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DESIGN OF A SCHEME TO PROTECT TRANSFORMERS AGAINST BUSHING INSULATION DAMAGE, IN ORDER TO MODERNIZE ENERGY FACILITIES

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This study's object is a relay protection scheme against damage to transformers (autotransformers) and 35–750 kV shunt reactors as a result of bushing insulation breakdown.

The study investigates the possibility of improving the efficiency of the relay protection of transformer equipment (TrE). The task relates to the widespread application of outdated TrE protection schemes and devices that account for their high cost, low operational efficiency, and may even harm TrE.

This paper reports the results of investigating current signals from the measuring terminals of bushings and formulates basic requirements for implementing modernized protection schemes based on microprocessor monitoring unit. The proposed protection scheme modernization demonstrates improved operational characteristics: increased safety for personnel and equipment, reduced probability of false trips, decreased weight and dimensions, as well as cost. These characteristics were achieved by using a microprocessor device, reducing the length of measurement circuits, excluding matching transformers from the scheme, applying coupling devices with protection circuit.

The effectiveness of using software filtering of current signals based on the discrete Fourier transform algorithm has been proposed and proven for excluding influence currents on the resulting unbalance vector. The inexpediency of accounting for all, except the 1st harmonic, components of insulation currents was demonstrated. The normalized value of the unbalance, while using full signals, was 14%, instead of 1.15%.

The results could be used to manufacture and operate relay protection schemes and devices against 35–750 kV TrE damage caused by breakdown of bushing insulation to improve the reliability of power facilities

Keywords: bushing insulation breakdown, transformer's relay protection, sum of currents method, balance method

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1. Introduction

Accidents and technological failures that occur with high-voltage transformer equipment due to damage to the insulation of high-voltage bushings are among the costliest ones. This is due to the fact that such an accident could lead to the complete loss of the transformer equipment itself and other equipment in the switch gear. According to [1], bushings were the cause of transformer outages in 11.5–37% of such cases (the different percentages are related to the transformer operating time and the presence of a tap-changer). According to the results reported in [2], from 16.3 to 43.8% of transformer accidents are associated with bushings, with the highest rate (43.8%) for equipment with a voltage of more than 700 kV. The analysis given in [3] reveals that more than half of accidents associated with bushings are accompanied by fires and serious consequences. In [4], the results of the study show that about 10% of damage to bushings are associated with violations of the grounding of the test-tap.

The issues of protecting equipment from damage to the insulation of the bushing have been addressed for more than a decade. The specificity of such protection is that the equipment that performs the protection function must diagnose the technical condition of the insulation during equipment operation under high voltage.

The Rules for the Arrangement of Electrical Installations (RAE) in clause 3.2.60 require the installation of a transformer bushing insulation protection device – KIV-500(750) (based on a method often termed "nonequilibrium-compensation", "sum of currents" or "balance"). The KIV device, according to RAE, must be configured to signal in the event of a partial breakdown of the insulation and to transformer shutdown in the event of a breakdown progression (up to a complete breakdown).

RAE confirm that the most effective method for diagnosing bushing insulation condition is control under operating voltage; defects in the insulation appear precisely under full operating voltage. Partial breakdown of the insulation can occur at any time after the transformer equipment is put under operating voltage, even if satisfactory results from diagnosing its condition were previously obtained during a test with reduced voltage.

Most of the so-called KIV systems installed in Ukraine on 500–750 kV equipment are technically outdated, which causes problems with the repair and operation of such systems. Therefore, this study and its results are relevant and could be used in the production and implementation of relay protection circuits and devices against damage to transformers (autotransformers) and shunt reactors of 35–750 kV as a result of breakdown of the insulation of the bushing.

The urgency of this task is even more acute taking into account the state of war in Ukraine when powerful transformer equipment and switchgear become targets of enemy strikes. Therefore, survived equipment, more than ever, needs effective protection and diagnostic systems and, during restoration, new components for such protection systems are needed.

2. Literature review and problem statement

In [3], the results of the study on detecting defects in the insulation of bushings using partial discharge registration are reported. Partial discharges are in many cases the primary cause of insulation breakdown but at present, operational measurements of partial discharge characteristics have not been widely used, especially in protection schemes. This is mainly due to the high cost of such systems and low reliability of the results due to the action of operational disturbances.

Damage to bushings is very often accompanied by serious consequences [4], which could be avoided if an accident protection system were used: due to the development of conductive tree-like formations in the insulation and disturbances in the grounding circuit of the bushing insulation test-tap. In [5], the authors analyzed the possible causes of failure, within a short time, of five 33 kV bushings with oil-impregnated paper condenser insulation. These accidents caused a power outage for about 130 thousand consumers in Oman.

In [6], the same accidents were analyzed, and the conclusions were drawn that the failures of the bushings were associated with an internal localized insulation breakdown. Such conclusions also indicate that fast-acting protection against insulation breakdown of the bushings can help avoid the severe consequences of such failures, reduce the time of power outage of consumers, and save expensive equipment.

In [7], the balance method for diagnosing the condition of the bushings is considered and it is proposed, in particular, to use the "training" of the diagnostic device and filtering of fluctuations in the value of the vector of unbalance of leakage currents. In the work, the authors confirm the presence of significant external influences on the result, but their approach can lead to an increase in the response time to the evolution of a defect in the insulation and lead to an equipment failure.

In [8], the theory of the balance method is considered; examples of calculating changes in the dielectric loss tangent (insulation power factor) and the capacitance of the main insulation by the unbalance vector are given. The paper considers the issue of the influence of voltage and temperature on the values of the diagnostic parameters of insulation, but the effects of asymmetry of operating voltages, the effects on the conductivity currents of insulation are not considered at all. Failure to take into account the action of operational influences leads to erroneous conclusions, the need to overestimate the settings of protection operation, and reduce the efficiency of such protection.

In [9] the experience of monitoring the state of bushing insulation under operating voltage, including using the balance method, is described. The paper notes that the fluctuations of three capacitances together with three values of the dielectric loss tangent, external influences, such as network asymmetry, making the analysis of the unbalance vector meaningless. At the same time, the work does not take into account that the balance method should not be used to track changes in active losses in insulation, but it is an effective method for detecting partial breakdown of insulation.

In [10], the results of studies are reported that the breakdown voltage value is affected by moisture content, oil absorption capacity of cellulose (associated with pores and cracks, structural damage), and the degree of aging of cellulose. In [11], similar factors of influence on the breakdown voltage value were obtained and a dependence on temperature and paper thickness was established. Papers [10, 11] are important because the authors provide factors of influence on the development of a defect, which is important when organizing protection, but do not consider practical and theoretical aspects of protection against damage to the insulation of bushings. The work shows that the breakdown of the bushing insulation can occur in a time that is much less than the time between scheduled preventive maintenance on the equipment and may differ for specific bushings.

