The object of this study is condenser-type insulation of high-voltage electrical equipment and elements of its overvoltage protection circuits, in the case of breaking the cable to the diagnostic device of technical condition of insulation under operating voltage.

The work reports a study on the overvoltage that can cause damage to high-voltage equipment with condenser-type insulation (bushings and instrument current transformers), equipped by hardware for monitoring the technical condition of insulation under operating voltage. Such overvoltage can occur as a result of damage of the cable from the test-tap of the device insulation and/or as a result of lightning and switching overvoltage on the buses of the switchgear.

The task relates to insufficient attention and lack of requirements of regulatory documents to the insulation protection schemes of devices with an increase in the number of implementations of devices for monitoring the condition of insulation under operating voltage in recent years. The relevance of the issue is predetermined by war in Ukraine, when electric power facilities and the system as a whole are subject of military attacks, causing both physical destruction and provoking overvoltage and short circuits that affect equipment that has not been destroyed.

The paper gives the results of modeling the overvoltage that may arise on the insulation test-tap of equipment with condenser-type insulation, when the cable to the monitoring device is damaged. The results of temperature tests of a complex protective resistor are presented. The use of a parallel resistor and a capacitor as the main protection elements has been justified. Such a scheme could limit the instantaneous overvoltage value for most devices at the level of no more than 1.6 kV, even without the use of additional protection elements, such as varistors or arresters, for example.

A methodology and recommendations for selecting protective elements and checking the compliance have been devised, both under the nominal operating mode and in the presence of high-frequency overvoltage

Keywords: condenser-type insulation, test-tap, monitoring under operating voltage

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IMPROVING THE PROTECTION OF HIGH-VOLTAGE EQUIPMENT WITH CONDENSER-TYPE INSULATION DURING TECHNICAL CONDITION MONITORING UNDER OPERATING VOLTAGE

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1. Introduction

High-voltage devices with capacitor insulation are one of the most common types of devices in operation at power stations and substations. The existence of the country's modern power system is impossible without the use of such devices. Capacitor insulation provides voltage equalization along the thickness of the dielectric (radial) and along its length (axial) due to its division into thin layers by concentric cylindrical foil gaskets. To ensure radial uniformity of the voltage distribution, the condition of equality of the products of the radius of the coating by its length for all layers must be met. The lengths of the coatings decrease from the inner electrode to the outer one in proportion to their radii. The last coating is connected to the measuring (diagnostic) terminal, which is designed to diagnose the state of the insulating structure. The diagnostic terminals of the devices can be used by personnel for periodic manual insulation tests or for continuous control (monitoring). The most common types of devices made according to this insulation design scheme are measuring current transformers and inputs.

During operation, the diagnostic output is blindly connected to grounded elements of the device design, for example, flanges, bases, etc. Violation of the output grounding causes an uneven distribution of the electric field strength between the insulation sections, which leads to their damage, and then damage to the entire device. For devices with a measuring output, the insulation of which withstands a test voltage of 20 kV, the maximum operating voltage at the output, as a rule, should not exceed 6 kV. For devices with a measuring output, the insulation of which withstands a test voltage of 2 kV, the maximum operating voltage should not exceed 500 V. Too high a voltage at the measuring output leads to partial breakdowns of the insulation and device failure. The insulation of the devices is exposed to high-frequency switching and lightning surges, which are often shorted to ground directly through the capacitor insulation. This is due to the fact that the impedance of the capacitor insulation is frequency-dependent, i.e., it drops to minimum values with increasing frequency of the applied voltage.

When organizing control of the insulation state under operating voltage, the diagnostic output is connected to the diagnostic device, i.e., additional elements appear between the output and grounding. In the best case, this is only a cable, in the worst case, inductive elements (matching transformers). The existence of these additional elements sharply reduces the reliability of the grounding of the diagnostic output and therefore exposes the insulation of the device to the threat of breakdown. A large number of devices in operation, equipped with devices for organizing control under operating voltage, especially in the 750 kV network, makes it relevant to study insulation protection in such schemes. Also relevant is the issue of personnel safety, which may accidentally come under the influence of high voltage in the event of periodic manual control of the insulation state, or as a result of damage to the cable of the stationary control circuit.

The relevance of the task increases taking into account the martial law in Ukraine when power facilities and the system as a whole are subjected to constant shocks. Such shocks cause both physical destruction of equipment and provoke overvoltage and short circuits that affect high-voltage equipment that has not been destroyed (survived).

2. Literature review and problem statement

In [1, 2], several interesting examples of failures of bushings associated with defects in the main insulation are given. Of particular interest are the first two examples from [1], which are directly related to the studies reported in this paper: an accident due to the development of electrically conductive tree-like formations along the insulation. Such an accident was clearly preceded by a partial breakdown of the insulation, which could be recorded by means of monitoring the state of the insulation under operating voltage. In a second example [1], the cause of the failure was a violation in the grounding circuit of the measuring (diagnostic) terminal of the bushing, which led to the appearance of partial discharges and sparking. In [1] it is noted that according to statistics by the Association of Southeast Asian Nations, defects associated with a violation of the grounding circuit of the diagnostic terminal account for more than 10% of the total number of failures of high-voltage bushings.

In [2], an interesting example of the presence of partial discharges in the main insulation of a 69 kV bushing is given, which were extinguished when the load current increased, due to heating and pressure increase in the bushing. In a second example given in [2], an oil bushing for a voltage class of 500 kV was considered, in it and similar bushings that were operated at significant temperature fluctuations (60°C) hydrogen was formed. It was formed as a result of partial discharges that arose due to the formation of a vacuum in the cavities of the insulating structure, with a sharp drop in the bushing temperature. Both cases [2] could have been detected by monitoring the condition of the bushings under operating voltage. In works [1, 2] it is noted that diagnosing the bushing insulation during operation can detect defects that develop before they lead to accidents. However, in those works no attention is paid to the issues of organizing such diagnostics.

In [3], it is stated that more than 30% of power transformer failures are associated with failures of the inputs. Increasing the reliability of operation of high-voltage equipment, in particular by diagnosing the condition of capacitor insulation, is a very urgent task but the authors of [3] do not consider the issue of the adapter protection circuit.

The industry standard for monitoring the condition of insulation of measuring current transformers [4] contains requirements for the circuit and cables for connecting stationary devices for diagnosing insulation under operating voltage (both periodic and continuous). The resistive protection circuit given in the standard ensures: personnel safety and the absence of the need to prepare the object for testing; safety of the controlled equipment at rated operating voltage, protection against surges by arresters and varistors). But the standard does not consider the conditions of the presence of high-frequency surges, and the speed of protection, and most importantly – the power of the pulses that they can divert to ground.

