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DIAGNOSTICS OF THE TECHNICAL STATE OF HIGH-VOLTAGE EQUIPMENT UNDER OPERATING VOLTAGE

The object of research is systems for online monitoring of the technical condition of oil-filled high-voltage electrical equipment during operation, which are used for automated diagnostics of the technical condition of equipment, resource forecasting and reducing of accidents.

The work is devoted to finding opportunities to reduce the cost of online monitoring systems, taking into account the military situation in Ukraine. The problem is caused by the need to use such systems to increase personnel safety and reliability of power grids, reduce the risk of failures due to deterioration of the technical condition of equipment due to unforeseen resource depletion or accelerated development of hidden defects due to military actions (excessive short-circuit currents, overvoltage). But taking into account the fact that the restoration of the power structure of Ukraine takes place in conditions of limited financial resources, one of the important tasks is to use online monitoring systems with an optimal price/diagnostic capabilities ratio to ensure the required level of diagnostics with a reduction in material costs for such systems.

The paper presents the results of an analytical study of the operation of online monitoring systems operated at various facilities over the past 20 years. The approach to diagnostics under operating voltage proposed in this study is aimed, first of all, at preventing emergency situations caused by the most frequent causes of accidents associated with: partial breakdown of capacitor insulation, increase in relative moisture saturation of transformer oil, appearance of dissolved gases in oil. The use of such an approach will increase the reliability of the power infrastructure and improve fault detection and preventive maintenance strategies while reducing the costs of organizing automated diagnostics in relation to "full-range" online monitoring systems of high-voltage equipment, which have been actively installed in Ukraine in recent years.

Keywords: *online monitoring systems, transformer oil, accident prevention, dissolved gas analysis, partial insulation breakdown.*

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1. Introduction

Operation of high-voltage electrical equipment in modern Ukraine in military conditions is associated with an increased workload on the personnel of diagnostic and testing laboratories. Equipment that is not externally damaged by military actions may have hidden defects due to overvoltages and short-circuit currents caused by missile and drone attacks on the electric power infrastructure of Ukraine.

The uninterrupted operation of electric power systems in our country is ensured by a planned preventive maintenance system. Such approach, under the critical operating conditions and a shortage of specialists, may not provide the proper level of prevention of emergency cases of equipment failures due to the accelerated development of hidden defects or wear of the resource. New operating conditions rises a number of scientific and practical problems both in the design of power facilities and the operation of equipment. A partial solution to the above problems is the implementation of automated online monitoring systems (OMS) of the main equipment. Such systems allow diagnostics of the technical condition of the equipment under the operating voltage and during operation to prevent emergencies caused by deterioration of the technical condition of the equipment and to increase the reliability of power supply. In addition, this approach provides the ability to predict the residual life of equipment, which in military conditions becomes a less urgent task. In addition, such diagnostic allows identifying defects, for example, in the main insulation of equipment with capacitor-type insulation, which cannot be detected under test voltage. OMS eliminates the influence of the human factor as well as reduces the time, personnel spend in potentially dangerous areas – high-voltage switchgear. OMS provides the ability to remotely obtain diagnostic information increases convenience for personnel, which are important in military conditions, since the electric power structure become priority targets for attacks.

In general, "full-range" online monitoring system (OMS) consists of primary sensors and monitoring unit (installed near the monitored equipment), additional automated workstation for the system's operator (responsible for visualizing information and dialogue mode with operating personnel) [1]. Fig. 1 shows an Example of installation of the OMS monitoring unit at the facility and some OMS's primary sensors.

There are a number of known areas of diagnostics of high-voltage equipment under operating voltage, such as full-range analysis of gases dissolved in transformer oil (DGA), moisture content in transformer insulation, partial discharge monitoring, temperature state monitoring, electrical parameters monitoring etc. [2]. These methods play an important role in detecting insulation degradation and predicting potential failures. Taking into account the military state and limited financial resources it is necessary to use online monitoring systems with an optimal price/diagnostic capabilities ratio to ensure the required level of diagnostics with a reduction in material costs for such systems.

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Fig. 1. Example of installation of the "full-range" OMS monitoring unit at the facility and some OMS's primary sensors

