Determination of power losses in the isolation of distribution networks

S. Shevchenko  
National technical University “Kharkiv Polytechnic Institute”,  
Ukraine  
E-mail: danylchenko.e@khpi.edu.ua

I. Borzenkov  
Sumy State University  
Ukraine  
E-mail: i.borzenkov@etech.sumdu.edu.ua

Abstract — The article deals with the problem of determining the power losses in high-voltage transmission lines, because their dielectric properties are lost over time. To calculate power losses, the methodology for determining losses in accordance with regulatory documents is presented and its imperfection is shown. Experimental research methods for PF-70A and PSD-70E type insulators have been developed to determine the capacitance of the insulator and the tangent of the dielectric loss angle. On the basis of the developed methodology, experimental studies were conducted to determine the capacitance of the insulator and the tangent of the dielectric loss angle for PF-70A and PSD-70E type insulators. In experimental studies, three conditions were examined under which insulators were investigated: a clean dry insulator, a dirty dry insulator, and a clean wet insulator. The results of the capacitance of the insulator and the tangent of the dielectric loss angle with different contamination of the insulators were obtained. The results of the experimental studies allowed us to calculate the losses of active and reactive power in the insulators of overhead lines. According to the results of the calculation, it was found that the value of the losses of the reactive power component is almost unchanged, regardless of the type of contamination, and the active component increases when contaminated and significantly increases when the insulator is wetted. Analyzing the obtained results, it is concluded that during operation, insulator contamination changes, which leads to changes in leakage currents and, as a consequence, power losses, so power losses are not constant, and they change during operation depending on the environment, weathering, the conditions and timing of this impact. The issue of determining power losses is not fully resolved and needs further, more detailed study.

Keywords — leakage current, insulation, glass insulators, porcelain insulators, tan delta.

I. INTRODUCTION

As it is known for all objects of power systems balances of the electric power are formed. Electricity balance is a quantitative characteristic that takes into account that the amount of electricity that is supplied to an object must always be equal to the amount of electricity that has come out of the object and that has been consumed inside it. However, there is also an unbalance of the system - as a consequence of the error in fixing the balance components with the devices, as well as the presence of losses that are not fixed at all by the devices, for example, technical losses, the value of which is determined by calculation, and commercial losses, which are explained both by the characteristics of the object and the impact on them of external forces.

The value of technical energy losses in the transmission of electrical energy in the insulating structures of overhead power lines according to [1], taking into account the degree of air pollution (DAP) is determined by the following formula:

\[ \Delta W_{\text{isol}}^{(P)} = \frac{u_{\text{nom}}^2}{3R_{\text{isol}}N_{\text{ins}}T_{\text{hum}}N_{\text{gir}}} \]  

where \( u_{\text{nom}} \) is the rated voltage OL, kV; \( N_{\text{ins}} \) - the number of insulators in the phase OL; \( N_{\text{gir}} \) - the number of insulator strings, which is taken when designing overhead lines; \( T_{\text{hum}} \) - duration in the calculated period of wet weather (fog, dew, rain, sleet, frost), h; \( R_{\text{isol}} \) is the electrical resistance of one insulator, kΩ, which is determined according to [2] by the formula:

\[ R_{\text{isol}} = 1345 - 215 \cdot (N_{p} - 1) \]  

where \( N_{p} \) - the number of the level of the degree of pollution of the atmosphere, which is determined according to [3].

As can be seen from formula (1), it does not take into account such parameters as: resistance to leakage current or the conductivity of the layer of pollution on the surface of the insulator skirt depending on the thickness of the insulator [4 - 9] and the time of exposure to weather conditions. Not taking into account these parameters introduces a significant error in determining the magnitude of the leakage current, and the reduced \( R_{\text{isol}} \) resistance formula (2), the value of which varies linearly depending on the DAP, does not provide complete information to determine the technical energy loss (1) in the insulating overhead lines during electrical transmission energy. The paper attempts to take the above parameters into account by indirect methods.

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The influence of weather conditions reduces the dielectric strength of insulators [6] and, in some cases, with intensive contamination of the surface of insulators leads to their overlap. Moistening the surface of the insulating structure leads to an increase in the specific conductivity of the contamination layer along the surface of the insulator and, as a consequence, to an increase in leakage currents, which in turn leads to an increase in energy loss.

