Predicting the service life of high-voltage insulators using actual leakage current values

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High-voltage insulators are the most massive elements of an overhead power line. The task of determining their current state and especially their residual life is crucial to ensure the reliability of the entire line. The issues of high-voltage insulators operation, physical processes occurring in the insulation, as well as factors leading to degradation of the insulation are considered in this study. The possibility of using the leakage current values of insulators for the control of the insulation and prediction of its resource is substantiated. The results of experimental studies of the leakage current of high-voltage insulators depending on their service life are considered.

Keywords: Dielectric surface, high-voltage insulators, leakage current, power lines, service life.

THERE are many causes of malfunction that can lead to power outages, including equipment failure, external factors, natural factors, improper maintenance and operation, improper installation, etc. Table 1 shows the statistics of damage to components of overhead power lines of voltage classes 110–750 kV for 1997–2007 (refs 1–7).

Figure 1 shows the summary data on the faults of overhead line elements obtained from Table 1.

The condition of insulators on power lines is of paramount importance for the successful operation of the power grid. Insulators that are damaged or do not meet the electrical requirements can lead to power outages. Insulation damage accounts for about 30% of the total number of violations in the operation of high-voltage power lines. The main causes of insulation damage are the effect of climatic factors, atmospheric and switching overvoltage, insulation aging, incompatibility with the natural and climatic conditions of operation, etc.[1–7].

Linear suspension insulators are usually characterized by a long service life and do not require large expenditure to maintain their normal technical condition. However, they work in the polluted atmosphere, and it is inevitable that after several months of operation the insulators are covered with contaminants. Therefore, it is advisable to take preventive measures for identifying the degraded insulators or those that have failed in their operation before they cause serious problems.

Methods of checking the condition of isolators vary from simple visual inspection to procedures using different testing equipment that differ in their degree of simplicity and reliability[8–10]. All the existing methods solve the problem of monitoring the condition of the insulators in order to determine the critical level of permissible insulation resistance[11–13]. At the same time, analysis of the prediction possibility of the insulator resource based on monitoring its condition according to the results of periodic testing is of particular interest.

The article proposes possible solutions to the problem of determining the resource of insulators on the basis of experimental studies.

Insulators failures can be divided into the following categories: surface contamination, flashover and breakdown.

Test methods, checks and measurements that determine the insulation condition of current-carrying parts of electrical equipment follow from the physical nature of the insulation. Any insulation used in electrical machines and apparatus is essentially a capacitance with a complex medium. For this reason, physical processes in the insulation when voltage is applied to it are similar to those that take place in a capacitor. For the convenience of considering these processes, in Figure 2 we depict insulation in the form of an equivalent circuit[14].

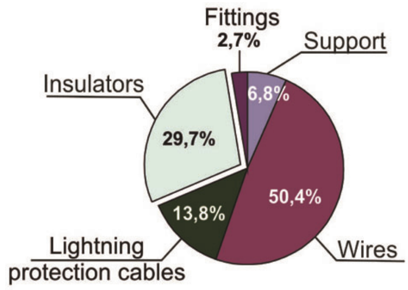

Figure 1. Summary data on the faults of overhead line elements.

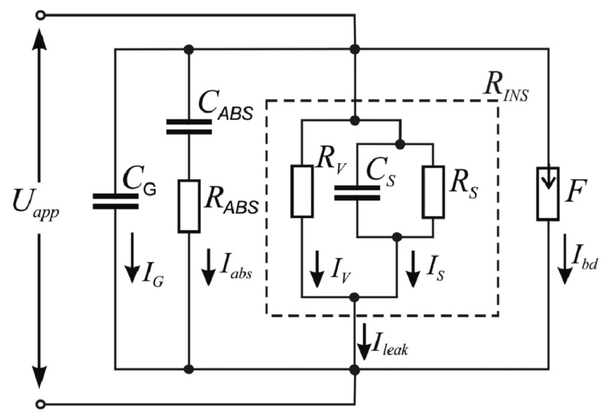

Figure 2. Insulator equivalent circuit. C_G, I_G, Geometric capacitance and charge current; R_{INS}, Insulation resistance; I_{leak}, Leakage current; I_{bd}, Current in isolation during breakdown; U_{app}, Voltage applied to the insulation during measurements and tests; R_V, Volume resistance; R_S, C_S, Resistance and capacity of the surface layer of contamination; R_{ABS}, C_{ABS}, Resistance and absorption capacity and F, Spark gap conventionally depicting breakdown in isolation.