Based on statistical data published in [3] more than 50 % of failures of power transformers are happened due to partial discharges, insulation flashovers, overheating, localized hotspots. The vibration analysis method to the online monitoring of power transformers was proposed in [4]; however this approach is mostly concentrated on the changes only in core and winding of the power transformer. The authors in [5] proposed hybrid on-line partial discharge monitoring system for power transformers, whose functioning is based on the simultaneous use of three known methods: high-frequency, ultra-high frequency, and acoustic. However, such approach is very complex and need comprehensive adjustment on-site, because different high-voltage equipment may have different levels of waves emission. Moreover, there are no clear dependency from partial discharges levels, registered at the high-voltage switchgear with probability of failure or residual life of the equipment. Author in [6] proposed to used: fiber grating sensor, the vibration signal of the inner core of the transformer, the temperature signal of the winding and the video monitoring signal of the transformer winding for condition monitoring. However, such approach is much expensive and can be implemented only for new transformers only at the stage of manufacturing at the facility. The paper [7] provides an overview of traditional DGA methods, such as the key gas method, the Duval triangle method, and the ratio methods. These methods allow for the detection of faults in transformers at an early stage, which helps to prevent serious failures. It is noted that despite the widespread use of DGA, the accuracy of interpretation of the results may vary depending on the diagnostic approach chosen. The authors suggest that increased diagnostic reliability can be achieved by increasing the standardization of DGA methodologies. The paper [8] discusses predictive maintenance strategies using DGA-based monitoring. The study discusses the benefits of using real-time gas measurements to detect emerging faults before they lead to catastrophic failures. Furthermore, the study highlights the need for improved algorithms to correlate gassing models with specific transformer failure modes, as current methods still rely on historical data analysis rather than real-time predictive modeling.

In work [9], important parameters used to monitor transformer paper and oil insulation degradation are introduced into existing thermal and moisture models described in the literature. The standard IEC 60076-7 Loading Guide model is improved by including the viscosity of fluids with controlled aging history to assess the behavior under hot spot conditions. Similarly, the moisture model is improved by including the acidity of oils and the degree of polymerization of paper. However, it is noted that further experimental validation is needed to confirm the accuracy of the model under different operating conditions. In work [10], a capacitive sensor designed to measure moisture in transformer oil in real time is proposed. The output of this sensor is recorded using a Frequency Response Analysis (FRA) device. Comparing the FRA results of a degraded oil with a reference FRA test, moisture content can be determined. The paper [11] discusses the use of fiber optic sensors for detecting moisture in transformer insulation. The presented research results show that fiber optic technology provides high sensitivity and reliability for real-time moisture assessment. However, such approach is much expensive and can be implemented only for new transformers only at the stage of manufacturing at the facility.

The authors of the [12] made complex analysis based on CIGRE studies and show that 37.31 % of power transfer failures which were occurred with fire or explosion were due to bushings failure, 25.4 % – due to failures in windings or leads and their insulation. However proposed method of improvement of bushing diagnostic based on dissipation factor changes analysis is complicated and is influenced by operational conditions, which is noted by authors themselves.

Thus, the research results by various authors confirm the relevance of the issue of implementing modern methods of online monitoring in order to increase the reliability of high-voltage equipment. On the other hand, certain technological limitations and cost considerations negatively affect the widespread implementation of advanced monitoring solutions in large power network, especially during military state and reconstruction period of electric-energy facilities in Ukraine.

The aim of this research is to analyze theory and practical experience of online diagnostic to substantiate methods of diagnosing the technical state of high-voltage equipment under the operating voltage, which can be wide spread in the electric power system in Ukraine, thanks to cost-effective approach. The presented research is also aimed to modernize obligatory transformer bushing insulation diagnostic (according paragraph 3.2.60 [13]) for transition to Ukrainian produced equipment and to increasing the reliability of the power infrastructure as well as reducing the risk of unplanned power supply interruptions.

2. Materials and Methods

This research is the result of about 20 years empirical and theoretical research based on: analysis of high-voltage electrical equipment designs, analysis of statistical results of defects and accompanying changes in values of diagnostic parameters, analysis of research results of scientists working in the field of operational diagnostics under, analysis of experience in implementing automated online monitoring systems for various equipment for voltage classes of 6–750 kV, analysis of requirements and recommendations of regulatory documentation: both Ukrainian and foreign. During research of the effect of using isolating transformers ТПС-0,66 on the insulation of high-voltage bushings, the results of recording high-frequency overvoltages on the buses of the switchgear using a high-voltage bushing as a voltage divider were used. The signal was recorded by the SAFE-T® monitoring system ("ENERGY AUTOMATION" LLC, Zaporizhzhia, Ukraine) using a high-frequency analog-to-digital converter with a recording frequency of up to 1 GHz and a resolution of 8 bits. Possible overvoltage on the test-tap insulation were determined by calculation. The oscillogram of the signal of the voltage drop on the measuring resistor from the current of the air capacitor (when using a ring electrode) was also obtained when using the setup mode of the SAFE-T® monitoring system. Tests of the reaction rate of thin-film capacitive sensors of relative water saturation of oil were carried out in laboratory conditions using a sealed vacuum chamber and an induction heater, several sensors from different manufacturers were used in the study, and absolutely comparable results were obtained. Results differed from each other by no more than the sum of the errors of two compared sensors, declared by the manufacturers of these sensors, which confirmed the hypothesis that thin-film polymers used in such sensors equally well absorb water molecules according to the law of equilibrium distribution of moisture. The given examples of the monitoring systems are also taken from the software of the SAFE-T® monitoring systems.