The determination of the leakage current and the conductivity of the contaminated layer of an insulating structure can be performed by measuring such insulation parameters as: dielectric loss tangent \( \tan\delta \) in the insulator design and insulant capacitance \( C_{\text{insul}} \) depending on DAP and type of weather conditions (fog, dew, rain, wet snow, frost). In the conducted research in laboratory conditions, three states of the insulator plate surface were studied: dry, clean; dry with a layer of dust; clean moistened with water. This approach to experimental research allows simulating at once several variants of the surface conductivity of an insulating part of insulators, which corresponds to different degrees of environmental pollution.

II. DETERMINATION OF THE CAPACITY OF THE INSULATOR AND TANGLES OF THE ANGLE OF DIELECTRIC LOSSES

The active component of the leakage current on the surface of the insulator in different sources [4 - 6] is determined by the expression:

\[
I_u = \frac{U}{R_u} \tag{3}
\]

where \( R_u \) is the leakage current resistance on the surface of the insulator if the contamination layer has a thickness \( \Delta \) with a specific volume resistance \( \rho \).

The leakage current resistance can be determined by the following formula:

\[
R_u = \frac{\rho \cdot L_u}{\pi \cdot \Delta \cdot D} \tag{4}
\]

where \( L_u \) is the creepage distance.

Therefore, from formulas (3) and (4) the leakage current will be determined as:

\[
I_u = \frac{U \cdot \pi \cdot \Delta \cdot D}{\rho \cdot L_u} \tag{5}
\]

Based on the expression (5), without having the values of such parameters as the thickness of the contamination layer \( \Delta \) and its specific volume resistance \( \rho \), it is impossible to calculate the leakage current. In addition, formula (5) is given for the calculation of a cylindrical smooth insulator, which makes its application in practice for the calculation of real structures almost impossible.

You should pay attention to the fact that the value of capacity \( C \) will vary depending on the absence or presence of a layer of pollution. This is due to the fact that the dielectric constant of the pollution layer will depend on its state and composition. Therefore, the determination of the capacity of the contaminated insulator will allow to take into account the presence on its surface of a certain type of pollution.

All of the above determines the need to clarify leakage currents. In this paper, we propose to determine the leakage currents by measuring two insulator parameters such as: capacitance \( C \), and dielectric loss tangent \( \tan\delta \) experimentally. On the basis of the obtained experimental results, it becomes possible to determine the active component of the leakage current by calculation.

To experimentally determine the capacitance \( C \), of the insulator and the dielectric loss tangent \( \tan\delta \), we performed 3 series of experiments, 100 experiments in each series, using the Vector 2M measuring device, which works on the basis of the Schering bridge principle (Fig. 2) and for measuring the parameters of insulation, capacitance and tangent of dielectric loss angle in high-voltage insulation at various values of test voltages.

The measurement process consists in balancing the bridge circuit by alternately adjusting the resistance of the resistor and the capacitance of the capacitor stores.
where $C_1$ is the capacitor under study, $R_1$ is the series resistance in the equivalent circuit of the capacitor under study, $C_2$ is the reference capacitor, $R_3$ is a non-induction resistor, $C_4$ is a variable capacitor, $R_4$ is a variable non-induction resistor connected in parallel with $C_4$.

Two types of insulators were chosen as objects of study:

- "PF-70A" Fig. 3, suspended porcelain insulator with a long creepage distance $l_{out} = 303$ mm and a minimum breaking load of 70 kN;

- "PSD-70E" Fig. 4, suspended glass double-wing insulator (for areas with a polluted atmosphere), enhanced insulating characteristics and a long creepage distance $l_{out} = 411$ mm with a minimum breaking load of 70 kN.

Measurements of the studied parameters were carried out for three states of the insulator plate surface (clean, dry, contaminated with a layer of dust, clean wetted water) using the “Normal” measurement circuit, which is shown in Fig. 5.

In measurements, two bridge switching schemes are used: the so-called “Normal” or “Direct”, in which the measuring element is connected between one of the electrodes of the tested insulation structure and the ground, and “Inverted”, where it is connected between the electrode of the test object and the high voltage output the bridge. The “normal” circuit is used when both electrodes are isolated from the ground, “Inverted” - when one of the electrodes is tightly connected to the ground.