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Table 1. Relationship between fault causes and fault type of overhead power transmission lines components with 110–750 kV

Fault component	110 kV Number	110 kV Percentage	220 kV Number	220 kV Percentage	330 kV Number	330 kV Percentage	500 kV Number	500 kV Percentage	750 kV Number	750 kV Percentage	110–750 kV Number	110–750 kV Percentage
Supports structures including:	207	2.6	92	7.8	11	10.0	12	6.2	2	40	324	3.4
Metal	98	1.2	22	1.9	3	2.7	3	1.5	2	40	128	1.3
Concrete reinforced	109	1.4	70	5.9	8	7.3	9	4.7	–	–	196	2.1
Wires	4240	53.3	406	34.3	25	22.7	82	42.5	2	40	4755	50.4
Lightning protection cables	1066	13.4	180	15.2	13	10.9	46	23.8	1	20	1306	13.8
Insulators	2269	28.5	448	37.7	52	47.3	39	20.2	–	–	2808	29.7
Fittings	171	2.2	59	5.0	10	9.1	14	7.3	–	–	254	2.7
Total	7953	100.0	1185	100.0	111	100.0	193	100.0	5	100.0	9448	100.0

When rectified voltage is applied, at the initial moment of time only the current I_G of the geometric capacitance charge flows through the insulator, i.e. of the capacitance determined by the geometrical dimensions of insulation. At this moment, the real environment, the insulation material, is not manifested, as if there is some vacuum between its boundaries (the plates of the capacitor C_G).

This current quickly ceases, an electric field arises in the dielectric due to positive and negative charges accumulating at the boundaries of the dielectric. Under the influence of this electric field, polarization occurs, which is characteristic of a real insulating material with a complex structure.

After the end of the charge of the geometric capacitance, an absorption current labs flows through the insulation material. This current is determined by the orientation characteristic of the insulation dipoles, as well as the charge of individual capacitors C_{ABS} (absorption capacitors), formed between the layers of insulation. The value of this current depends on the defects and heterogeneity of the insulation, as well as the active resistance of individual adjacent areas, the so-called absorption resistances.

After completing the polarization process, i.e. absorption capacitance charge, I_{abs} becomes zero, but leakage current continues to flow through the insulation, which is the sum of the conduction current I_V (volume current) and the surface current I_S that is determined by the total insulation resistance conventionally shown in Figure 2 as R_{INS}.

Resistance R_{INS} depends on resistance R_V of the material of the insulator to direct current, and on the values of resistance R_S and the reactance values of capacitance C_S of the superficial layer of surface contamination (insulation condition).

The conduction current I_V can be defined as

$$I_V = \frac{U_{app}}{R_V}, \tag{1}$$

where U_{app} is the applied voltage to the insulator and R_V is the volume resistance (resistance of the dielectric material).

The surface current I_S is determined from the following equation

$$I_S = U_{app}\left(\frac{1}{R_S} + j\omega C_S\right). \tag{2}$$

When the insulator surface is moistened, the capacitive resistance (ωC) of the surface contamination layer increases significantly compared to the active one (R_S). Therefore, the value of the surface current I_S is determined only by the resistance value R_S.

If the voltage applied to the insulation exceeds its electric strength, it is broken down or flashed over on the surface, accompanied by burnout and destruction of the damaged area. The spark gap F in the circuit in Figure 2 conditionally depicts such a breakdown of the insulation.

Thus, the main indicator of the insulation condition is the leakage current I_{leak}. The presence of internal and external defects (damage, moisture, surface contamination) reduce the resistance (R_{INS}) of the insulation. In steady state, the resistance R_{INS} of the insulation can be determined by measuring the current I_{leak} passing through the insulation, according to the voltage applied to it U_{app}

$$R_{INS} = \frac{U_{app}}{I_{leak}}. \tag{3}$$

The process of establishing the leakage current is described in the literature[15,16].