The main assumptions of research are:

– implementation of OMS significantly improves the reliability of high-voltage electrical equipment under operating voltage, reducing the probability of accidents, caused by hidden defects and equipment aging, especially under military conditions;
– traditional diagnostic methods based on scheduled-preventive maintenance may be insufficiently effective under increased workloads and a shortage of specialists;
– automated monitoring systems allow to detect hidden defects that cannot be identified using standard diagnostic methods, such as testing under test voltage;
– microprocessor-based diagnostic devices helps to minimize the influence of the human factor and increases the accuracy of equipment condition assessments;
– there are a number of known and innovative methods, models and parameters for diagnostics of high-voltage equipment under operating voltage, all of them can improve diagnostic effectiveness and residual life estimation with different rates;
– almost every additional diagnostic method increases the cost of the monitoring system itself, sometimes disproportionately to the probability of a defect that it could detect, which can sometimes lead to the situation when the cost of the monitoring system become an equal to the cost of the device being diagnosed.

The main hypothesis of research – in current situation Ukrainian electric-energy structure should concentrate on the implementation of online monitoring system according to regulatory documents demands as well as on the methods which can provide the most often defects detection, to prevent failures which occur with fire or explosion. Developing a theory for manufacturing of low-cost monitoring systems can help to cover more equipment with automated systems, increasing the reliability of the electric power system and personnel safety.

3. Results and Discussion

3.1. Monitoring the insulation condition of equipment with capacitor insulation

Failures of the main insulation of electrical equipment with capacitor-type insulation (bushings, measurement current transformers, measurement capacitive-type transformers) is one of the most common causes of equipment failures for classes 110 kV and higher. The Electrical Installation Rules (PUE – Pravila ulashtuvannya electroustanovok) in paragraph 3.2.60 demands installation of a transformer bushing insulation diagnostic (protection) device – KIV-500(750) (the realization of such device is very wide, mainly base on method, which often called in different way: "three phase bank" or "sum of currents" or "unbalance"). Such device (further KIV) should be adjust to provide signalization in case of insulation partial break-down, and to provide switching-off in case of breakdown progress (before complete break-down) [13].

The classic wiring scheme (Fig. 2) includes the use of a specialized transformer (T1) – ТПС-0,66 (Russian Federation), used for "balancing" the scheme – by connecting the measuring terminals (test-taps) of the bushings to different taps of its primary winding. In practice, there are also schemes using three ТПС-0,66 – when the bushing of each phase is connected to a separate transformer. It should be taken into account that such transformers, are not manufactured in our country and more over – during high-frequency overvoltages, which occur on the switchgear's buses, cause unacceptable overvoltages on the insulation of the test-tap. Such overvoltages can cause damage to the equipment, especially for modern bushings with the so-called resin impregnated paper (RIP) insulation, in which the ratio $C_3/C_1 \approx (1–3)$, unlike old oil impregnated paper (OIP) bushing. Using of ТПС-0,66 has a particularly negative effect in schemes with three transformers. A scheme with one transformer can also have problems in operation for groups of single-phase equipment due to overflows due to the non-equipotentiality of the grounding points of the equipment in a three-phase group. It should also be taken into account that the main reason for the unreliability of the unbalance method is the influence of the operating modes of the power system. Changes of mutual angles between the vectors of phase voltages of the power system and their amplitudes are lead to errors and wrong diagnostic conclusions.

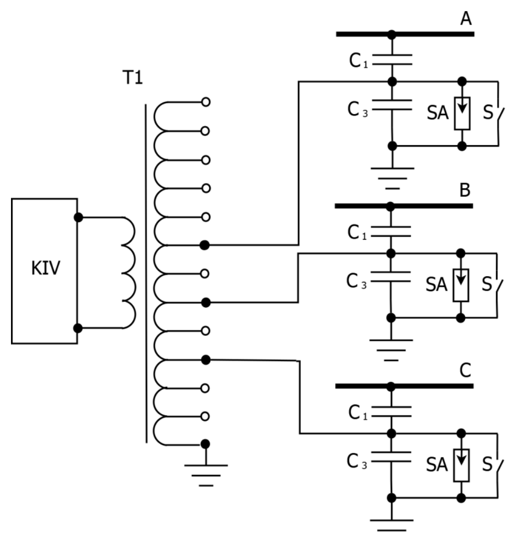

Fig. 2. Transformer bushing insulation diagnostic (protection) scheme, which is wide spread at the electric-energy facilities in Ukraine (C_1, C_3 – capacitances of the bushings insulations, *SA* – surge arresters, *S* – protection switches)

According to the results of mathematical modeling, it was established that even without the use of ТПС-0,66 transformer, the voltage on the insulation of the measuring terminal during overvoltages with a frequency of more than 18 kHz can lead to damage of the insulation.

Therefore, connecting the measuring circuits of the KIV device without using modern high-speed protection devices (varistors, arresters) is impossible. But the obtained value of the critical frequency of overvoltage is also quite small, because during operation of the equipment, the frequency of lightning and switching overvoltages can be about 1 MHz.

An example of a recorded oscillogram of an overvoltage pulse at the 500 kV bushing, obtained by OMS is shown in Fig. 3. The overvoltage occurred at phase B with "redirection" to adjacent phases. Fig. 4 shows the results of recording pulse voltages on the 220 kV autotransformer.