In [5], the types of protection circuits for input monitoring sensors are discussed: resistive type, capacitive type and varistor type (based on a metal oxide varistor (MOV)). That paper is the largest work on the importance of protecting the output insulation during diagnostics under operating voltage. The author notes the presence of significant overvoltage on the output insulation in the event of a cable break at the rated operating voltage; however, the author has not conducted any studies on the effects of high-frequency overvoltage or prolonged operation of the protection circuit. The author considers the need to use fast-acting limiters of switching and lightning impulses, as well as the need for an appropriate design of the sensor to prevent moisture from entering the measuring output assembly. It should be noted that the author uses the term "sensor" but "sensors" means that this device must convert the conductivity current into signals that can be read by instruments. Indeed, devices installed on the measuring output to organize control under operating voltage can be divided into two types: sensors and adapters. Adapters must provide mechanical protection of the measuring output, electrical contact of the output with the diagnostic device and protection: against cable breakage and overvoltage. Sensors, in addition to the adapter functions, additionally provide current signal conversion.

The equipment manufacturer [6] provides information that their input adapter has three levels of protection. The protection scheme includes six voltage limiters; two overvoltage protection schemes (commuting and transient); automatic grounding of the diagnostic input inside the housing. The manufacturer does not provide a wiring diagram or other additional information on how exactly these protections are implemented, as well as research or results of their protection scheme.

In work [7], it is emphasized that the adapter must provide conversion of leakage current into voltage (no more than 10 V), which is supplied to the electronic control unit; tightness; protection against voltage surges. However, the authors do not provide any information about the adapter protection scheme and any results of research on the adapter's operation in the event of a cable break and/or overvoltage.

A Ukrainian manufacturer of online monitoring systems provides information with a functional diagram of the adapter protection scheme [8]. Such a circuit has a resistive type of protection with high-speed protection devices such as MOVs and gas-filled arresters but the results of the study of the operation of such a circuit are not given.

In work [9], the authors provide information about a connection device for insulation monitoring that uses capacitor protection with several gas-filled arresters as protective semiconductor elements but the results of the study of the operation of such a circuit are not given.

In [10], the connection to the diagnostic output is considered but without any attention to protection and a safe diagnostic process for equipment and personnel.

In paper [11], only one MOV element is reported as a protective element in the sensors proposed in the work, and no attention is paid to the operation of the circuit during overvoltage and/or cable damage.

According to clause 9.4 of the normative recommendations [12], input monitoring devices are installed on potential or diagnostic outputs of inputs to ensure operational testing and monitoring of the dielectric loss tangent. It is noted that they should allow continuous monitoring or periodic checking of inputs without removing them from service. Since such devices replace the existing cover of the diagnostic outputs, the user must ensure that the device is correctly fitted to prevent moisture from entering the diagnostic output assembly. No recommendations on the protection scheme against overvoltage and/or cable damage are given in the standard.

In addition to studying the processes in the equipment under nominal operating modes, it is also necessary to consider the processes that occur in the presence of deviations from the nominal mode, namely during lightning and switching overvoltage, the presence of which has been noted in a number of works. Thus, in [13], changes in the insulation parameters of a capacitor-type high-voltage input are shown during fast and very fast overvoltage – up to 20 MHz; however, such high frequencies were not registered during the research, as shown in [14], and the current GOST 13109-97 "Electric energy. Electromagnetic compatibility of technical means. Standards of quality of electric energy in general power supply systems" also describes overvoltage frequencies up to 1 MHz. In [15], a substation is also modeled, considering a frequency of about 1 MHz. Taking into account the above, it is especially important to take into account the processes that can occur at an overvoltage frequency of up to 1 MHz.

Despite the rapid development of the scientific area of diagnosing the condition of equipment under operating voltage, manufacturers and researchers have not paid sufficient attention to the protection of devices when implementing such diagnostics. Analysis of scientific, practical, and regulatory literature [3–12] reveals that it almost completely lacks the results of research into processes that can occur in equipment when control devices are connected to the diagnostic output instead of grounding.

Neglecting the issues of protection and reliability of operation of devices with capacitor insulation, when organizing control over their technical condition under operating voltage, can cause a device failure. Thus, there is a task necessitating the study of possible effects on the insulation of devices, as well as improving insulation protection schemes under such modes.

3. The aim and objectives of the study

The purpose of our study is to improve protection schemes for diagnosing the insulation of devices under operating voltage. The study of overvoltage on the insulation and the possibility of damage to the protective elements themselves will allow us to form theoretical foundations for the construction of protection schemes for monitoring insulation under operating voltage, as well as to devise practical recommendations for the production and implementation of control tools.

To achieve the goal, the following tasks were set:

– to investigate the impact of high-frequency overvoltage on devices with capacitor insulation, when the cable to the device for diagnosing the state of the main insulation under operating voltage breaks and/or the appearance of high-frequency overvoltage;

– to investigate the operation of the elements of the protection scheme under continuous mode;

– to devise a methodology for selecting the main protective elements and recommendations for ensuring the safety of the insulation of devices when organizing control under operating voltage.

4. The study materials and methods

The object of our study is capacitor insulation of high-voltage electrical devices with elements of its protection circuit when monitoring the technical condition under operating voltage.

The hypothesis of the study assumes that due to the fact that the diagnostic output of the device is disconnected from the grounded parts of its structure for connection to the diagnostic circuit, there is a risk of damage to its grounding circuit. The appearance of high-frequency overvoltage with instantaneous values higher than the amplitude values of the highest operating voltage can cause the appearance of voltages that are dangerous for the insulation of the device and can cause its damage. The use of a capacitor in parallel with a resistor in the protective circuit of the measuring output adapter can ensure long-term safe operation of the device in the event of damage to the cable to the diagnostic device and/or the appearance of high-frequency overvoltage on the buses of the switchgear.

Before starting the study, the following assumptions were accepted: the results of the study for the voltage class 750 kV can be extrapolated to other classes; maximum possible frequency of overvoltage – 1 MHz; the device can be operated with a damaged cable from the diagnostic output under continuous mode.

In the process of research, the capacitance of the insulating structure of the device is imagined as an ideal capacitor – the inductive and resistive components of which were neglected. The resistive, capacitive, and inductive components of cables and connecting wires were not taken into account. Changes in the characteristics of protective elements and the insulation itself due to the surface effect (with an increase in the frequency of the applied voltage) were not taken into account.

