combination of contamination and negative Δt produces the most critical operating conditions.



a) b)

Fig. 7. Graphs of leakage current *Iв* dependence on:
(a) exposure time at different Δt (φ=100%);
(b) exposure time at Δt=+1°C (φ=100%).

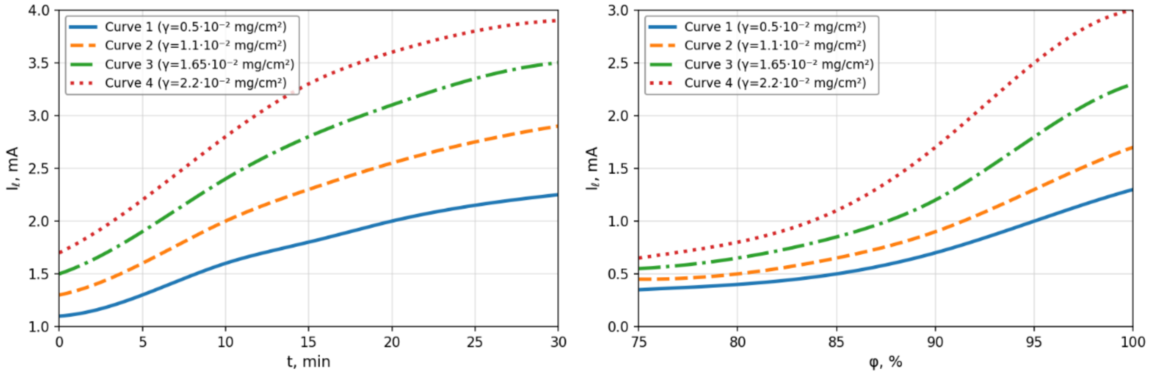


a) b)

Fig. 8. Graphs of leakage current *Iв* dependence on:
(a) exposure time at Δt=−2°C (φ=100%);
(b) exposure time at different γ values for Δt=+1°C (φ=100%).

The simultaneous action of condensation and a hygroscopic contamination layer significantly enhances conductivity, bringing the system closer to critical operating conditions. As shown in Fig. 9b, within the range of φ>90%, a sharp transition to high values of *Iв* is observed.

The growth of *Iв* exhibits a threshold character: when φ>90%, a continuous conductive layer is formed, and surface contamination further intensifies this effect.



a *b*

Fig. 9. Graphs of leakage current Iв dependence on:
(a) exposure time at different γ values for Δt=−1∘C (φ=100%);
(b) relative humidity at different γ values (τ=11min).

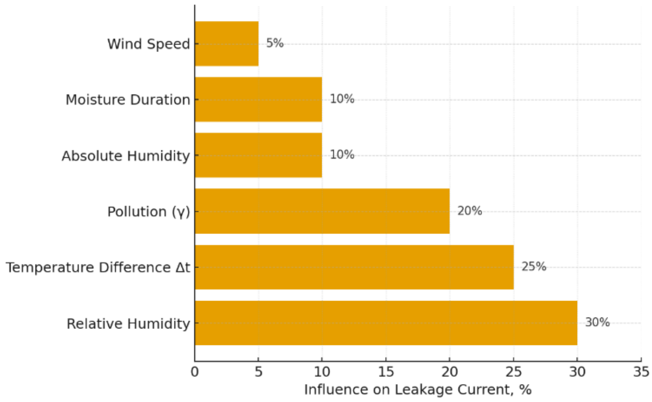


Fig. 10. Integral assessment of the relative influence of factors on insulator leakage current

The obtained results (Fig. 10) indicate that the dominant factor is relative air humidity (30%), which determines the conditions for moisture condensation on the insulator surface. The second most significant factor is the temperature difference (25%): negative values of Δt intensify condensation processes, sharply increasing the leakage current. Another important factor is the surface density of contamination (20%), which creates additional conductive paths.

Secondary but still relevant factors include absolute humidity (10%) and moisture exposure duration (10%), which determine the rate of surface layer saturation. The least significant factor is wind speed (5%), which generally exerts a stabilizing effect through partial drying of the insulator surface.