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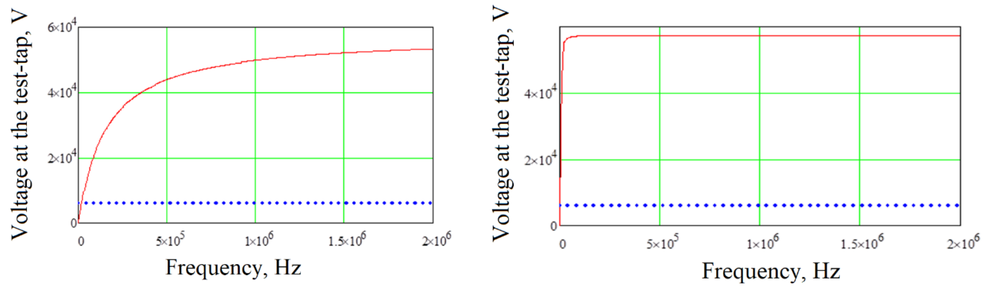


a *b*

Fig. 3. Change in voltage at the test-tap: *a* – when changing the frequency of the operating voltage (resistance of the protective resistor in the adapter connecting to the bushing terminal is 514 Ohm), the dotted line indicates the permissible voltage limit; *b* – when the frequency of the operating voltage changes and there is ТПС-0,66 transformer (resistance of the protective resistor in the adapter connecting to the test-tap is 514 Ohm), the dotted line indicates the permissible voltage limit

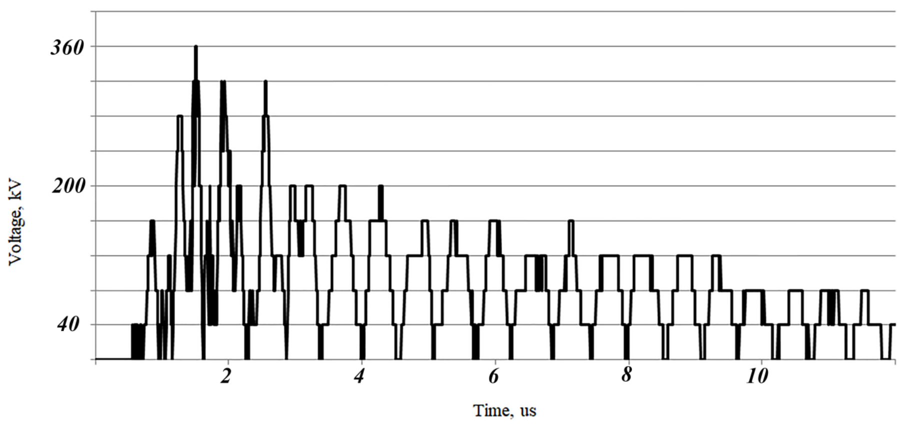


Fig. 4. Result of recording pulse voltages on buses of 220 kV autotransformer

small-sized feed-through transformers, providing galvanic isolation of the circuits from high-voltage equipment to the sensitive microprocessor device (Fig. 7), which allow to change the wiring diagram showed in Fig. 2.

The next advantage is an ability to use protection complex resistor (*R* – in Fig. 7, *b*) against cable breakage inside the test-tap adapter, it can help continuously keep voltage at the safe level – for personnel and equipment. Such protective resistor caused problems with "classic" KIV balancing due to leakage current division through protective resistor.

Thus, as a result of all the studies, the use of the improved approach for obligatory transformer bushing insulation diagnostic and protection (according paragraph 3.2.60 [13]) was proposed. It based on microprocessor device which has a number of advantages. The first advantage is the ability to compensate for phase voltage asymmetries, which provoke the appearance of unbalance vector, which is recognized as an insulation defect by "classic" KIV-500 type devices. Such compensate signals can be used from measurement voltage transformers, but in many cases their using is impossible due to switchgear scheme. The aluminum electrode is installed on the lower flange of the bushing in the area of the first skirt of the insulator (Fig. 5). The electrode must be isolated from the grounded parts of the tank. The electrode is made of sheet aluminum, the width of the electrode is determined by the voltage class and is 50–100 mm, and the bushing ring is cut to prevent the formation of a short-circuited turn around the bushing. The electrode is fastened to the flange using a ring clamp, without interfering with the design of the bushing. The principle of the method is that an air capacitor is formed between the high-voltage busbar and the electrode, the leakage current (Fig. 6) of which is considered the reference. A coaxial cable is connected to the electrode, which transmits the reference signal to the monitoring unit.