In works [12, 13], approaches to diagnosing the technical condition of bushing insulation under operating voltage are described. Online monitoring of the condition of the equipment is aimed at early detection of the development of a defect and deterioration of the condition of the equipment. Protection of equipment from damage to bushing insulation is aimed at preventing damage to the transformer equipment itself, preventing the serious consequences of such damage, preserving the equipment of the switchgear and the lives of personnel. In [12], the problem of using the matching transformer TPS-0.66 (Russian Federation) in the protection and monitoring circuits of high-voltage bushings is considered, but in the context of monitoring the technical condition, but not protection. The task is important, but the work does not consider other sources of influence on the results of the protection schemes.

Paper [14] reports the results of studies on the influence of operating voltage asymmetries on the unbalance vector and a method for minimizing their influence, which can be applied when implementing protection schemes, but other influences were not considered.

In [15], a new approach to organizing protection against bushing insulation damage is proposed. The paper describes a protection scheme in which the authors use a measuring device to record bushing insulation currents, which is installed near the TrE. The measuring device transmits a signal to the terminal in the relay room via a digital interface; the authors also emphasize the need for an effective insulation protection scheme against overvoltages during the implementation of the scheme. This approach is very promising, but the described implementation has a number of disadvantages. The first is the lack of galvanic isolation of the insulation test-taps between themselves and the measuring device (which can lead to failure of the measuring device, the appearance of circulating influence currents between the circuits of different phases). The measuring device used the balance method, but without initial balancing (all three bushing in the example had the similar values of main insulation capacitance, so the authors did not see any negative impact from this). The absence of initial balancing of the unbalance vector for bushing with different capacitance values will make it impossible to determine the correct values of the triggering setpoints. The authors also use the so-called device learning (training) algorithm when the device records fluctuations in unbalance values for some time and then considers such fluctuations not as a deterioration in the insulation state but as external influences. The use of such an algorithm is also confirmed by the results of the protection system. According to the system, the equipment was turned off when the bushing insulation capacitance changed by 6%, but in fact it turned out that the change was 52% (from 560 to 853 pF). Algorithms for filtering the final values of the equipment condition criteria, an unjustified increase in setpoints often lead to the protection being triggered after an emergency. That is why this approach is unacceptable for protection circuits and devices.

In work [16], protection circuits for test-tap adapters when organizing insulation state monitoring under operating voltage were studied in detail, but the issue of the operation of the equipment protection circuit itself was not considered.

The balance method is convenient for use in protection schemes against damage to the insulation of the bushing but for its effective use, it is necessary to study the operational influences on the values of unbalance, as well as introduce algorithms to minimize these influences. Approaches to building monitoring and protection systems differ; therefore, the requirements for equipment and its operational problems are somewhat different. Manufacturers and researchers have not paid enough attention to designing modern protection systems against damage to the insulation of the bushing.

The matching transformer TPS-0.66 should be excluded from protection schemes because of the following:

– purchasing it is unacceptable;

– large inductance can cause damage to the insulation of the bushing during high-frequency overvoltage;

– the transformer has limited current matching capabilities (at the level of 3%), that is, it may be impossible to balance the scheme to zero, in the presence of bushing with different passport values of the capacitance of the main insulation;

– the transformer has rather large mass and dimensions (exceeding 17 kg).

In existing schemes, the signal from the matching transformer cabinet, installed near the protected equipment, extends to the relay protection cabinet where the KIV device itself (protection terminal) is installed. Such a scheme can also pose a danger to the insulation of the bushing in case of cable damage. The analog signal is additionally exposed to interference (the length of the cables laid along the high-voltage open switchgear can reach several hundred meters, or even more than 1 km). According to the requirements of clause 3.4.8 in RAE – under the conditions of mechanical strength, the conductors of the secondary circuits, namely the current ones, must have a cross-section of at least 2.5 mm^2 for multi-core copper conductors. That is, the price of such a cable can be quite high.

Additional disadvantages of existing protection schemes include:

– the use of relay schemes that are difficult to configure and maintain;

– the lack of the ability to automatically record parameters, deviations, and analyze retrospective events;

– old relay schemes often do not identify the location (equipment phase) with a defective bushing;

– the lack of the ability to local diagnostics and signaling the state of the equipment in the event of damage to the cable to the relay room;

– defect registration is usually performed by personnel by visually checking the values on the devices;

– the systems are subject to influences and signal distortion, which leads to the need to increase the setpoints and a corresponding decrease in the effectiveness of the protection.

Microprocessor systems could eliminate all of the listed disadvantages from protection schemes for transformers (autotransformers) and shunt reactors 110–750 kV caused by bushing insulation breakdown.

The task of constructing protection schemes for transformers against damage to the insulation of the bushing is not considered in detail in the scientific literature. In works [3, 7–16], the theory of the basic method of such protection – the balance method – is considered in detail but most of them focused on attempts to combat fluctuations in the main diagnostic criterion of the method, due to the influence of extraneous factors on it. This approach has a major drawback – significant delays in the operation of the protection, there is a risk of low efficiency of such schemes. A likely reason for why that approach was not considered by scientists is the lack of adequate primary information about such signals that can be obtained only during operation under operating voltage.

Thus, there is an issue related to the implementation of an effective scheme for protecting TrE from bushing insulation damage.

3. The aim and objectives of the study

The purpose of our study is to design a scheme for protecting transformers from bushing insulation damage for modernization at energy facilities. This will make it possible to define a general approach to modernizing TrE protection schemes to increase the reliability of protection operation; to improve safety for equipment and personnel; to enhance the quality of TrE operation and protection schemes.

To achieve the goal, the following tasks were set:

– to investigate the current signals of the complex conductivity of bushing insulation, which are used as the primary source of the insulation state when implementing the protection scheme; to devise a method for minimizing external influences on the unbalance vector;

– to design the structure of the modernized protection scheme based on the balance method and a microprocessor device; to define general requirements for its implementation.

4. The study materials and methods

The object of our study is a relay protection scheme against damage to transformers (autotransformers) and shunt reactors of 110–750 kV caused by bushing insulation breakdown.

The hypothesis of the study assumes that the insulation conductivity currents of the bushing, which are used to form the unbalance vector in the protection and monitoring schemes of the bushing, include influence currents that distort the value of the unbalance vector. Investigating and devising a methodology for minimizing influence currents for microprocessor protection devices will make it possible to improve the efficiency of protection schemes. The use of a microprocessor protection device will make it possible to improve the efficiency, safety, and ease of operation of the equipment.