Since the insulators along the leakage path have a variable diameter as well as an uneven density of contamination, the density of leakage currents in some areas is not the same. In places with higher density, resistance of the contamination layer increases due to the most intensive drying. The voltage drop and heat release in these areas grow, which leads to subsequent increase in the contamination layer resistance. As a result, linearity of the voltage distribution over the contaminated surface of the insulator is sharply disturbed.

A significant increase in voltage in the dried areas causes the occurrence of surface partial discharges, which are observed on the surface of the insulator in the form of blue-coloured discharges. These discharges shunt the dried zones and acquire the arc character. In this case, there are significant jumps in leakage currents, which are the cause of developing resistant partial arcs.

The achievement of a certain value by the leakage current along the contaminated and moistened surface of the insulator, sufficient to dry the surface area and form a stable partial arc, leads to the fact that the arc does not go out, but quickly stretches and covers the entire insulating gap.

A separate partial discharge is, as a rule, accompanied by scattering of small energy and an insignificantly small destructive effect. However, multiple repetition of discharges over a long time gradually leads to the insulation destruction till the complete breakdown. The prolonged effect of partial discharges on a solid dielectric can cause its destruction with developing conductive charred traces on the surface, tracks, the appearance of which causes a sharp decrease in discharge voltage even with a dry dielectric surface.

With long-term use, ultraviolet radiation and surface discharges can significantly increase the level of wear. Partial surface discharges are not the only cause of electrical aging of high-voltage insulation. With prolonged exposure to voltage in the insulation, there can also occur electrochemical aging processes. In addition, there also occurs thermal aging of the dielectric material, i.e. gradual deterioration of the characteristics of internal insulation during prolonged heating occurs due to the fact that chemical processes occur or accelerate with the rise in temperature. Deterioration of the contact connection in the insulator string and in the places of its connection to the current-carrying surfaces also leads to their heating and negatively affects the insulator resource[17].

The specific content and rate of chemical reactions in insulation can be significantly different depending on the properties of the dielectrics and aging conditions, that is, on the temperature, amount of air (oxygen) remaining in the insulation during manufacture, or its rate during aging, the presence of chemically active impurities (contamination) and especially moisture, on the contact with metals and properties of these metals, etc. The electric field can also have a noticeable effect on the aging process.

These processes lead to decreasing the insulation resistance R_{INS} and, accordingly, increasing the leakage current and ultimately to rapid aging and failure[18,19].

There are many causes of insulator aging that also cause uncertainty in estimating the expected lifetime of an insulator. If the wear process is slow, the insulator may work satisfactorily during a long period of time. However, in the areas subject to contamination, wear may accelerate and the insulator may fail after a short period of time. Studies show that some insulators work well for 18–20 years, while others fail after a few months of operation.

The analysis of laboratory data and the published literature allows formulating the following hypotheses of insulator aging[18–21]:

(i) In the course of operation, due to a combination of mechanical effects and ultraviolet radiation, there is a slight erosion of the insulator surface that increases its irregularities and leads to accumulation of dirt on it.
(ii) With moistening, a conductive medium is formed on the surface of the insulator that changes the nature of the leakage current from capacitive to resistive.
(iii) Uneven distribution and humidity of contamination cause uneven distribution of voltage gradient over the surface and in places with high voltage the gradient partial surface discharge occurs, which increases the leakage current.
(iv) The flow of partial discharges and leakage current is accompanied by local heating and contribute to the aging of the insulator material.
(v) As the surface irregularities increase, the accumulation of contamination in them increases with acceleration in the aging of the insulator.

On this basis, the leakage current value can serve as a criterion for the current condition of the insulation of high-voltage insulators, and can also be used to predict the service life of insulators[22–25].

In this study, a glass disc insulator-type PS120B has been used for experimental purposes. Table 2 provides the technical characteristics of the insulator. Figure 3 shows the photograph of the same.