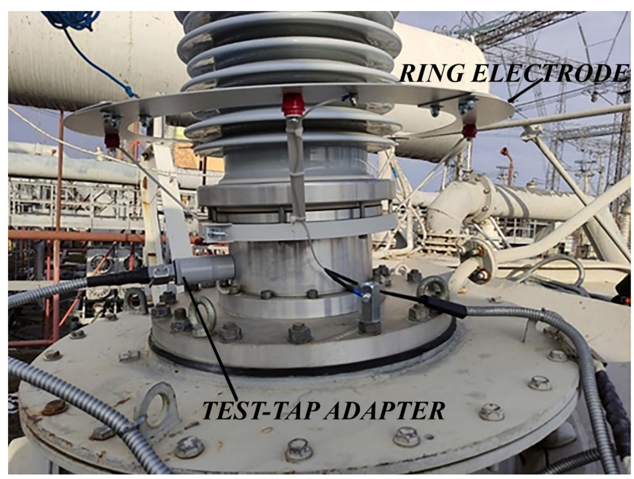


Fig. 5. Example of the ring electrode and the test-tap adapter installation

The next advantage is safety of the wiring scheme for insulation of the bushing – refusal from the matching transformer ТПС-0,66, which has large weight and dimensions and a negative impact on the bushing insulation during overvoltage. Authors propose to use

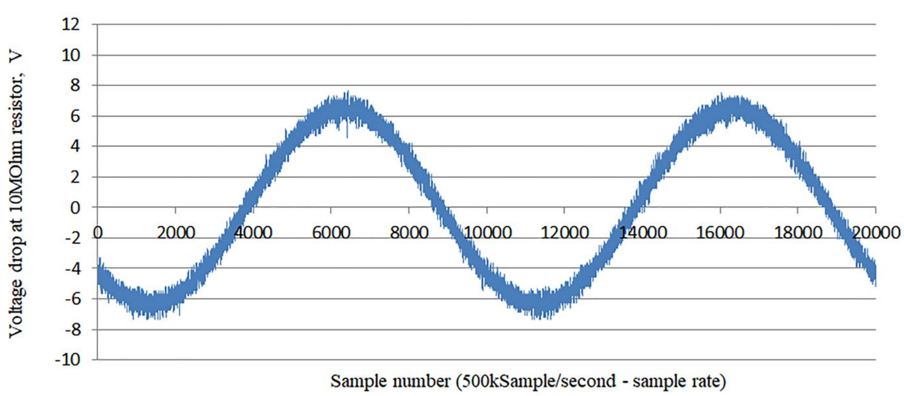
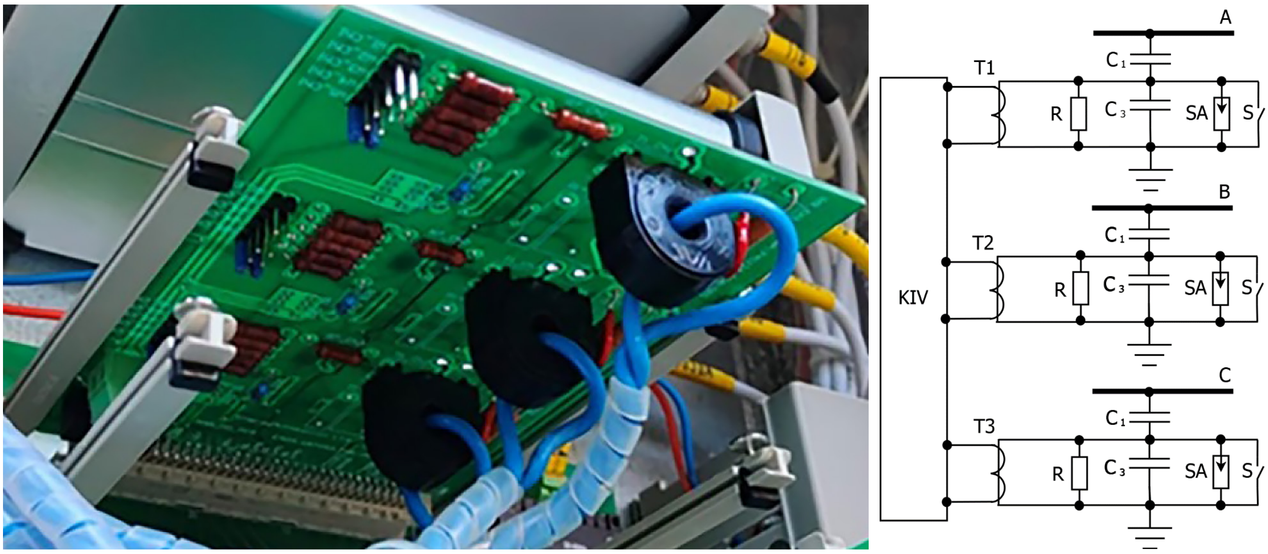


Fig. 6. Example of oscillograms from a ring electrode installed on this 330 kV bushing



a *b*

Fig. 7. Isolating transformer: *a* – example of transformer; *b* – wiring diagram of isolation transformer (T1–T3)

Additional advantages are: automated balancing, software setting of alarm thresholds, historical data analyzing, remote data transmit, the possibility usage in one group of apparatus with large differences in main insulation capacities.