Before the start of the study, assumptions were adopted: the results of the study for the voltage class of 500 kV could be extrapolated to equipment of other voltage classes.

In the process of our study, the insulating structure of the bushing is imagined to be an ideal capacitor whose inductive and resistive components were neglected.

In the study:

– the bushing insulation conductivity current is considered to be the current that flows in the middle of the insulation under the action of the applied voltage;

– the influence currents is considered to be the currents in the insulation test-tap circuit that are induced by the electric fields of the working neighboring installations, their and their own busbars, interference, and other physical phenomena not related to the bushing insulation;

– the complex conductivity current is considered to be the sum of the part of the insulation current that falls on the bushing test-tap and the influence currents;

– the normalized unbalance current is considered to be the ratio of the value of the geometric sum of the balanced complex conductivity current vectors of the three-phase group of bushing (which belong to one connection of the busbar system of the distribution installation) to the arithmetic mean value of the rated insulation conductivity of these bushings.

In the general case, the unbalance current vector is equal to

$$\overrightarrow{I_{nb}} = \overrightarrow{I_a} \cdot k_a + \overrightarrow{I_b} \cdot k_b + \overrightarrow{I_c} \cdot k_c, \quad (1)$$

where I_a, I_b, I_c are the insulation conduction currents of the corresponding bushings;

k_a, k_b, k_c are the conditional coefficients responsible for balancing the vector, when putting the protection or monitoring device into operation, to a value close to zero.

The normalized value of the unbalance current used is

$$I_{nb} = \frac{\left|\overrightarrow{I_{nb}}\right|}{\dfrac{\left|\overrightarrow{I_{na}}\right| + \left|\overrightarrow{I_{nb}}\right| + \left|\overrightarrow{I_{nc}}\right|}{3}} \cdot 100, \quad (2)$$

where I_n – rated (at balancing, or at rated voltage) insulation conductivity currents of corresponding bushings.

The physical content of the unbalance current vector that occurs after balancing, which is important for the protection scheme, can be written as

$$\overrightarrow{I_{nb1}} = function\begin{pmatrix} \Delta C_{1a}, \Delta C_{1b}, \Delta C_{1c}, \\ \Delta \mathrm{tg}\delta_{1a}, \Delta \mathrm{tg}\delta_{1b}, \Delta \mathrm{tg}\delta_{1c} \end{pmatrix}, \quad (3)$$

where ΔC_1 – changes in the capacitances of the main insulation;

$\Delta \mathrm{tg}\delta_1$ – changes in the tangent of the angles of dielectric losses of the main insulation.

But in addition to the parameters that form the "usable" physical meaning of the value of the unbalance vector, there are also parameters that exert a significant impact on its change but are not related to the technical condition bushing insulation. Therefore, during actual operational control, the value of the unbalance vector can be written as

$$\overrightarrow{I_{nb2}} = function\begin{pmatrix} \overrightarrow{I_{nb1}}, \overrightarrow{\Delta U_a}, \overrightarrow{\Delta U_b}, \overrightarrow{\Delta U_c}, \\ \overrightarrow{\Delta I_{va}}, \overrightarrow{\Delta I_{vb}}, \overrightarrow{\Delta I_{vc}} \end{pmatrix}, \quad (4)$$

where ΔU – changes in the vectors of the working (applied to the insulation) voltage after balancing;

ΔI_v – changes in the vectors of the influence currents after balancing.

From (4) it becomes clear that to achieve effective protection operation, it is necessary to minimize the effects of asymmetries (both in amplitude and in phase value) and harmonic distortions of the working voltages, influence currents. For effective protection operation, it is necessary that the value $\overrightarrow{I_{nb1}}$, and not $\overrightarrow{I_{nb2}}$, is in formula (2), i.e., $\overrightarrow{I_{nb}} = \overrightarrow{I_{nb1}}$.

The studies reported in this work relate to reducing the impact of harmonic distortions of voltages and influence currents; they are based on the theoretical laws of electrical engineering and algorithms of digital signal processing according to the discrete Fourier transform. Microsoft Excel 2019 (Microsoft Corporation, Redmond, WA, USA) was used for calculations and graphic design of results.

The complex conductivity current and voltage signals from the measuring windings of voltage transformers (VTs) analyzed in the work were recorded directly by one of researcher. The recording was performed during the operation of the 500 kV open switchgear, under operating voltage, from the main control room of the substation. The currents from the insulation test-tap of the bushing of the three-phase group of 500 kV shunt reactors were recorded. The capacitances of the main insulation (C_1) of three bushings had almost the same values – 490 ± 2 pF; the difference in the values of the conductivity currents is caused only by the presence of a small phase voltage asymmetry: the data are given in Table 1.

When registering signals, a 4-channel synchronous analog-to-digital converter (ADC) with a sampling frequency of 100 kHz and a bit depth of 16 bits was used, the range was ± 10.4 V, the ADC error was not worse than (0.006 x (converted value) + 0.0038 x (range)).

When theoretically calculating the required operating setpoints, the requirements for the levels of the highest voltages and one-minute test voltages according to DSTU EN 60137:2022 "Insulated bushings for alternating voltages exceeding 1000 V (EN 60137:2017, IDT; IEC 60137:2017, IDT)" were used. Data on the calculation coefficients are given in Table 2.

The reserve factor for permissible voltage for 60 s (K_{60}) is used in further studies as a criterion for the need for the fastest possible shutdown of equipment.

Table 1

Equipment parameters

Reactor phase	Operating phase voltage, kV	C_1, pF	Estimated value of conduction current, mA
ph. A	288.675	492	44.62
ph. B	283.478	488	43.46
ph. C	287.231	490	44.22

Table 2

Permissible voltage levels for insulation accepted in the study

Rated voltage, kV	Highest operating voltage, kV	Permissible voltage for 60 s, kV	Safety factor for operating voltage	Safety factor for voltage permissible for 60 s (K_{60})
35	36	77	1.03	2.14
110	123	205	1.12	1.67
150	170	255	1.13	1.50
220	245	435	1.11	1.78
330	362	505	1.10	1.40
500	550	695	1.10	1.26
750	800	870	1.07	1.09

5. Results of research on modernizing transformer equipment protection schemes against damage to bushing insulation

5. 1. Results of research on the complex conductivity current signal of bushing insulation

Fig. 1 shows the conductivity current signals (Ia, Ib, Ic) of the bushing insulation of a 500 kV three-phase group of shunt reactors and the total unbalance current signal (Inb).