The studies reported in our work are based on the theoretical laws of electrical engineering on the impedance of electrical circuit elements, the equivalent circuit of the insulating structure of the apparatus with paper capacitor insulation.

The main signal recorded when monitoring the technical condition of the main insulation is the complex conductivity current (I_i) flowing through the insulation of the apparatus under the influence of the applied phase voltage (Fig. 1).

The space between the grounded part and the structural elements under high voltage can be represented by a chain of capacitors connected in series. For the purposes of this study, it is convenient to represent this chain as a total capacitor

C_1 – the capacitance of the main insulation. The capacitance of the last layers of insulation (between the diagnostic terminal and the grounded parts of the device structure) is usually designated C_3 (sometimes – C_2). The measuring terminal is used to control the values of the dielectric loss tangent (tgδ_1) and its changes, the change in the capacitance of the main insulation (ΔC_1), the characteristics of discharge activity (characteristics of partial discharges).

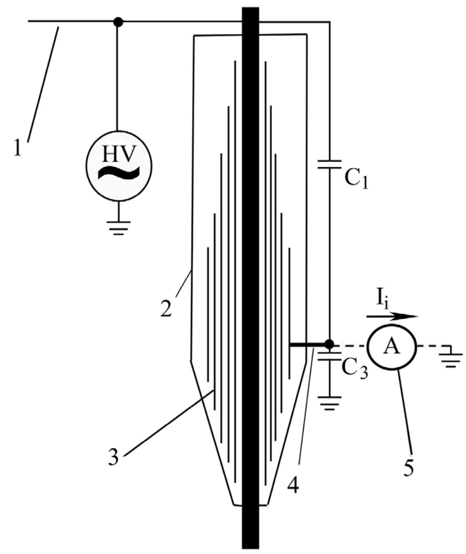


Fig. 1. Equivalent circuit of the device with capacitor insulation, the measuring output (test-tap) is grounded during operation in the absence of control under operating voltage: 1 — high-voltage bus; 2 — input; 3 — capacitor plates; 4 — measuring (diagnostic) output; 5 — diagnostic device

The most common examples of simplified schemes for organizing control over the technical condition of the insulation of devices under operating voltage are shown in Fig. 2.

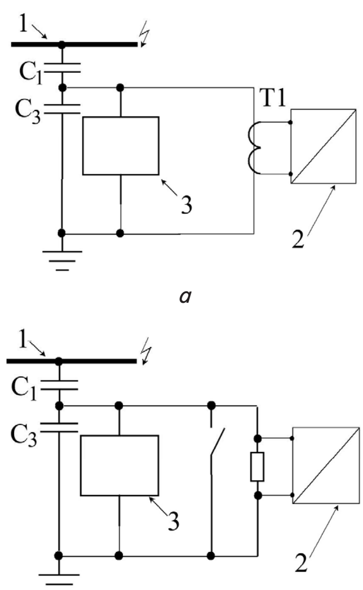


Fig. 2. Possible structural schemes for organizing insulation control under operating voltage: *a* — automated monitoring; *b* — periodic control; 1 — high-voltage bus; 2 — diagnostic device; 3 — adapter with protection circuit

As shown in Fig. 1, such circuits must have an adapter for connecting to the diagnostic output and the diagnostic device itself, the circuit may also have a grounding device, especially during periodic monitoring. The adapter is mounted directly on the measuring output node or directly near it and must have reliable contact with the diagnostic output. The adapter must ensure signal transmission to the diagnostic device and the safety of the insulation at the same time.

Fig. 3 shows a diagram of the device's insulation replacement with the main protection elements: a resistor and a capacitor.

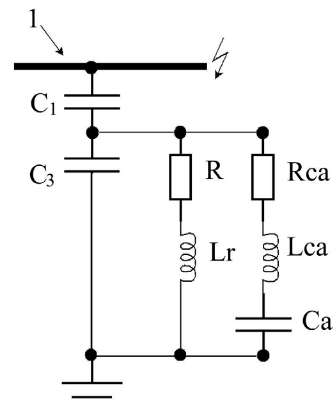


Fig. 3. Basic insulation replacement scheme with cable break protection elements

The scheme takes into account the possibility of using a resistor and a capacitor as the main protective elements. The scheme in Fig. 3 takes into account the resistive (R) and inductive components of the protective resistor (Lr), as well as the capacitive (Ca), inductive (Lca), and resistive (Rca) components of the capacitor. Fast-acting protection elements such as varistors, suppressors, gas dischargers are not shown in the scheme since they are the last stage of protection and do not participate in the modeling of the processes considered in this article. Of course, such fast-acting protection elements must necessarily be present in the real scheme.

Based on the equivalent circuit, a system of equations was compiled that makes it possible to model processes in the circuit when changing the values of its main elements and the frequency of the applied voltage

$$\begin{cases} z_1 = -\dfrac{j}{\omega \cdot C_1}, \\ z_3 = -\dfrac{j}{\omega \cdot C_3}, \\ z_r = R + j \cdot \omega \cdot L_r, \\ z_{ca} = R_{ca} + j \cdot \left(\omega \cdot L_{ca} - \dfrac{1}{\omega \cdot C_a} \right), \\ \dfrac{1}{z_2} = \dfrac{1}{z_3} + \dfrac{1}{z_r} + \dfrac{1}{z_{ca}}, \end{cases} \tag{1}$$

where ω is the angular frequency $\omega = 2 \cdot \pi \cdot f$ (f is the frequency of the voltage applied to the insulation);

C_1 and C_3 are the insulation capacitances, respectively, of the main and last layers;

R is the active resistance of the protective resistor;

L_r is the inductance of the protective resistor;

R_{ca} is the active resistance of the protective capacitor (ESR);

L_{ca} is the inductance of the protective capacitor (ESL);

C_a is the capacitance of the protective capacitor;

z_1, z_2, z_3, z_r, z_{ca} are the designations of the complex resistances of the circuit sections.

Based on the system of equations (1), a VBA macro was built in the Microsoft Office 2019 Excel software package (USA), with the help of which the circuit operation was simulated.

Based on our literature review, the study of the impact of surges was carried out up to the frequency of such surges – 1 MHz. The values of switching impulse voltages for their duration only at the level of 0.5 of the pulse amplitude, which is 1000–5000 μs, are taken from GOST 13109-97 and are given in Table 1. These voltages were used in the simulation as the maximum possible voltage values since the data on possible switching given in the document have lower values than lightning voltages.