Measuring transformers with capacitor-type insulation for voltage classes of 110–750 kV are also one of the most accident-hazardous types of electrical equipment, despite the implementation of a set of diagnostic measures to assess their condition during production and operation. The diagnostic approach described above can also improve the situation with accidents due to poor technical conditions of insulation of such transformers. Document SOU N MPE 40.1.46.301:2006 "Inspection of the insulation of transformers in the 330–750 kV line under operating voltage" [14] recommends the implementation of insulation condition monitoring of current transformers (CT) under operating voltage. Such monitoring can be also realized with the same approach as for the transformer bushings, but with some different construction of the test-tap adapter (Fig. 8). Monitoring of capacitive voltage transformers (VT) with capacitor insulation can also be organized according to the same principles. If there is test-tap in the VT's design – the same design of test-tap adapter as for CT can be used (Fig. 8). If there is no test-tap in the VT's design – VT should be installed at the isolation base and the special designed adapter should be used (Fig. 9). Such adapter consists only from small-sized feed-through transformer on the grounding bus.

During OMS operation, especially in the absence of signals from the measuring windings of the VT, attention should be paid to the rough change in the capacitance of the main insulation of the monitoring object. Values of the insulation power loss factor (tgδ_1) (which, as a rule, are subject to a number of operational influences: temperature, humidity, precipitation, errors in reference signals) should be only used as additional parameter.

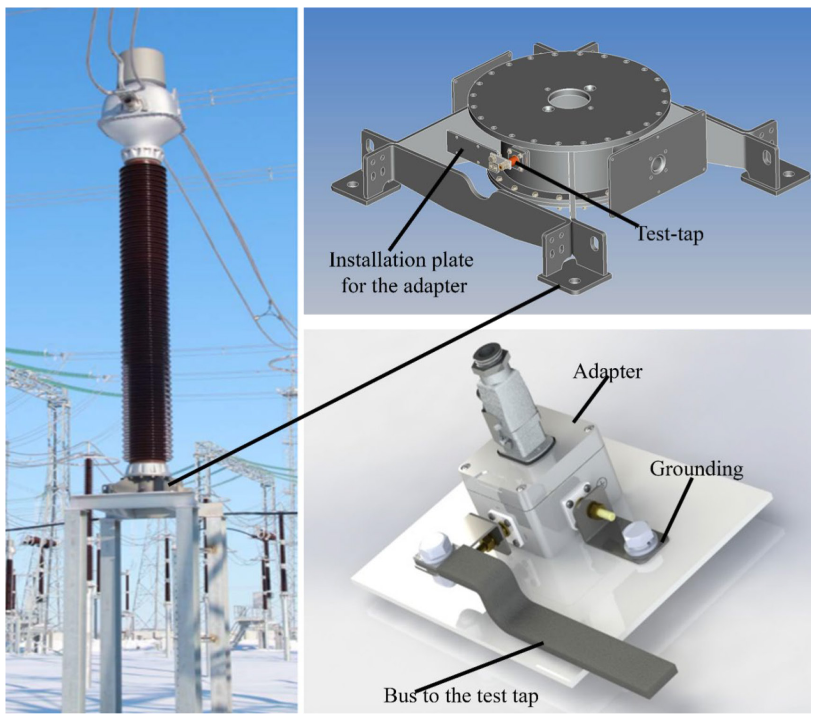


Fig. 8. Example of installation of the test-tap adapter on the AGU-765 (CT manufactured by KONČAR, Croatia)

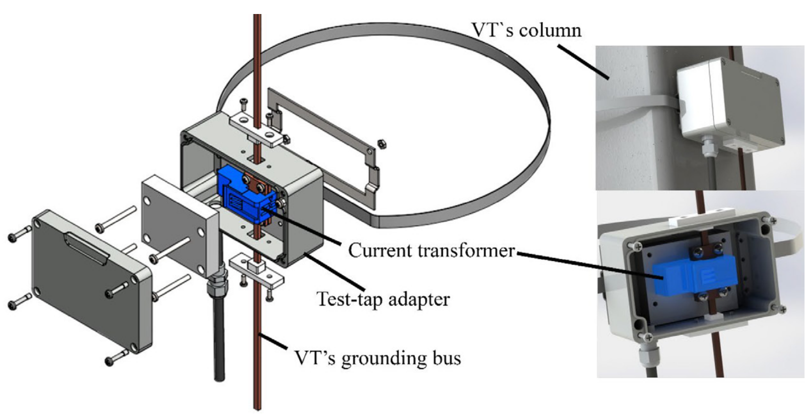


Fig. 9. Adapter for electrical equipment without special test-tap for diagnostic purposes

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Fig. 10 shows an example of recording the change in the capacitance of the main insulation of a 330 kV oil-filled current transformer, recorded by the OMS. Analysis shows that the partial breakdown of the insulation, in this case, was not accompanied by a preliminary increase in active losses in the insulation.