Thus, critical operating conditions for insulation systems are formed by the combination of three factors: high relative humidity, negative temperature difference, and the presence of a hygroscopic contamination layer. These findings provide the basis for developing a predictive model of the durability and reliability of insulation structures under the influence of climatic factors.

Conclusions and perspectives.

1. The relevance of this work is determined by the need to improve the reliability of high-voltage insulation systems in industrial power engineering, since surface leakage currents serve as an indicator of insulation material degradation and a potential cause of equipment failures. An analysis of scientific sources shows that most studies focus on diagnostic methods, whereas quantitative dependencies between leakage current and the influence of specific atmospheric and anthropogenic factors have not been sufficiently investigated. The practical significance of this research lies in the possibility of applying the obtained results to optimize operating modes, enhance the efficiency of power supply systems, and implement automated control systems.

2. The experimental investigations made it possible to obtain generalized graphical dependencies reflecting the contribution of each factor (humidity, temperature, contamination, wind, moisture exposure duration) to the formation of leakage currents. Based on the obtained results, an integral assessment of the relative influence of factors was constructed: the most significant contributions are relative humidity (30%), temperature difference (25%), and surface contamination (20%).

3. The practical value of this work consists in the possibility of using the obtained dependencies to predict the performance of high-voltage insulators under different climatic conditions and to optimize the operating modes of equipment. The prospects for further research are related to the development of mathematical models that combine experimental data with artificial intelligence algorithms, as well as the determination of threshold values of leakage currents to improve automated insulation condition monitoring systems.

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ЕКСПЕРИМЕНТАЛЬНЕ ДОСЛІДЖЕННЯ ВПЛИВУ ФАКТОРІВ НАВКОЛИШНЬОГО СЕРЕДОВИЩА НА ПОВЕРХНЕВІ СТРУМИ ВИТОКУ ВИСОКОВОЛЬТНИХ ОПОРНИХ ІЗОЛЯТОРІВ

А. Котиш, К. Петрова, В. Павленко, О. Воляник

Анотація. *Забезпечення надійності високовольтних ізоляційних систем є критичним фактором безпечної та ефективної експлуатації енергетичного обладнання. Поверхневі струми витоку, що формуються під дією атмосферних і техногенних чинників, викликають старіння ізоляційних матеріалів, зниження їх діелектричної міцності та підвищують імовірність аварійних відмов. Особливу увагу приділено комплексному впливу відносної вологості, температурних перепадів, забруднення поверхні та швидкості вітру, які у поєднанні формують критично несприятливі умови для функціонування ізоляційних систем і потребують впровадження автоматизованих підходів до моніторингу та управління їхнім станом.*

Метою роботи є експериментальне визначення впливу ключових кліматичних і техногенних факторів на струми витоку опорних ізоляторів, оцінювання відносного внеску їх впливу та побудова узагальнених графічних залежностей.

Отримані результати можуть бути використані для прогнозування працездатності ізоляційних систем та розроблення автоматизованих методів оптимізації режимів експлуатації енергетичного обладнання.

Дослідження виконано на ізоляторах типу ІОС-35-1000 УХЛ, що експлуатуються на підстанціях центральноукраїнського регіону. Встановлено, що домінуючими чинниками впливу є відносна вологість (30 %), негативна різниця температур (25 %) та поверхневі забруднення (20 %). Абсолютна вологість, тривалість зволоження та швидкість вітру впливають на струм витоку другорядно, при цьому вітер частково знижує провідність поверхні. Експериментальні графічні залежності відображають динаміку формування провідного шару під різними умовами зволоження.

Критичні умови експлуатації ізоляційних систем виникають при поєднанні високої вологості, негативної різниці температур та наявності гігроскопічного шару забруднень. Отримані результати можуть бути використані для прогнозування надійності ізоляційних конструкцій та удосконалення автоматизованих систем контролю стану ізоляторів.

Ключові слова: ***високовольтний ізолятор, струм витоку, поверхневе забруднення, атмосферний фактор, експериментальне дослідження***