Table 1

Lightning impulse voltages according to GOST 13109-97

Location of connection points	Nominal network voltage, kV				
	110	220	330	500	750
Power transformer (PT)	480	750	1050	1550	1950

According to GOST 13109-97, the probability of exceeding the switching impulse voltages specified in Table 1 is no more than 5% for overhead lines with metal and reinforced concrete supports and 20% for overhead lines with wooden supports.

The protective resistor was considered as a "grid" of 21 series-parallel connected SMD resistors (1200 Ohm, 1 W each) with a total resistance of 514 Ohm, as given in [4, 8]. Since manufacturers of such resistors do not provide data on the inductance of such resistors, the inductance calculation was performed as for a straight conductor of rectangular cross-section [16]

$$L_1 = \frac{\mu_0 \cdot A}{2 \cdot \pi} \cdot \left(\ln\left(\frac{2 \cdot A}{b+c} \right) + \frac{1}{2} \right), \tag{2}$$

where $\mu_0 = 4\pi \cdot 10^{-7}$ H/m – magnetic constant;

A, b, c – resistor dimensions.

For a resistor with dimensions (6 × 4 × 2) mm, the inductance will be 1.432 nH, according to [16], with increasing frequency, the inductance of the resistor will decrease due to the surface effect, and will be approximately equal to 1.1 nH, a larger value was used for modeling. The total inductance of the resistor grid will be 0.6136 nH and taking into account the inductive couplings on the board, the total inductance was taken at 1.62 nH.

The parameters of the protective capacitors are taken from the documentation of metallized polypropylene film capacitors (MKP) [17] at the level of average values at 50 Hz: $R_{ca} = 100$ mΩ, $L_{ca} = 20$ nH. The continuous allowable voltage for the given example of capacitors is set to 875 V, with the possibility of a short-term (30 ms) voltage excess of up to 150 % of the continuous allowable voltage. The values are not exact characteristics and can be specified during engineering calculations for specific models of resistors and capacitors. The calculations given are not related to the design of a protective circuit for a specific device, but rather an emphasis on the problem and a possible example of protective circuits design.

Also, during the research, thermal tests of the maximum permissible power dissipation of a grid of 21 series-parallel connected SMD resistors (1200 Ohm, 1 W each) with a total resistance of 514 Ohm were carried out. The tests were carried out by applying voltage to the printed circuit board with a set of resistors from a laboratory autotransformer, and the temperature of the surface of the board with resistors was measured using a pyrometer. The resistors on the board were soldered using POS-40 solder, the melting point (solidus) is 235°C. The temperature of 235°C is critical for most metal-oxide film resistors (a metal-oxide film resistor is made by coating a ceramic core with tin oxide with antimony). The tests were carried out on the board in an air cooling environment and on the finished product, the elements of which are protected from environmental influences by an organosilicon sealant.

5. Results of research on the insulation protection scheme and its elements

5. 1. Results of research on the influence of high-frequency overvoltage on devices with capacitor insulation

During the study, 21 cases of different ratios of the capacitances of the main insulation and the last layers with different values of the protective capacitor for equipment of voltage class 750 kV were modeled. Some results of modeling the voltage on the open measuring terminal for different cases are shown in Fig. 4–7.

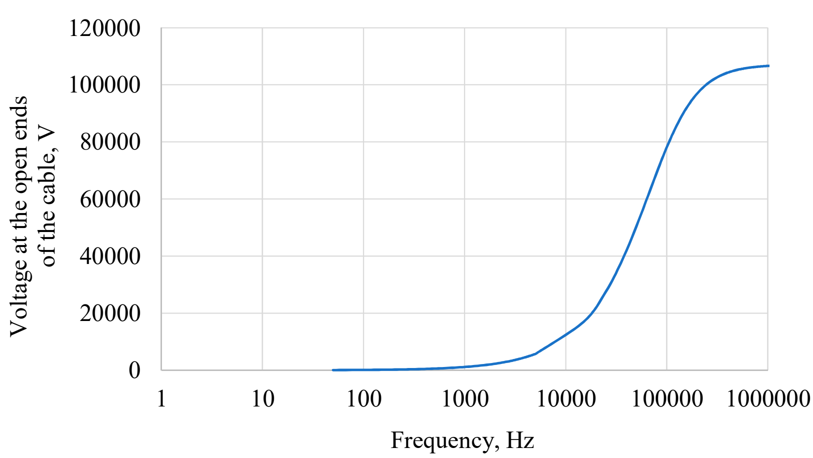


Fig. 4. Voltage change depending on voltage frequency (peak voltage 1950 kV, $C_1 = 800$ pF, $C_3 = 2500$ pF, resistance of protective resistor $R = 514$ Ohm, without protective capacitor)

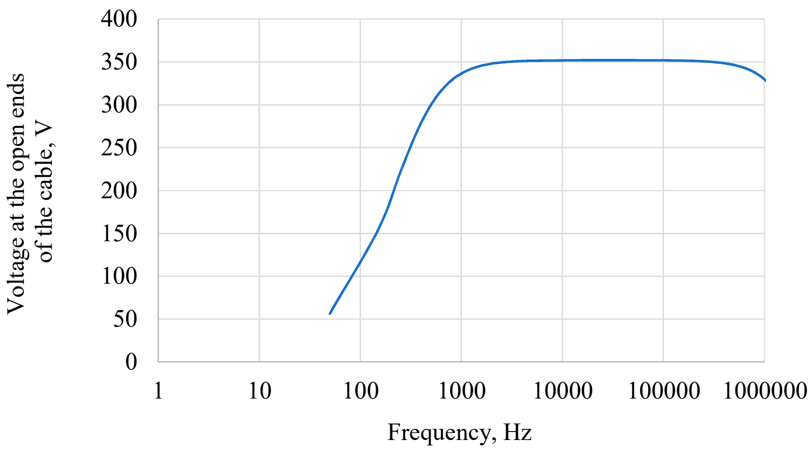


Fig. 5. Voltage change depending on voltage frequency (peak voltage 1950 kV, $C_1 = 800$ pF, $C_3 = 2500$ pF, resistance of protective resistor $R = 514$ Ohm, capacitance of protective capacitor $C_a = 1$ μF)