Analysis of the harmonic composition of the bushing insulation conductivity current ph. A is shown in Fig. 2; the data are given for the relative amplitudes of higher harmonics (relative to the amplitude of the 1st harmonic).

Fig. 2 demonstrates that the largest amplitudes of higher harmonics are in the frequency range up to 500 kHz, and a harmonic with a frequency of 44.7 kHz is also present, with a rather large amplitude, which is caused by the ingress of an RF-communication signal into the complex conductivity current.

The currents of other phases have approximately the same distribution of harmonic amplitudes.

Fig. 3 shows the signals from the instrument voltage transformer (VT) (ph. B bus voltage, with the initial phase reversed by 180°), as well as the calculated value of the 1st harmonic of this signal and the current signal of the complex conductivity of the ph. B bushing insulation.

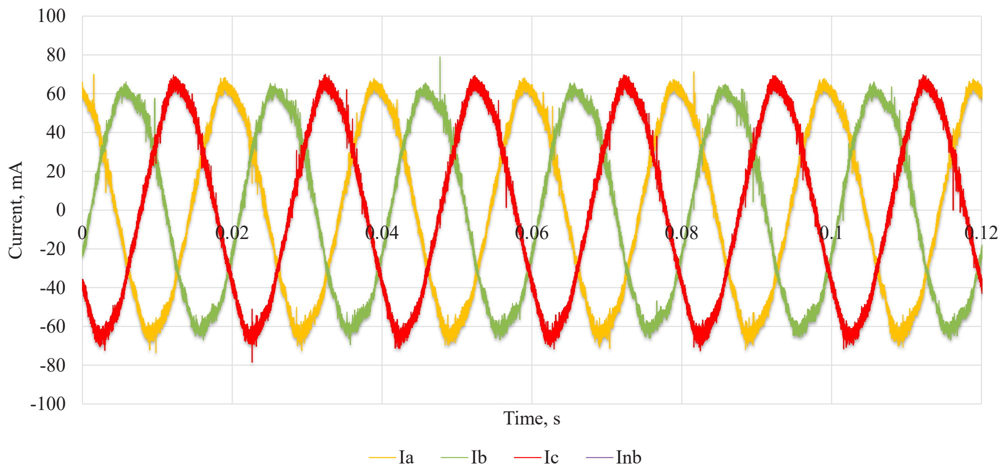

Fig. 1. Complex conductivity current signals of 500 kV bushings

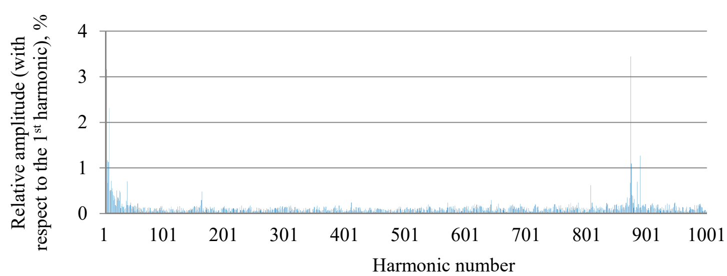

Fig. 2. Harmonic composition of the current from the insulation test-tap of the bushing of phase "B"

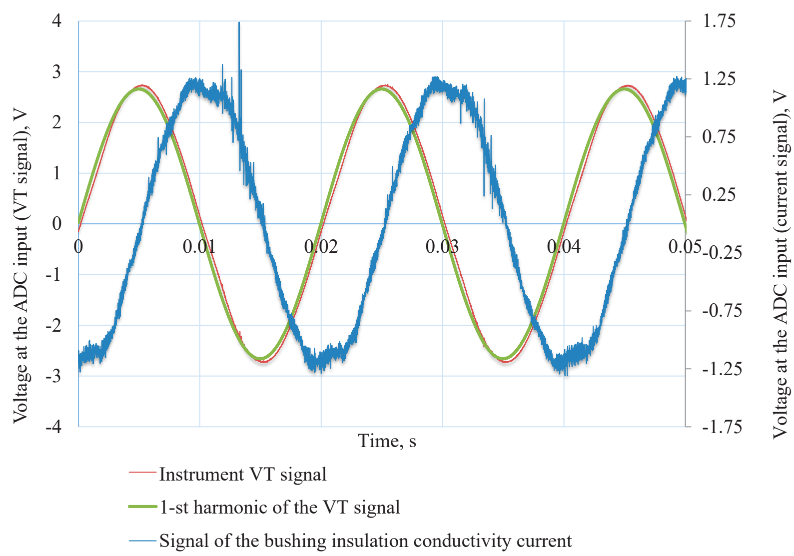

Fig. 3. Signal from instrument voltage transformer and current of complex conductivity of phase "B" bushing

Analysis of the spectral composition of the VT signal (Fig. 4) reveals that the signal is almost completely devoid of components above the 100th harmonic.

Fig. 5 shows the results of the comparison of the relative values of the 2^{nd} to 10^{th} harmonics for the signal from VT and the current of the complex conductivity of the ph. B bushing insulation. Similar comparison result was obtained for all three phases. From this comparison, it can be assumed that the 2^{nd} to 10^{th} harmonics in the signal from the insulation test-tap of the bushing are present due to their presence in the operating voltage. Some harmonics, for example, the 7^{th}, are amplified in the current signal, possibly under the influence of some physical processes in the bushing insulation. The study of this phenomenon was not the task of our study.

Fig. 6 shows the output current signal from the insulation test-tap of the bushing ph. A with the superimposition of the plot of the 1st harmonic of the signal and the plot of the sum of the first ten harmonics of the signal, which shows that the resulting signal, in addition to the presence of interference, has distortion in the effective value and phase.

Fig. 7 shows a synchronous oscillogram of signals from the insulation test-taps of three bushings, the total unbalance signal, as well as plots of the calculated values of the first harmonics of all four signals.

For the unbalance signal, a plot of the third harmonic, which is decisive, is also shown, as can be seen in Fig. 7.

Fig. 8 depicts the unbalance signal and its first harmonic, which can effectively characterize the technical condition of bushing insulation for protection operation.

Fig. 9 illustrates analysis of the amplitudes of the first 10 harmonics of the unbalance current signal and the calculated value of the normalized unbalance obtained for the first ten harmonics ($I_{S1\text{-}10}$), with normalized value $I_{nb\,\%} \approx 5\%$. This calculation shows that even with the use of a high-pass filter, the unbalance value can remain quite high.

Table 3 gives results from calculating current values and the normalized value of unbalance for complete signals and their 1^{st} harmonics.