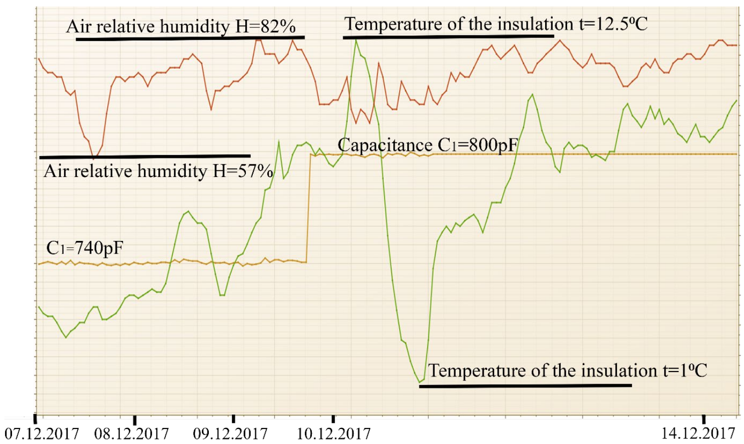

Fig. 10. Example of partial breakdown of the capacitor-type insulation registered by the OMS

3.2. Monitoring of moisture content in transformer oil

The next important method of online monitoring is relative water saturation of oil monitoring. The maximum saturation of oil increases with increasing temperature. After the moisture content of oil reaches the saturation level, emulsion and free water begin to appear. Emulsion formation is an extremely dangerous phenomenon for high-voltage oil-filled equipment. Thus, it is obvious that it is necessary to control not the absolute moisture content of the oil, but also the relative moisture saturation of the oil at the current operating temperature of the oil. An important note is that an increased value of absolute moisture content leads to accelerated wear of the insulation resource, while a high value (100 %) of relative moisture saturation leads to a decrease in the dielectric characteristics of the insulating structure. Based on research [15], it was confirmed that the breakdown voltage of oil depends not only on the quantitative content of dissolved water. Relative humidity of the oil, is associated with an increase in the conductivity of impurities in the oil with an increase in the concentration of water.

Thus, relative moisture saturation will allow not only to determine the risk of emulsion formation, but also to more accurate determination the moisture content of solid insulation and the degree of reduction of dielectric characteristics of oil. Relative water saturation sensor must be immersed directly in the tank of the electrical apparatus and measure moisture saturation without any preparations and temperature transformations. At the same time, temperature reduction of the measured value allows to monitor the dynamics of the increase in moisture concentration in the equipment, tracking of which will be difficult without reductions, due to constant fluctuations in the temperature of the equipment.

For operational online monitoring of the moisture content characteristics of transformer oil, the most suitable sensors are those that measure the relative saturation and temperature of the oil at the installation location. Such sensors are very sensitive and have extremely low time (60–70 s) of reaction to the changes of the oil saturation by water (Fig. 11).

3.3. Monitoring the concentrations of dissolved gases in the oil of power transformer equipment

The next important feature is monitoring the characteristics of gas content of transformer oil is for determining the current technical condition of transformer equipment under operating voltage. This method can help to identify the presence of: partial discharges, electrical arc, overheating and insulation materials decomposition.

The presence of gases in transformer oil indicates the presence of defects in oil-filled equipment, so it helps to identify wide range of most often defects in the equipment. Online monitoring systems can be used to determine the defect type and its localization using different mathematical models (Fig. 12), the most common models and their key-gases are described in the Table 1.

Recommendations for equipping transformers with stationary gas analyzers are set out in a number of international and domestic standards and recommendations [17–22]. Monitoring of the concentrations of all gases in online mode allows to record the presence of a defect in transformer equipment, as well as to record the dynamics of concentration increase. This is very important since absence of a positive trend in the concentration of many gases during defects progress.

The most economical approaches for online DGA are: only hydrogen monitoring; only methane monitoring; the sum of the concentrations of combustible gases monitoring. For automated interpretation of gas analysis control results, it is most appropriate to install devices that allow monitoring at least three gases – C_2H_2, CH_4, C_2H_4, which allows using the "Duval Triangle" to interpret gas analysis results.