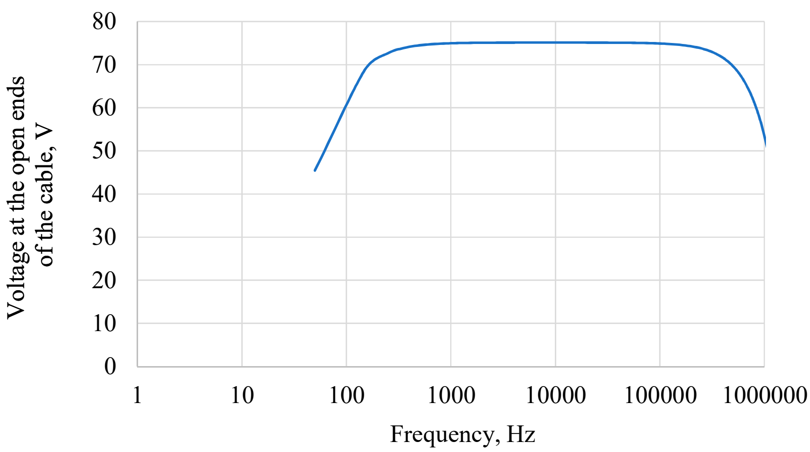


Fig. 6. Voltage change depending on voltage frequency (peak voltage 1950 kV, $C_1 = 800$ pF, $C_3 = 2500$ pF, resistance of protective resistor $R = 514$ Ohm, capacitance of protective capacitor $C_a = 4.7$ μF)

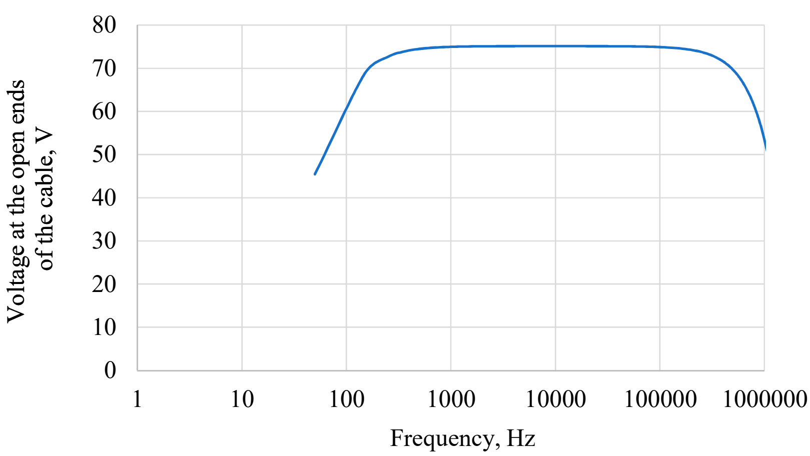


Fig. 7. Voltage change depending on voltage frequency (peak voltage 1950 kV, $C_1 = 300$ pF, $C_3 = 2500$ pF, resistance of protective resistor $R = 514$ Ohm, capacitance of protective capacitor $C_a = 2.2$ μF)

The simulation was performed for the range of protective capacitance values of 0.01...4.7 μF and the range of basic insulation capacitance of 300...1200 pF, frequency range of 50...106 Hz. As a result, the maximum voltage values were determined for various combinations of basic insulation capacitance and protective capacitor values (Fig. 8).

Thus, a formula for estimating the maximum surge value will take the form

$$U\left(U_p, C_1, C_a\right) = \frac{U_p}{1{,}950{,}000} \cdot A \cdot C_a^B, \tag{3}$$

where U_p is the expected peak voltage, V (as the simulations were performed for the maximum overvoltage amplitude corresponding to the equipment voltage class of 750 kV);

C_1 is the capacitance of the main insulation in pF;

C_a is the capacitance of the protective capacitor in μF.

A, B are coefficients that can be determined from Fig. 9.

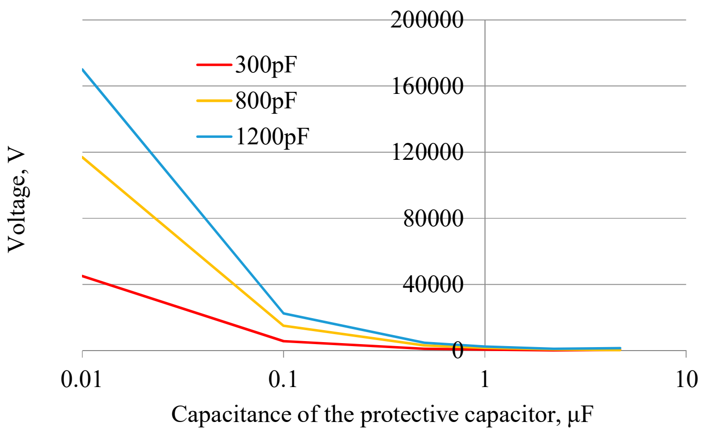


Fig. 8. Change in maximum voltage depending on the capacitance of the protective capacitor (C_a) for different values of the capacitance of the main insulation of the device

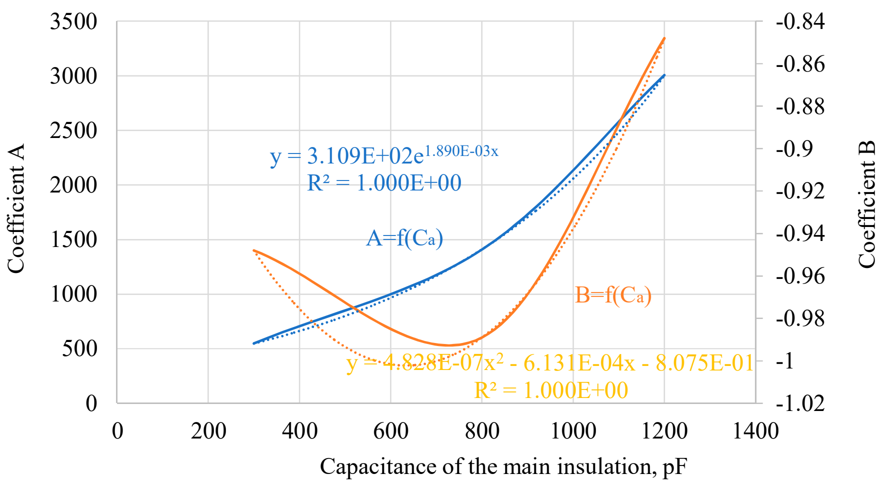


Fig. 9. Determining the coefficients *A* and *B* for formula (3)

The values of the coefficients of equation (3) – A and B depend on the capacitance of the main insulation of the device; they can be determined from Fig. 9 graphically or by the approximation curve formula (shown by dotted lines of the corresponding color).

5. 2. Results of investigating the operation of protection circuit elements under a continuous mode

The permissible current through the protective capacitor is determined according to the data reported in [17]. For simplicity, the approximate value of the current can be determined by the approximating function represented in the plot of Fig. 10.