Table 2. Technical parameters of the insulator

Type	Materials	H (mm)	D (mm)	L (mm)
PS120B	Glass	127	255	320

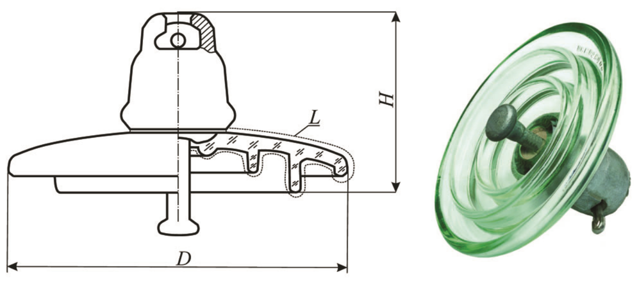

Figure 3. Image of the PS120B-type insulator.

For measuring I_{leak} values and assessing the possibility of determining the condition of high-voltage insulators and predicting their service life in the laboratory, an experimental set-up was devised based on high-voltage equipment AID70/50. Figures 4 and 5 show a photograph and schema of the experimental set-up respectively.

To measure the leakage current to the OI (insulator), high voltage is supplied from the output of the test transformer T2. Voltage regulation is performed at the low side of the test transformer by means of a single-phase laboratory autotransformer T1 with the voltage regulation limit from 0 to 250 V. The value of the voltage applied to the insulators is measured using a voltage sensor (VS) made in the form of a resistive voltage divider R1, R2. To measure the values of the leakage current, a current sensor (CS) made on a current shunt R3 is used. The measured voltage and current signals are fed to the oscilloscope A1. For visual inspection, the magnitude of the leakage current is measured using a PA1 milliammeter. To protect transformers T1 and T2 from damage when a current exceeds the nominal values, current protection is performed on the basis of a current relay K1 connected via a current transformer TA1 to the secondary circuit of the autotransformer T1. If the current in the measuring circuit reaches the pick-up setting, the power supply to the test bench stops.

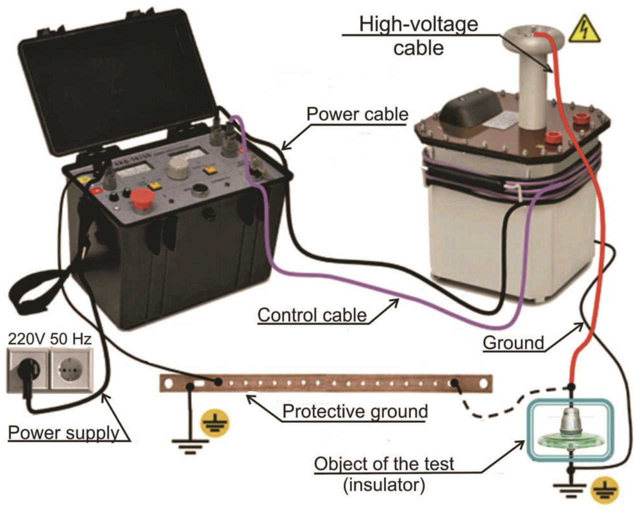

Figure 4. Experimental set-up.

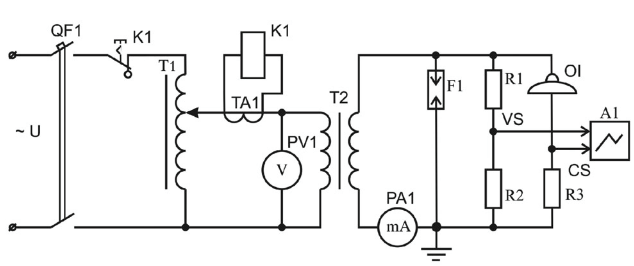

Figure 5. Testing bench circuit for measuring insulator parameters. QF1, Automatic switch; T1, Single-phase autotransformer; T2, Test transformer; TA1, Current transformer; K1, Electromagnetic current relay; VS, Voltage sensor; CS, Current sensor; OI, Object of the test (insulator); F1, Spark gap; A1, Oscilloscope; PV1, PA1, Electrical measuring instruments.

The measurements were carried out indoors under the following conditions: ambient temperature 21°C and humidity 43%. Before testing, the insulator surfaces were cleaned by washing with isopropyl alcohol and rinsing with distilled water in order to remove any traces of dirt and grease. For each insulator, leakage current was measured under dry conditions using AC voltage. The measurements were performed as follows: with the output voltage smoothly increasing in the range from 0 to 19 kV in 1 kV increments, its voltmeter values by PV1 were recorded, as well as the corresponding leakage current I_{leak}. The leakage current by PA1 was measured 60 sec after voltage was applied to the insulator.