As can be seen from the results given in Table 3, the normalized value of the unbalance corresponds to the emergency value if the diagnostics is performed by a device that registers the effective value of the signal (for example, a milliammeter, which is often used for this purpose). This is due to the presence of interference and harmonic distortions on the signals (influence currents, voltage distortion by harmonics, etc.).

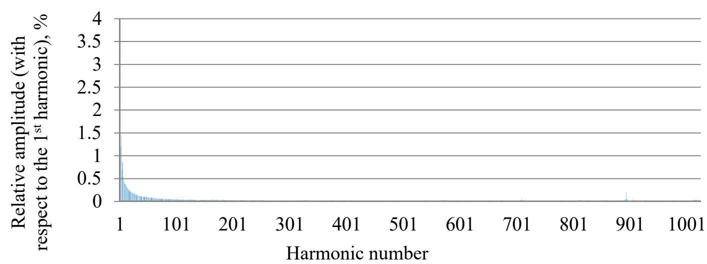

Fig. 4. Harmonic composition of the signal from the voltage transformer of phase “B”

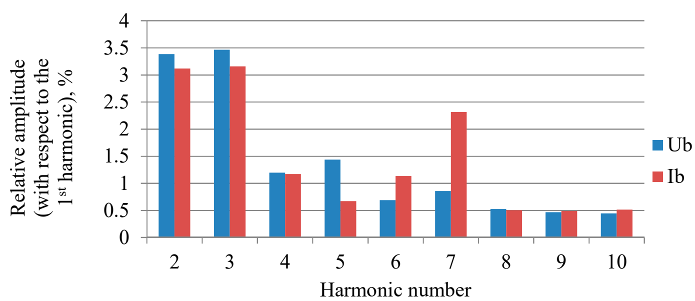

Fig. 5. Harmonic composition of the signal from the voltage transformer (Ub) and current from the insulation test-tap of the bushing of phase “B” (Ib)

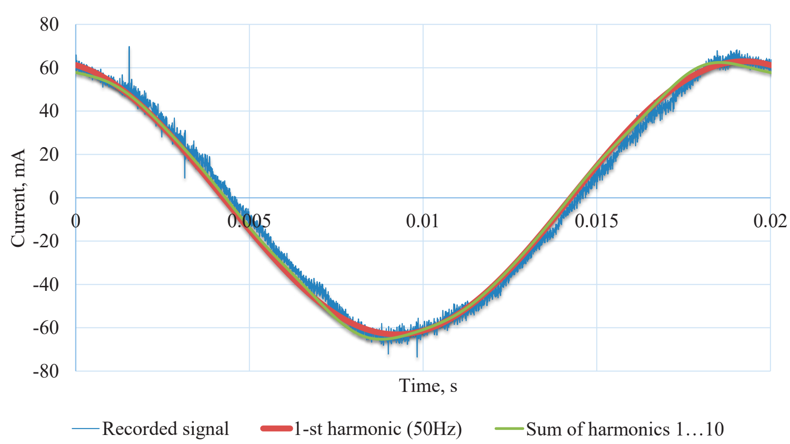

Fig. 6. Current signal from the insulation test-tap of the phase “A” bushing and its calculated spectral components

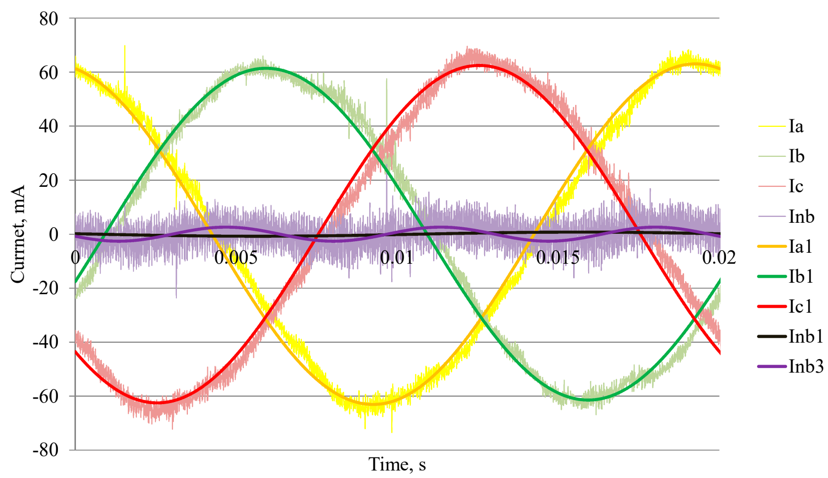

Fig. 7. Current signal from insulation test-taps of 500 kV bushing (Ia, Ib, Ic) and their calculated 1st harmonics (Ia1, Ib1, Ic1), unbalance signal (Inb), and its calculated 1st (Inb1) and 3rd (Inb3) harmonics

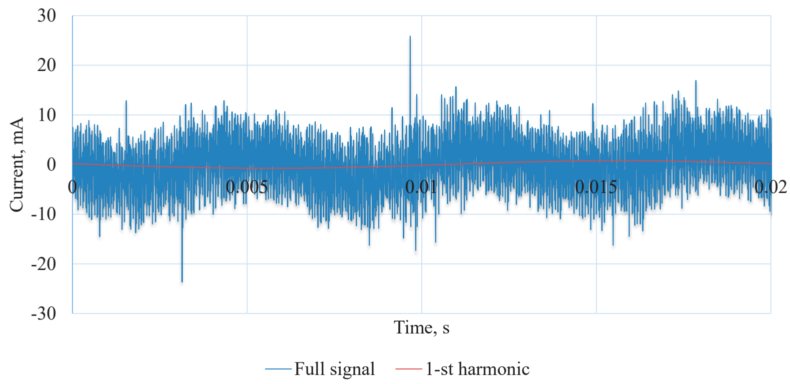

Fig. 8. Unbalance of current signals received from the measuring terminals of bushings and its first harmonic

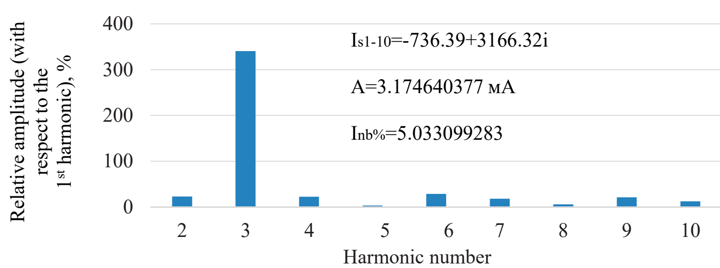

Fig. 9. Harmonic composition of the unbalance current signal of 500 kV bushings

Table 3

Results from calculating diagnostic parameters of the insulation condition of bushings