The technical specifications of most manufacturers of metal-oxide film resistors do not contain data that make it possible to calculate the heating temperature of a particular resistor when current flows through it. It should also be noted that the heat transfer conditions of a real complex resistor are complicated and may differ from a single resistor, so it is better to conduct an experiment with a complex resistor.

To determine the heating, full-scale heating tests of such an assembly were conducted. The tests were conducted for the board without sealant and the board installed in the adapter housing, filled with silicone sealant, the results are shown in Fig. 11.

As a result of our tests, it was found that the transition of the POS-40 type solder to the molten state occurs earlier than the thermal destruction of the resistors themselves. For a first test (board without sealant), the critical current was 200 mA, the melting of the solder began after 20 s of applying such a current, while the board withstood a current of 150 mA under a continuous mode with an overheating value of about 142 °C. In a second test (with sealant), the critical current value was 250 mA, while the board withstood a current of 200 mA under a continuous mode with an overheating value of about 185 °C.

In both cases, the tests were stopped at a temperature of about 220 °C. Fig. 12 shows photographs of the boards after the tests: in Fig. 12, *a*, the displacement of the resistors and the collection of solder into conglomerates are visible – as a result of its melting, and Fig. 12, *b* shows a spot of solder flowing into the cavity of the silicone body as a result of solder boiling.

As a result of our tests, an acceptable load factor was established for the complex resistor board (rated power 21 W). Based on the results in Fig. 11, and the conditions that the ambient temperature can reach +45 °C, overheating of the resistor board should not exceed 145 °C, to ensure reliable operation of the board under a long-term mode (temperature not more than 190 °C) – the load factor should not exceed 0.7.

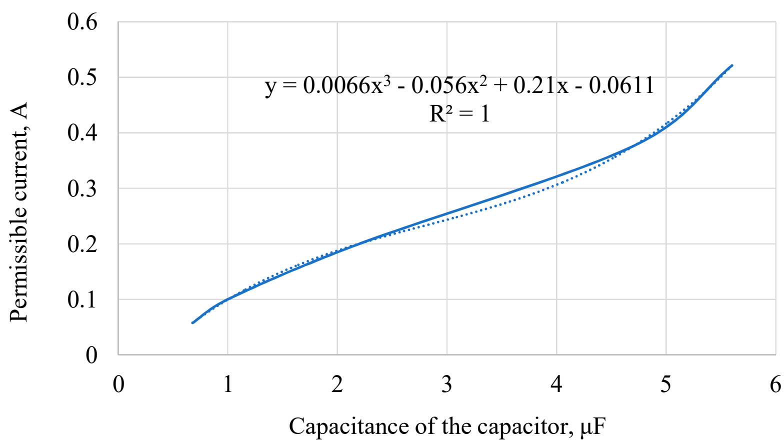


Fig. 10. Determining the maximum continuous allowable current through a protective capacitor

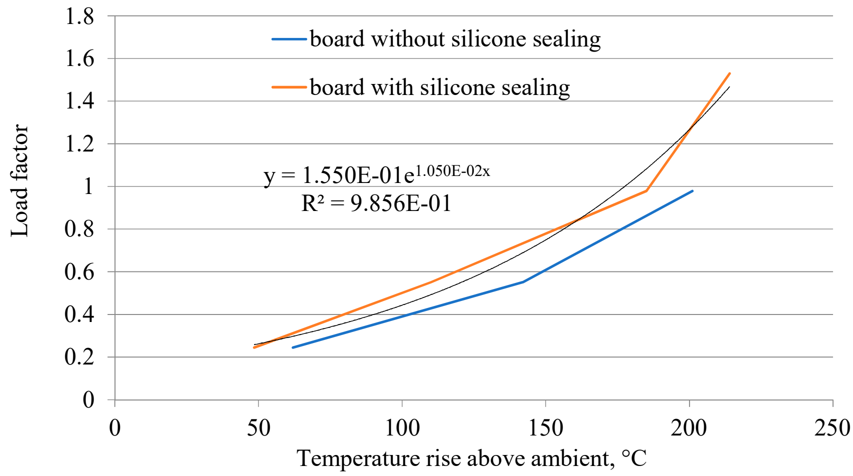
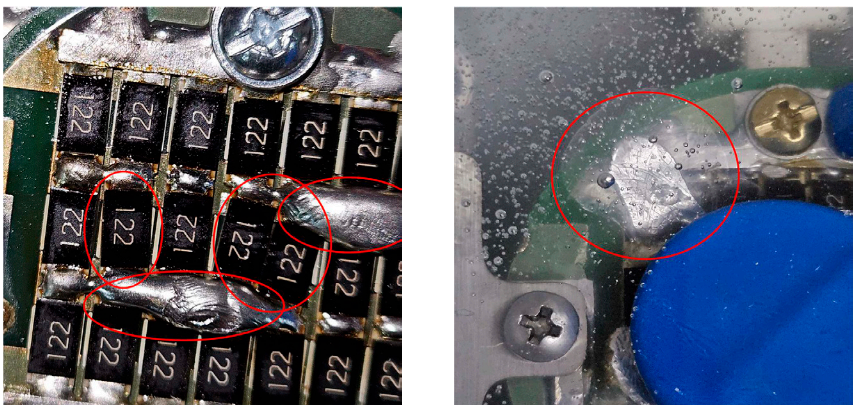


Fig. 11. Dependence of the temperature rise of a complex resistor on the board on load factor



a *b*

Fig. 12. Photographs of the integrated protective resistor boards after current heating tests: *a* — as a result of the solder melting, the resistors began to shift, and the solder collected in volumetric drops; *b* — as a result of the solder boiling, the solder drop moved into the cavity of the sealant thickness from the board tracks

Naturally, in parallel with the use of the main protective elements in the protective circuit of the adapter, fast-acting elements of protection against high-frequency overvoltage should be used, such as diodes-suppressors, varistors, arresters. Such protective elements should have higher operating voltages than the calculated voltages on the main protective elements: resistors and capacitors, but not more than the permissible voltages for these elements.

Thus, a methodology for selecting the main protective elements and recommendations for ensuring the safety of the insulation of devices can be formulated as follows:

– according to formula (3), knowing the peak voltage for the required voltage class (Table 1), the capacitance of the main insulation of the device and the permissible value of the overvoltage at the output, calculate the required value of the capacitance of the protective capacitor;

– set the permissible impulse voltage of the capacitor, which should be greater than the permissible value of the overvoltage at the output, for example, according to [17] – 150% of the continuous permissible voltage;

– set the permissible effective value of the continuous alternating voltage (50 Hz) on the capacitor, for example, according to [17] – the permissible amplitude value is 20% of the continuous permissible voltage;

– check that the current (50 Hz) through the capacitor does not exceed its permissible continuous current;

– check that the current through the resistor (50 Hz) does not exceed its permissible continuous current, taking into account the set load factor – 0.7.