In the course of testing, leakage currents of PS120B type insulators were measured: 30 new, 26 were in operation for 10 years and 16 were in operation for 30 years. Waveforms related to leakage current were collected as information about voltage through a resistance (R3) of 10 kΩ connected to the output of the insulator. The leakage current had a pronounced component of the frequency 50 Hz with random small emissions (Figure 6).

According to the data obtained, in Figure 7 the leakage current values for new and pre-existing insulators as a function of the applied voltage have been plotted. The figure shows the range of variation of leakage current values from the minimum (min(old10)) to the maximum (max(old10)), as well as the average (aver(old10)) values were in operation for 10 years insulators and the range of variation from the minimum (min(new)) to the maximum (max(new)), as well as the average (aver(new)) values of the leakage current of new insulators and the average values (aver(old30)) of the leakage current were in operation for 30 years insulators.

The figure shows that for new insulators there is practically no variation in the leakage current from the average value. This suggests that the insulation state of the new insulators is almost identical. At the same time, for used

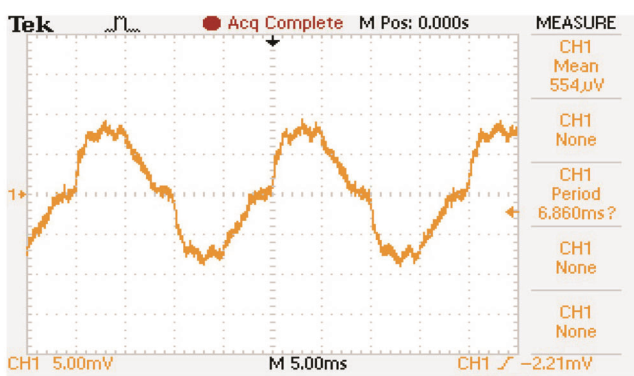

Figure 6. Leakage current oscillogram for the PS-120B insulator for applied voltage U_{app} = 10,000 V.

insulators this spread is from ±5% to ±23%. Moreover, with an increase in the applied voltage, the value of the deviation of the leakage current from the average value increases. This is due to different operating conditions and, accordingly, different degrees of insulation degradation.

Analysis of the results shows that the values of leakage current of insulators depend on their service life. So, for example, the leakage current of insulators that were in these operating conditions for 10 years is approximately 1.25 times greater than that of the new ones, and the leakage current of insulators that have been used for 30 years is more than twice that of new insulators. Analysis of the results shows that the values of leakage current for new and used insulators differ by 20–25%. This increase in leakage current leads to a significant decrease in the discharge characteristics of the insulators[15,18,19,24,25]. Leakage currents and discharge voltage are mutually dependent. For example, Pleshkov and Kotysh[15] give the dependence of 50% of discharge voltages on the leakage current of an insulator, which is under operating voltage.

This shows that the level of insulation ceases to correspond to the natural and climatic conditions of operation, a high probability of insulation flashover occurs. Thus measures are required to prevent flashover and restore the required level of insulation. Increasing the leakage

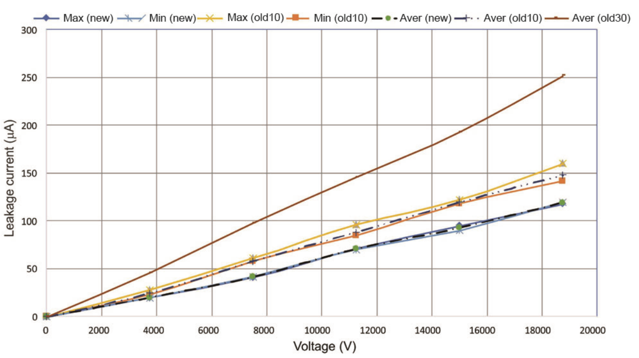

Figure 7. Insulator leakage current-dependence on applied voltage for new (new) and used (old) insulators.