The test voltage $U_{HV}$ supplied to the object “Pestle” of the insulator according to the “Direct” measurement circuit was 10 kV. The obtained average values of the results of measurements of the capacitance of the insulator $C_x$ and the dielectric loss tangent $\tan \delta$ are presented in Table 1.

| Type     | Insulator Surface Condition | Dry clean | Dry dirty | Clean wetted with water |
|----------|-----------------------------|-----------|-----------|-------------------------|
|          | $C_x$, pF | $\tan \delta$, % | $C_x$, pF | $\tan \delta$, % | $C_x$, pF | $\tan \delta$, % |
| PF-70A   | 87.82     | 9.12       | 82.86     | 21            | 120.3      | 20.9           |
| PSD-70E  | 67.76     | 2.039      | 65.72     | 2.067         | 77.31      | 3.49           |

As can be seen from Table 1 for different states of contamination of the surface of an insulator plate, the values of capacitance $C_x$ have different values and even exceed the values given in [5]. Therefore, if we take into account the varying parameter $\tan \delta$, the active component of the leakage current $I_a$ over the surface of the insulator will also have different values.

### III. Calculation of the Active Leakage Current on the Surface of the Insulator

At alternating voltage, in insulation, a current flows, which is ahead of the applied voltage by phase $\phi$ (Fig. 6), which is less than 90 degrees at a small angle $\delta$, due to the presence of active resistance.
where \( U \) is the voltage on the dielectric; \( I \) is the total current through the dielectric; \( I_a, I_c \) are, respectively, the active and capacitive components of the total current; \( \phi \) is the phase shift angle between the applied voltage and the total current; \( \delta \) - the angle between the total current and its capacitive component.

Considering the simplest dielectric, you can write the expression dissipated in it under the influence of an alternating voltage power:

\[
P_a = U \cdot I_a,
\]

where \( U \) is the voltage applied to the dielectric, \( I_a \) is the active component of the current flowing through the dielectric.

The dielectric substitution circuit is usually represented as a series-connected capacitor and active resistance. From the vector diagram (see fig. 6):

\[
I_a = I_c \cdot \tan \delta
\]

where \( \delta \) is the angle between the vector of the total current and its capacitive component \( I_c \).

Consequently

\[
P_a = U \cdot I_c \cdot \tan \delta
\]

but current

\[
I_c = U \cdot \omega \cdot C,
\]

is the capacitance of a capacitor of a given dielectric at an angular frequency \( \omega \).

As a result, the power dissipated in the dielectric is

\[
P_c = U^2 \cdot \omega \cdot C \cdot \tan \delta
\]

that is, the energy loss dissipated in the dielectric is proportional to the tangent of the angle \( \delta \), the frequency of the applied voltage and the capacitor capacitance.

Based on the experimental data obtained, Table 1, knowing the capacitance \( C \) of the insulator, can determine the reactive \( I_p \) current by known formulas:

\[
X_C = \frac{1}{2 \pi f \cdot C}
\]

(6)

\[
I_p = \frac{U}{X_C}
\]

(7)

where \( U \) is the applied voltage to the test object in our case is 10 kV.

Knowing the reactive component of the current \( I_p \), as well as the tangent of the dielectric loss angle \( \tan \delta \), it is possible by a known formula to calculate the active component of the leakage current \( I_a \):

\[
\tan \delta = \frac{I_a}{I_p}
\]

(8)

Then, expressing from (5) the active component of the leakage current \( I_a \), we obtain:

\[
I_a = I_p \cdot \tan \delta
\]

(9)

Substituting the obtained experimental average values into (6) (7) (9), we obtain the desired reactance values of the insulator \( X_c \), the reactive component of the current \( I_p \), and the active component of the current \( I_a \), which are summarized in Table 2 for the PF-70A type insulator and in Table 3. The required parameter values for the PSD-70E isolator are summarized.