It should also be noted that despite the presence of a protection scheme in case of cable damage, no less attention should be paid to this element of the scheme. According to the requirements of clause 3.4.8 of PUE [18], according to the conditions of mechanical strength, the conductors of secondary circuits, namely current ones, must have a cross-section of at least 2.5 mm^2 for copper and at least 4 mm^2 for aluminum. The electrical circuits of diagnostic terminals must certainly be classified as such circuits, taking into account the possible consequences of their damage. It should also be noted that this clause requires the use of cables with multicore conductors since the high-voltage output adapter is a removable element, and clause 3.4.7 of PUE prohibits the use of aluminum conductors on switchgears of 220 kV and above. Considering the responsibility of the diagnostic (measuring) output circuits and the requirements of PUE, it can be concluded that the adapter connection to the monitoring device must be performed using a cable with copper stranded conductors with a cross section of at least 2.5 mm^2.

The calculation results for devices for the voltage class 750 kV (the highest phase operating voltage

5. 3. Results of devising a methodology for selecting the main protective elements and recommendations

The simultaneous use of a protective resistor and a capacitor reduces the level of overvoltage on the insulation of the measuring output to permissible values in the event of a cable break to the diagnostic device and/or the appearance of high-frequency overvoltage with a frequency of up to 1 MHz and levels of up to 1950 kV (for devices for a voltage class of 750 kV). It should be understood that the use of a capacitor is permissible only in circuits where the current of the complex conductivity of the insulation is controlled (Fig. 2, *a*), that is, when in normal operation the protective elements are shunted by the cable. When monitoring by the voltage drop control method (Fig. 2, *b*), the results will be distorted by the protective capacitor, and control of the dielectric loss tangent and discharge activity in the insulation will become impossible. This is due to the fact that temperature changes in the capacitor parameters will distort the dielectric loss tangent of the insulation, and high-frequency pulses caused by partial discharges in the insulation will short to ground through the protective capacitor, bypassing the registration circuit. That is, such a protective circuit is permissible in devices with a diagnostic (measuring) output adapter, and not with a sensor. That is why the use of adapters, rather than sensors, is more advisable.

is 441.673 kV), performed according to the devised methodology, are given in Table 2. In the calculations, conditionally, capacitors were selected according to [17] with a continuous allowable voltage of 875 V. The allowable peak voltage (duration up to 30 ms) for them is approximately 1300 V, and the effective value of the continuous allowable alternating voltage is approximately 120 V. The value of the protective complex resistor in the calculation is 514 Ohm, with a long-term permissible operating current value according to the methodology at a level of approximately 170 mA. In the actual design of the circuit, it is possible to choose other capacitors, or their characteristics, taking into account the dimensions of the elements and the required values of voltages and currents.

Table 2

Calculation results for the main protective elements of the measuring output adapter circuit

C_1	C_a	A	B	U_{Mi}	U_D	I_{cc}, A	Z_{ca}	I_C	I_{CP}, A	I_R
300	2.2	549	–0.9484	260	15.78	0.042	1446	0.011	0.20	0.031
800	2.2	1421	–0.9892	651	42.08	0.111	1446	0.029	0.20	0.082
1200	4.7	3039	–0.8480	818	48.63	0.166	677	0.072	0.37	0.095
1300	4.7	3676	–0.7886	1084	52.69	0.180	677	0.078	0.37	0.103

Note: C_1 – capacitance of the main insulation, pF;
C_a – capacitance of the protective capacitor, μF;
A, B – coefficients according to (3);
U_{Mi} – maximum impulse voltage at the measuring output;
U_D – effective value of continuous alternating voltage, at cable break (50 Hz);
I_{cc} – current of complex conductivity of the main insulation, A;
Z_{ca} – resistance of the protective capacitor at (50 Hz), Ohm;
Parameters under a continuous operation mode at the highest operating voltage:
I_C – actual current through the capacitor, A;
I_{CP} – maximum permissible current through the capacitor, A;
I_R – actual current through the resistor, A.

From the results of Table 2 one can see that the currents through the capacitor and resistor do not exceed the permissible values for them, and the voltage at the measuring terminal does not exceed the permissible values for it even in the event of a cable break from the measuring terminal and overvoltage with the maximum value.

6. Discussion of results based on investigating the influence of the types and characteristics of elements in the protective circuit

Special feature of the proposed protection circuit is the simultaneous use of a resistor and a capacitor, in contrast to works [3–5, 7–11], in which only one main protection element is used, or it is absent altogether. In the proposed circuit, the capacitor provides a low impedance of the protective circuit at high-frequency overvoltage, and the resistor provides a high long-term current and reliability of the circuit in the event of cable damage. This is due to the fact that the impedance of the capacitor is frequency-dependent, and the resistor for reliability is made in the form of a network of series-parallel connected resistors. In contrast to [3, 4, 7–11], in which the choice of the main protective elements and their characteristics is not justified at all, while in [12] there are even no requirements for their presence. Our work substantiates the need to use the main protective elements and provides a methodology for selecting their characteristics. Unlike [5], in which the calculation of overvoltage on the insulation of damaged cables was performed only for the nominal operating mode, our study was also performed in the presence of high-frequency overvoltage. These differences allow us to build a more reasonable protection scheme for a specific device and avoid fatal errors when organizing insulation control under operating voltage.

The proposed solutions, unlike those in other studies, are based on a deep analysis of possible effects on insulation when using control schemes under operating voltage. In contrast to known results, our work has studied the effect on insulation of cable damage and/or the occurrence of high-frequency overvoltage on the buses of the switchgear and has studied the overheating of a complex protective resistor in a long-term mode. The studies have allowed us to draw reasonable conclusions and approaches to the protection of devices with capacitor insulation when organizing control over its technical condition under operating voltage.