Physical signal	Estimated value, mA	1st harmonic, mA	Full signal, mA
Insulation test-tap of bushing ph. A	44.62	44.60	44.75
Insulation test-tap of bushing ph. B	43.46	43.44	41.56
Insulation test-tap of bushing ph. C	44.22	44.19	46.44
Unbalance	–	0.51	6.45
Normalized value of unbalance %	–	1.16	14.58

5. 2. Results of designing a structural diagram and defining general requirements for the microprocessor protection scheme equipment

Fig. 10 shows the designed structural diagram for implementing the protection and online diagnostics of TrE state. The scheme is modified based on [15] but it takes into account all the specified shortcomings. Signals from VT can be fed directly to a remote terminal in the relay room. Thus, it will be possible for the terminal to assess the presence of an unbalance in the operating voltages before generating signals for the operation of the setpoints and block them in the presence of a corresponding voltage unbalance. A more effective way would be to connect the signals to the protection monitoring unit for synchronous registration of complex conductivity currents and voltages, which could make it possible to use a model with compensation for voltage asymmetries [14].

The basic elements of the protection scheme, thanks to which the efficiency is improved, are:

– insulation test-tap adapter with the function of protection against cable damage and overvoltage (Fig. 11);

– protection monitoring unit (PMU) – protection module that performs direct measurement, signal processing (including the possibility of adjusting accordingly to the values from VT), diagnosing the current technical condition of bushings, data storage and transmitting them to a remote terminal installed in the relay room;

– the remote terminal (Fig. 12) receives data from PMU, operates the corresponding relay signals in the protection scheme, issues operational and retrospective data to personnel and automated systems.

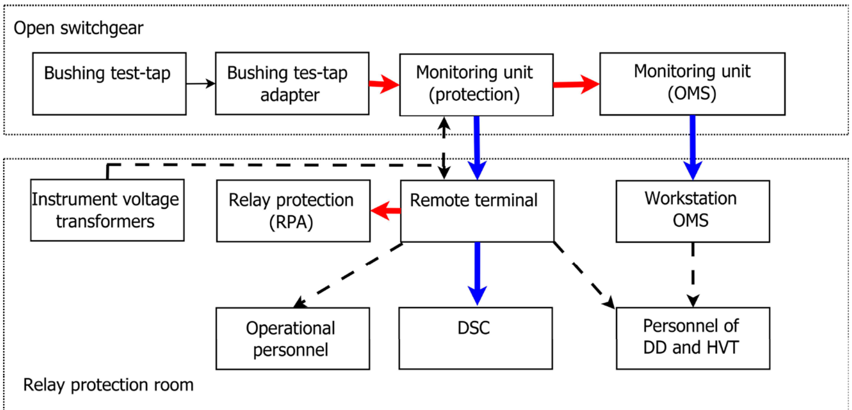

Fig. 10. Structural diagram of the modernized protection scheme (abbreviations: «OMS» — online monitoring system, «DSC» — distributed control system, «DD and HVT» — department of diagnostics and high-voltage testing service, «RPA»— relay protection and automation, blue color marks connections via digital data exchange interfaces, and red — conventional electrical connections, dotted lines mark optional connections and directions of information transmission

Fig. 11. Insulation test-tap adapter AIV-08, mounted on the bushing

Fig. 12. Remote terminal for SAFE-T® monitoring unit

Taking into account the data given in this work – if in the worst case the breakdown of the first condenser-layer of the bushing occurred under the action of the highest operating voltage (*Unr*) and the design of the bushing provides for *N* condenser-layers, it is recommended to calculate the signal setpoint from the following formula

$$T_1 = \frac{100}{N}. \quad (5)$$

The triggering (shutdown) setpoint should be calculated from formulas (6); it is necessary to choose the smallest of the obtained values

$$T_2 = \left(K_{60} - 1\right)\cdot 100 \vee T_2 = \frac{200}{N}. \quad (6)$$

In this case, the shutdown will occur if two condenser-layers are broken down, or the level of the one-minute test voltage is reached.

Such a calculation of setpoints holds provided that the other layers of the bushing condenser insulation do not have significant defects. It should also be taken into account that theoretically the equipment must withstand the specified voltage for 60 s without damage, and the breakdown voltage value is inversely proportional to the time of application of such voltage. It is advisable to set the triggering setpoint for shutdown with a time delay to prevent the transformer equipment from turning off due to the action of random interference. It is advisable to set the triggering delay time to no less than three times the average cycle of performing one measurement by the monitoring unit. At the same time, this time should be an order of magnitude less than the time of possible defect development, which in this assumption is 60 s. That is, based on our chain of assumptions:

– the delay time of the triggering setpoint for the equipment to turn off should be 6 s;

– the measurement cycle of the monitoring unit should not exceed 2 s.

An example of calculating the setpoints for a 500 kV bushing, taking into account the assumptions given in Table 2 and the explanations to it, is provided in Table 4.

The insulation protection schemes against cable damage were discussed in detail in [16]; all the conclusions and results should be used in adapters for protection schemes. Such adapters are produced by the Ukrainian enterprise "ENERGY AUTOMATION" LLC (Zaporizhia) under the brand name AIV-08. In addition, based on the research conducted, at the enterprise prototypes of the monitoring unit and remote terminal for SAFE-T® systems were fabricated, which could be used specifically in protection schemes. The monitoring unit for protection was built on the basis of a standard monitoring unit described in [12], which provides the following advantages:

– the insulation test-tap of the bushing remains dead-grounded (solid-grounded), without the presence of significant inductances in the grounding circuit, unlike TPS-0.66;

– there is galvanic isolation of the circuits from different phases and the absence of overflows from the non-equipotentiality of different grounding points of single-phase equipment in three-phase groups;

– the safety of the connection scheme for insulation of the controlled bushing and personnel is ensured – the voltage at the open ends of the cable during the rated operation mode of the equipment can be limited to safe values.

The monitoring unit for protection, although it has the same appearance and dimensions, unlike the usual one:

– is powered by the constant operational voltage of voltage relay protection devices;

– has an average execution time of one cycle of diagnosing the state of bushing insulation of 600 ms (when analyzing 6 periods with a discreteness of not worse than 1 ms) and is selected by the User (a longer analysis time means greater protection against the influence of random interference);

– has a setting for delaying the activation of setpoints;

– has the functions of recording parameter values and events, time synchronization from GPS;

– is equipped with a remote terminal;

– the equipment provides for cyber protection measures, which is mandatory especially during martial law (preventing interference in work, seizure or replacement of data, changes in setpoints by an unauthorized User or attacker).