**TABLE II. Calculated Values of the Desired Values of the Insulator Type PF-70A**

| Insulator Surface Condition | \( U \) \( kV \) | \( f \) \( Hz \) | \( X_c \) \( \Omega \) | \( I_p \) \( A \) | \( I_a \) \( A \) | \( P_a \) \( W \) |
|-----------------------------|----------------|---------------|----------------|----------------|----------------|----------------|
| Dry clean                   | 10             | 50            | 3.63 \( 10^{-2} \) | 0.3 \( 10^{-2} \) | 2.5 \( 10^{-2} \) | 0.25            |
| Dirty dry                   | 10             | 50            | 3.85 \( 10^{-2} \) | 0.3 \( 10^{-2} \) | 3.8 \( 10^{-2} \) | 0.58            |
| Clean wetted with water     | 10             | 50            | 3.85 \( 10^{-2} \) | 0.4 \( 10^{-2} \) | 7.9 \( 10^{-2} \) | 0.79            |

**TABLE III. Calculated Values of the Desired Values of the Insulator Type PSD-70E**

| Insulator Surface Condition | \( U \) \( kV \) | \( f \) \( Hz \) | \( X_c \) \( \Omega \) | \( I_p \) \( A \) | \( I_a \) \( A \) | \( P_a \) \( W \) |
|-----------------------------|----------------|---------------|----------------|----------------|----------------|----------------|
| Dry clean                   | 10             | 50            | 4.7 \( 10^{-2} \) | 0.2 \( 10^{-2} \) | 4.3 \( 10^{-2} \) | 0.043           |
| Dirty dry                   | 10             | 50            | 4.8 \( 10^{-2} \) | 0.2 \( 10^{-2} \) | 4.3 \( 10^{-2} \) | 0.043           |
| Clean wetted with water     | 10             | 50            | 4.1 \( 10^{-2} \) | 0.2 \( 10^{-2} \) | 8.5 \( 10^{-2} \) | 0.085           |

As can be seen from tables 1, 2 and 3, under different states of the surface of an insulator plate, the capacitance \( C \) of the insulator changes, and the dielectric loss angle changes and, as a consequence, the active component \( I_a \) of these losses appears.

**IV. CONCLUSIONS**

During the work we see that during the operation of insulator chains made of porcelain and glass at different levels of atmospheric pollution zones and weather conditions, the leakage currents on the surface of the insulators can change their values. It is also seen that the capacitance and the tangent of the dielectric loss angle of an insulator also change their values depending on the type of contamination of the insulator plate.

It is also necessary to note that the applied voltage to one insulator when conducting research in laboratory conditions was 10 kV, however, in actual operating conditions, the voltage distribution over a string of insulators fig. 1, depending on the voltage class of the overhead power line, has different voltage values.

As we see this question on the specification of leakage currents on the insulating structures of power lines need additional research. Since it is not known, the behavior of leakage current values in actual operating conditions during

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Визначення втрат електроенергії при ізоляції розподільних мереж

В статті розглядається питання визначення втрат потужності в ізоляційних конструкціях високовольтних ліній електропередачі, оскільки з часом експлуатації ізоляторів втрачаються їх діелектричні властивості. Для розрахунку втрат потужності наведено методику визначення втрат відповідно до нормативних документів та показано її недосконалість. Розроблено методику проведення експериментальних досліджень для ізоляторів типу ПФ-70А та ПСД-70Е для визначення ємності ізолятора та тангенса кута діелектричних втрат. На основі розробленої методики проведено експериментальні дослідження для ізоляторів типу ПФ-70А та ПСД-70Е. Під час експериментальних досліджень було розглянуто три умови за якими досліджувались ізолятори: чистий сухий ізолятор, брудний сухий ізолятор та чистий зволожений ізолятор. Отримані результати експериментальних досліджень дозволили розрахувати втрати активної та реактивної потужності в ізоляторах повітряних ліній. За результатами розрахунку було виявлено, що значення втрат активної та позитивні втрати в ізоляторах повітряних ліній. За результатами розрахунку було виявлено, що значення втрат реактивної потужності майже не змінюється, а активна складова збільшується при забрудненні і значно збільшується при намочуванні ізолятора. Проаналізувавши отримані результати зроблено висновок, що під час експлуатації змінюється забруднення ізоляторів, що призводить до зміни втрат потужності.

Ключові слова - струм витоку, ізоляція, склоізолятори, порцелянові ізолятори, тангенс дельта.