We report results of the study on the effect of high-frequency overvoltage on devices with capacitor insulation when the cable is damaged to the device for diagnosing the condition of the main insulation under operating voltage. The absence of a capacitor in the protection scheme for a device with a main insulation capacity of 800 pF (Fig. 4) can, when the cable is damaged, lead to an increase in voltage at the measuring output at the level of hundreds of kV. With the advent of a capacitor with a capacity of 1 μF (Fig. 5) the voltage value on the output insulation was limited to the level acceptable for it, but such a voltage value (about 1.6 kV) can be dangerous for the protective elements themselves (primarily the capacitor). A capacitor with a capacity of 4.7 μF (Fig. 6) will limit the voltage in the same circuit to a level of no more than 250 V, which is acceptable for most devices and protective elements. Fig. 7 shows that the voltage limitation for a device with a smaller basic insulation capacity (300 pF) to acceptable values (less than 70 V) occurs already with the use of a capacitor with a capacity of 2.2 μF. High voltage values in the absence of a protective capacitor are due to a drop in the insulation impedance of the device, in the absence of a change in the impedance of the protection elements installed in the measuring output circuit. The use of a capacitor leads to a sharp decrease in the voltage at the output to safe values, which is due to the dependence of the capacitor impedance on the frequency. In this case, as shown in Fig. 8, the required capacitor capacity depends on the capacity of the basic insulation of the device for which it is intended to protect. This is due to the fact that the protective capacitor works in conjunction with the capacities of the basic insulation, which are also frequency-dependent.

Formula (3) together with Fig. 9 allow us to determine the approximate values of the peak overvoltage values depending on the capacitance of the main insulation of the device and the capacitance of the protective capacitor. Determining the values by approximating functions (Fig. 9) will introduce some errors but their influence on the final result of a specific practical calculation is not decisive.

The permissible values of the long-term current for polypropylene film capacitors are usually given by the manufacturers of such capacitors, but for an approximate calculation it can be determined by the approximating function (Fig. 10).

The results of thermal tests of the protective complex resistor shown in Fig. 11 demonstrated that the presence of a sealant somewhat improves the conditions for heat dissipation from the resistor board. The improvement in heat dissipation is explained by the better thermal conductivity of the sealant, an increase in the heat capacity, and heat dissipation area of the cast structure.

Our results for the dependence of temperature rise in the complex resistor on load factor prove that it is advisable to use resistors with a load factor of no more than 0.7. This load value is due to the fact that the resistors must be installed tightly to each other to ensure small adapter dimensions (which is especially important for inputs), which worsens heat dissipation. Another influencing factor is the uneven distribution of current between the branches of the complex resistor, due to fluctuations in their resistance during production. Based on the analysis of our results, recommendations were formulated for the protection of the insulation of devices when organizing control under operating voltage.

Based on our research, a methodology for selecting the main protective elements and recommendations for ensuring the safety of insulation of devices when organizing control under operating voltage has been devised. The results of calculations (Table 2), according to the devised methodology, showed that for devices with a voltage class of 750 kV and a basic insulation capacity of up to 1300 pF, it is sufficient to use a capacitor of up to 4.7 μF with a complex resistor resistance of 514 Ohms and a total nominal dissipation power of 21 W. The main recommendations for implementing control schemes from the point of view of their safety for the isolation of the highest voltage devices have been formulated.

The proposed solutions resolve the task related to the need to protect insulation from the consequences of a malfunction in the control scheme under operating voltage. The solutions have no fundamental restrictions on use when applying the method of current control by the complex conductivity of the insulation and the absence of the need to control the tangent of the dielectric loss angle and discharge activity. The constructed model of the insulation scheme of the apparatus with elements of the main protection can be used as a basis for further refinements and research. The practical significance is the possibility of using the results in the design of monitoring systems and organization of periodic control over the condition of apparatus with capacitor insulation under operating voltage.

The results of our study are aimed at increasing the reliability of operation of high-voltage equipment and the electric power system as a whole.

Our study revealed the existence of an important problem, which relates to the possible damage of devices with capacitor insulation, which are equipped with devices for monitoring the state of insulation under operating voltage. The issue is exacerbated in connection with the current wartime conditions, when missile strikes on energy facilities cause abnormal effects on electrical equipment and can also cause damage to cable connections on distribution devices. As a result of modeling and calculations, a simplified methodology was devised for assessing possible overvoltage on the insulation of the diagnostic (measuring) output and the selection of characteristics of protection elements.

The main disadvantage of this study is that when using elements in protection schemes with characteristics different from those given in our work, the obtained quantitative values may change (including the coefficients of the formulas). The use of approximating functions of experimental and calculated data, which introduce certain errors into the results of calculations using such approximating functions, can also be considered a disadvantage. Despite the above shortcomings, the methodology reported could be used as a basic one for further refinements or calculations of a specific scheme with different element parameters.

Prospects for further advancement of such research include further development of the scientific area in monitoring the technical condition of insulation, refinement of the constructed models by refining the parameters of protective elements, design of improved replacement schemes.

7. Conclusions

1. A study on the impact of high-frequency overvoltage on devices with capacitor insulation has been conducted for the case when the cable to the device for diagnosing the state of the main insulation under operating voltage is broken. It was established that when using a protective resistor as the main protection element, overvoltage on the insulation of the measuring output can reach hundreds of kV, which would definitely lead to device failure and an emergency at the power facility. The use of a capacitor with a capacity of 1 μF (for a conventional device for a voltage class of 750 kV and a basic insulation capacity of 800 μF) reduces the overvoltage on the insulation to an acceptable level (about 1.6 kV), but still such that it can damage the protective elements themselves. The use of a capacitor with a capacity of 4.7 kV limits overvoltage to an acceptable level for the device and protective elements (no more than 250 V). In this case, naturally, the required value of the protective capacitor capacity depends on the level of overvoltage and the capacitance of the main insulation. For comparison, for a conventional device for a voltage class of 750 kV and a basic insulation capacitance of 300 μF with a protective capacitor of 2.2 μF, the overvoltage is limited to a level significantly lower than the permissible level for the device and protective elements (no more than 70 V).

2. The operation of the protection circuit elements under a long-term mode has been studied. The permissible load value on the protective resistor should not exceed 0.7 of the rated one (at least for regions with the highest ambient temperature of +45 °C).

3. It is proposed to use a protective resistor and a protective capacitor in parallel as the main elements of insulation protection in the event of a cable break. A methodology for selecting the main protective elements has been devised, which takes into account not only the possibility of cable damage from the diagnostic output but also the appearance of high-frequency overvoltage, as well as the operation of protective elements under a long-term mode. The methodology is convenient for automating the calculation process due to the possibility of using the above approximating functions. The methodology makes it possible to calculate the required value of the protective capacitor capacitance and determine

the main required characteristics of the protective resistor and capacitor based on the peak voltage, the capacitance of the main insulation of the device, and the permissible value of the overvoltage at the output. Practical recommendations are given for selecting the characteristics of additional high-speed elements for protecting the circuit from overvoltage and the cable from the diagnostic output.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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