Table 4

Example of calculating setpoints for protection against bushing insulation damage for voltage class 500 kV

Number of condenser-layers in the bushing main insulation	16
Highest operating phase voltage	317.54
One-minute test voltage for one condenser-layer (new bushing), kV	43.44
Number of broken insulation condenser-layers of the bushing:	Approximate phase voltage per one working insulation condenser-layer of the bushing due to breakdown of the specified number of condenser-layers, kV:
1	22.49
2	25.52
3	29.01
4	33.08
5	37.89
6	43.66
Signal setpoint, %	6.25
Shut-off setpoint, %	12.5 (partial breakdown of two condenser-layers)

6. Results of research on modernizing protection schemes against damage to bushing insulation: discussion

When studying the signals of currents of complex conductivity bushing insulation, it was found that the current contains a large number of additional components – influence currents (Fig. 1). Influence currents detected during our study consist of the following:

– currents from high-frequency interference (Fig. 2) and even a signal from high-frequency communication;

– currents from harmonic components of the operating voltage (Fig. 3) – according to studies, the influential amplitude values are not higher than the 10th harmonic (Fig. 4), they can arise due to nonlinear loads and processes in the transformer equipment;

– harmonic distortions of the current signal due to the action of physical processes in the insulation of the bushing itself or other influences, for example, the 7th harmonic was amplified in the current in relation to the same harmonic in the voltage (Fig. 5).

Influence currents distort the actual values of the signals and the unbalance vector:

– amplitude and initial phase of the currents (Fig. 6);

– amplitude and initial phase of the unbalance vector (Fig. 7);

– effective values of the insulation conductivity currents and the unbalance current (Table 3).

The high-voltage bushing is a capacitor, connected between the high-voltage buses and the ground. That is, it is an element of the circuits for the flow of high-frequency signals to the ground, which explains the content of a large number of high-frequency interference in the composition of the complex insulation conductivity current and even a signal from high-frequency communication. Therefore, the signal recorded from the insulation test-tap of the bushing contains a number of components (interference) that are not related to the technical condition of the bushing insulation.

When assessing the insulation condition of bushings, it is advisable to analyze only the 1st harmonics of the currents, which give a normalized value of the unbalance free from the action of extraneous influences (Fig. 8). It is the growth of the normalized value of the unbalance of the main insulation conductivity current that has a physical connection with the presence of a partial breakdown of the insulation. Registration of the full signal (sum of the full signals of the complex conductivity currents) will lead to the dependence of the result on random influences (Fig. 8). This is due to the fact that the harmonic components on different phases may have different amplitudes and initial phases, when added, they will not be compensated but will be amplified in the resulting current. The same results will be achieved when adding other components of the influence and interference currents.

The use of hardware filters in protection schemes can reduce the negative impact of high-frequency components but such filters can also introduce their own negative impacts into the protection scheme. Hardware filters usually have a nonlinear attenuation coefficient and pass frequencies near the cutoff frequency to a significant extent. In addition, hardware filters can have a negative impact on the unbalance vector due to the effect of temperature and time on its elements. The calculated value of the normalized unbalance $I_{nb\,\%} \approx 5\%$, obtained for the first ten harmonics ($I_{S1\text{-}10}$), indicates that when using such a high-frequency filter, the unbalance value, under the influence of influences, remains high (Fig. 9). Our study proposes performing effective filtering of complex conductivity current signals using the discrete Fourier transform algorithm. Unlike hardware RC filters, the proposed technique provides high filtering efficiency and no influence on the signal and its processing, which makes the use of hardware filters impractical compared to the proposed method.

Comparison of the results of diagnostics by full signals and 1st harmonics, given in the study (Table 3), shows the inexpediency of taking into account all other components (the normalized value of unbalance was 14%, instead of 1.15%).

During our study, the main problematic points of existing schemes for protecting the transformer substation from bushing insulation damage were analyzed, the presence of which, first of all, can be explained by the use of outdated element base and approaches. The modernized scheme designed during our study (Fig. 10) has a number of advantages; this is explained by the use of a microprocessor monitoring unit that calculates the normalized value of the unbalance current based on the 1st harmonics of complex conductivity currents:

– the possibility of using test-tap adapters (Fig. 11) with protection against cable damage (due to the low input resistance of the monitoring unit circuits);

– analog signals from the insulation test-taps of bushing are sent only to the monitoring unit located directly next to the protected equipment, and not to the relay room;

– the signal to the relay room is transmitted via a digital channel to a remote terminal (Fig. 12), which provides additional protection against interference, as well as the possibility of reducing cable costs;

– if the cable from the switchgear to the relay room is damaged – the monitoring unit continues to diagnose the equipment and performs local signaling about its condition;

– advantages of microprocessor technology (automatic event recording, the possibility of retrospective data analysis, all data is available not to the relay board in the remote terminal and locally, near the monitoring unit).

The proposed scheme provides for the exclusion of matching transformers, reduction of the length of cable routes, reduction of mass and dimensions of the protection circuit devices while simultaneously increasing efficiency and safety for personnel and the equipment itself.

The peculiarity of the proposed protection scheme is the use of a monitoring unit adapted to the protection functions with a remote term, which provides data transmission in digital form over long distances, unlike existing protection schemes described, for example, in [12].

Requirements have been defined for the hardware part of the microprocessor monitoring unit, which makes it possible to obtain the value of the normalized unbalance current every 500 ms (when analyzing 6 periods of signals recorded with a periodicity of not less than 1 ms). Such time provides the necessary, analytically obtained, update time of the values of the normalized unbalance vector – 2 s.

An algorithm for selecting protection triggering setpoints is proposed, which, unlike existing ones, depends on the normalized unbalance current, and not on its absolute value. The algorithm depends on the voltage class, which ensures a connection with the insulation test standards during design and production. The algorithm for selecting setpoints is aimed at providing effective and reliable protection, unlike existing schemes, when the setpoints give unreliable trips or, conversely, are triggered after an equipment failure. An example of calculating setpoints based on the proposed method is given in Table 4. From the calculation results, it can be seen that as a result of a breakdown of about 37% of the insulation (6 condenser-layers for the given example), the voltage on the working condenser-layer will reach the approximate value of such voltage at a one-minute test voltage. When selecting setpoints, it should be taken into account that the voltage distribution across the layers of the bushing insulation will not occur evenly, and the working layers may have their own defects. That is, the fact that all the condenser-layers withstood such a voltage level during the tests may not mean that the working insulation condenser-layers will withstand it for the same time in the event of a partial breakdown in operation. Therefore, it is recommended to use the change in unbalance corresponding to the breakdown of one condenser-layer, use as a signal setpoint, and, as a shutdown setpoint – the value of the test one-minute voltage for insulation or the breakdown of the second condenser-layer. It is necessary to choose the smallest of the obtained values, taking into account the above facts.