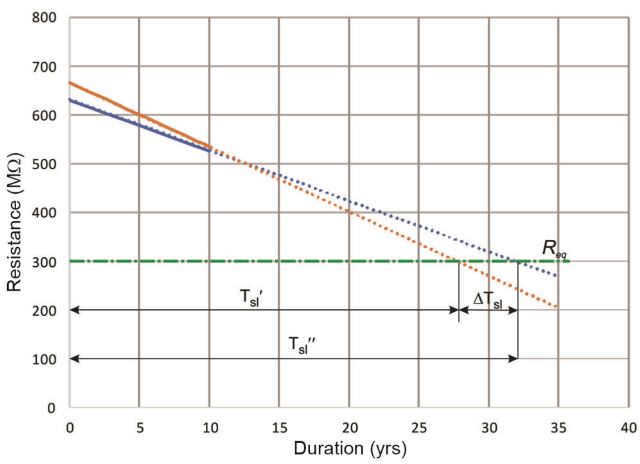

Figure 8. Graph showing the predicted service life of insulators.

current also leads to increasing power losses. Using the data obtained on the average leakage current for new and used insulators, we determined the dependence of changing resistance of the insulator depending on its service life (Figure 8).

Taking the minimum allowable value of the insulator resistance as 300 MΩ, we build a prediction line of the expected service life (T_{sl}' и T_{sl}'') of various groups of insulators. The forecast line is built by making use of the following assumptions: the life of the insulators is in the steady-state section of the life cycle of the insulators; the prediction is carried out by piecewise linear extrapolation based on the determination of the rate of change of leakage current of the insulator.

Figure 8 shows that the estimated service life of insulators differs by the value of ΔT_{sl}, which for the conditions of the insulators under study in operation is about 14%.

It is obvious that if there is a change in the natural and climatic conditions of the area of operation, the predicted service life of the insulators will be different.

Electrical aging can occur at electric field strengths that are many times (5–20) lower than the breakdown voltages. With increasing voltage applied to the insulation, the rate of electrical aging increases, and the service life decreases accordingly.

Overhead lines of power transmission with voltage of 35 kV and above are the main link in power transmission systems. As has been discussed above, there are many reasons for degradation of the insulation, the prolonged exposure of which leads to its premature failure and emergency situations that reduce the reliability of the power supply system. These factors increase the uncertainty in estimating the expected lifetime of an insulator.

The insulating characteristics of the insulators are strongly reduced by their contamination. Gaseous and dusty ash of chemical and metallurgical origin, thermal power plants as well as salt deposits in areas with saline soil which is typical of power grids in Kazakhstan, are the most dangerous.

The analysis of accidents of overhead lines shows that several of them fail every year as a result of changes in the material properties of the wires and their contact connections: destruction of wires due to corrosion and vibration effects, abrasion, wear, fatigue, oxidation, etc. In addition, every year the damage to porcelain, glass and polymeric insulators keeps increasing. With long-term operation, ultraviolet radiation and surface discharges can significantly increase the level of insulator wear. Therefore, defects and faults occurring in the insulators require immediate measures to localize and repair them.

The existing insulation monitoring methods may not be effective, due to the low information content of visual inspection and checks, and the inability to identify most of the causes of insulation failures. This is also a time-consuming and expensive task, and does not allow predicting the possible service life of insulators.

Comparing the actual leakage currents with the accepted maximum permissible values, we can assume the possibility of insulation failure. The personnel responsible for the operation of the insulators must receive information about the ratio of the operating voltage of the set and the expected flashover voltage. Obtaining such information in general should be attributed to the diagnosis of the insulation.

Thus, by monitoring the value of the insulation resistance (leakage current) of the insulator, it is possible to predict its degree of contamination and insulation resistance of the minimum allowable limit at which its operation should be stopped (the estimated service life T_{sl}).

Reducing the damage to the insulators and extending their service life can be achieved by improving the level of diagnostics and control over the technical condition of the insulators under operating conditions.

To implement the proposed method, an experimental system of continuous remote monitoring of the insulation condition of high-voltage insulator strings for 500 kV overhead lines during their operation on poles has been developed. This is a set of local subsystems that collect and transmit information through GSM networks in real time from leakage current sensors of the overhead line insulator strings placed on the poles, to the control centre, as well as processing and storing information at control points of various levels[26,27].

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