The proposed solutions, unlike other studies, are aimed specifically at implementing a protection scheme, rather than monitoring and diagnostics. Analysis of current signals made it possible to devise effective measures to combat influence currents and the effects of harmonics in the operating voltage. Our study proved that the use of complete complex conductivity current signals would cause the emergence of an unbalance vector with a value that may exceed the value of a defective bushing (Table 3).

The proposed solutions completely resolve problematic issues, identified in the work, related to existing scheme for protecting TrE from bushing insulation damage for voltage classes of 35–750 kV.

The practical significance is the possibility of using the results in the production and implementation of microprocessor-based systems for protection against bushing insulation damage, as well as in the modernization of existing schemes.

The results of this study are aimed at increasing the reliability of operation and protection of high-voltage TrE and the power system as a whole.

Our research revealed the existence of an important problem of implementing new modern schemes for protecting the power transmission lines from bushing insulation damage and modernizing the existing ones in operation. This issue in Ukraine is exacerbated by the impact of military operations: the destruction and damage by the enemy of power facilities, which necessitates the restoration of equipment using effective and cheaper solutions.

The designed protection scheme could be used as a basis for modernizing existing schemes and further research on increasing the effectiveness of power transmission line protection.

The solutions reported here do not have any fundamental restrictions on use; they could be used to protect against damage to any capacitor-insulated bushings that have a measuring (diagnostic) output. The study was performed on equipment with a voltage class of 500 kV, the assumption that these results can be extrapolated to equipment of other voltage classes is quite fair and does not create restrictions on the use of the results. The inductive and resistive components of the bushing insulation resistance could in practice give additional changes to the unbalance vector, but, as a rule, the unbalance due to the growth of active losses is significantly less than with a partial breakdown. When implementing protection, it should be taken into account that the proposed method is based on the operation of the protection after a partial breakdown of the insulation. Restrictions on use can only be associated with the characteristics of the microprocessor unit; it must provide processing and transmission of the result to the terminal (in the relay hall) in a time not exceeding 2 s. It is also necessary to take into account that the analog-to-digital converter of the microprocessor unit must have galvanic isolation from the insulation test-tap of the bushing and other channels and a sufficient range – depending on the transformation coefficient of the selected current transformer. Of course, the bit resolution of the analog-to-digital converter must also provide sensitivity – at least an order of magnitude higher than the signal setpoint level.

The main drawback of our work is that an objective study of the time from damage to the first bushing condenser-layer to damage to the next and possible complete breakdown of the insulation was not performed. In the example given in [12], the time from the breakdown of the first condenser-layer to the device being taken out of operation was more than 40 hours, during which time there was no breakdown of additional layers. According to the assumptions adopted in this work, our result can be fully explained: the voltage as a result of the breakdown of one of the 13 condenser-layers rose on each of the layers that remained in operation by approximately 8%. The highest permissible operating voltage for equipment of the 330 kV class is approximately 110% of the rated. Under the condition of operation with the rated voltage level and the normal state of the working layers of insulation, the device could operate for a long time, possibly until the next planned and preventive maintenance. As shown in the example from [17], when by chance, during the planned and preventive maintenance, an increase in the capacitance of the main insulation of the bushing by more than 50% was detected. Our data indicate that in both examples [12, 17] no increase in the value of the dielectric loss tangent angle was recorded. The issue of permissible time exposure needs to be investigated and clarified.

Prospects for further studies include improving algorithms and schemes for minimizing the effects on diagnostic results; research, modeling, and forecasting the probable time of complete insulation breakdown after the alarm setpoint is triggered.

7. Conclusions

1. We have investigated the complex conductivity current signals of bushing insulation, which are used as the primary source of the insulation state when implementing TrE protection scheme against damage to bushing insulation. It was found that the signal from the bushing insulation test-tap contains a large number of interferences that distort its shape and have a significant impact on the results of insulation state assessment. A method for minimizing external influences on the unbalance vector using the discrete Fourier transform algorithm has been proposed. It was proven that to calculate the normalized value of the current unbalance, it is advisable to use only the 1st harmonics of the complex conductivity currents of the bushing insulation. The 1st harmonics of the complex conductivity currents correspond to the actual values of the conductivity currents of the bushing insulation and are directly related to the state of their insulation. Using the proposed method could make it possible to obtain the normalized value of the unbalance for the protection scheme, which is associated precisely with the presence of a partial breakdown of bushing insulation, and not with voltage distortion or other effects on the current signals. Unlike known algorithms, which are aimed at filtering fluctuations and masking changes in the unbalance vector, the proposed method is suitable for use in protection schemes due to the instantaneous response to a partial breakdown of the insulation. At the same time, this method is insensitive to harmonic distortions of the operating voltage and other high-frequency influences; the normalized value of the unbalance, in our study, was 14%, when using full signals, instead of 1.15%. The result is explained by the exclusion of influences from the output signals, and not by the "fight" with the consequences of their actions in the resulting signal, namely, fluctuations in the amplitude of the unbalance vector.

2. The structure of a modernized protection scheme based on a microprocessor device has been designed. The proposed scheme differs from known protection schemes in that analog signals from the bushing insulation test-tap are extended only to the monitoring unit, which is located directly near the protected equipment, and not to the relay board. This approach, in combination with algorithms for filtering influences and interference on signals of complex insulation conductivity currents, ensures stable protection operation, reduces the number of interferences, and reduces costs for cable connections. It also provides increased safety (damage to this cable from the insulation test-tap does not pose a danger to personnel and equipment). The advantages are explained by the use of a microprocessor monitoring unit, which uses the proposed algorithm for processing insulation current signals to eliminate influences on the value of the normalized unbalance. The use of hardware filters may not provide the required interference attenuation coefficient, but the reactive elements of such filters may affect the operation of protection schemes under the influence of temperature and characteristics changes over time. The general requirements for the implementation of such a scheme have been defined. It is proposed to use the change in unbalance corresponding to the breakdown of one condenser-layer as a signal setpoint, and, as the shutdown setpoint – the value of the test one-minute voltage for insulation or breakdown of the second condenser-layer. The modernized protection scheme allows one to obtain the value of the normalized unbalance current, free from the action of influences, every 500 ms (when analyzing 6 periods of signals recorded with a frequency of not less than 1 ms).

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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