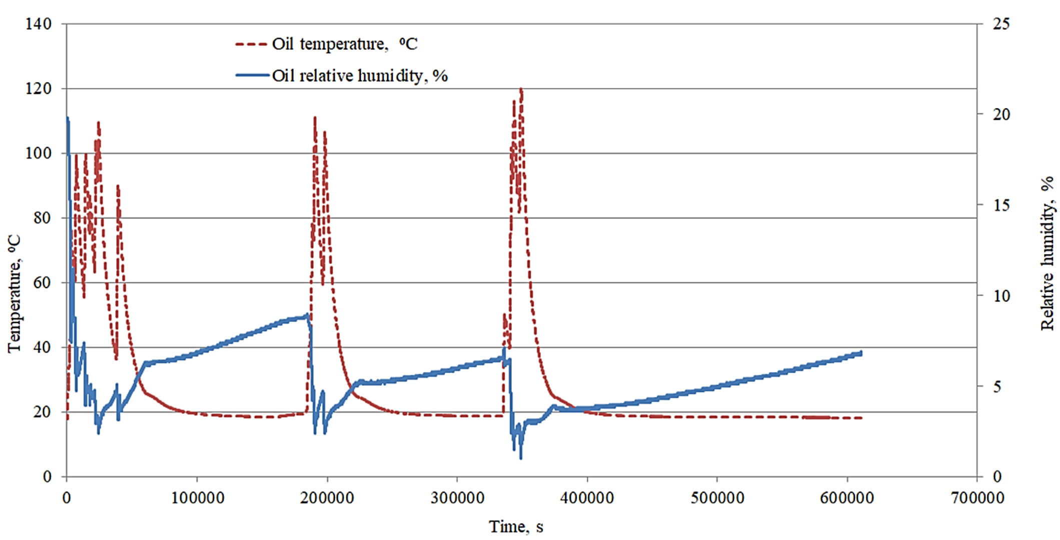

Fig. 11. Oil relative water saturation changes with temperature changes registered by thin-filmed capacitor sensor

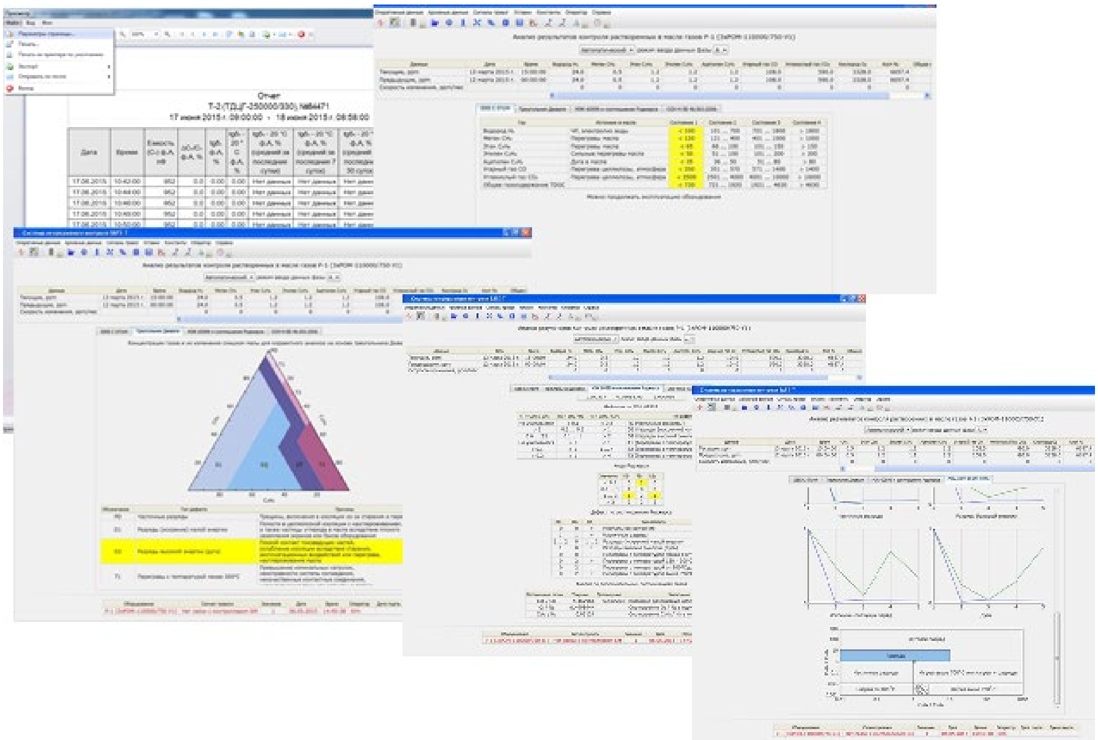

Fig. 12. Examples of tools for analyzing gas analysis results in the SAFE-T® OMS [16] (methods comply with SOU-N EE 46.501.2006 [17])

Table 1

Methods of interpreting defects

Defect/Gas	CO	CO_2	H_2	C_2H_2	CH_4	C_2H_4	C_2H_6	O_2	N_2
Method of monitoring the total concentration of combustible gases (analogous to TCGC according to IEEE C57.104-1991)	+	–	+	+	+	+	+	–	–
"IEC60599 Ratio"	–	–	+	+	+	+	+	–	–
Decomposition of cellulose	+	+	–	–	–	–	–	–	–
Depressurization of the on-load tap-changer tank	–	–	+	+	–	–	–	–	–
Depressurization of the tank, oxidation processes	–	–	–	–	–	–	–	+	+
"Rogers' Ratios"	–	–	+	+	+	+	+	–	–
Limit concentration and rate of rise method (IEEE analogue), C57.104-1991)	+	+	+	+	+	+	+	–	
Images of defects	–	–	+	+	+	+	+	–	–
Graphical method (Electric Technology Research Association (Japan))	–	–	–	+	–	+	+	–	–
Duval's Triangle	–	–	–	+	+	+	–	–	–

3.4. Discussion of results

Thus, as a result of the work carried out, it was established that in order to reduce the number of emergency situations related to the most frequent defects in high-voltage oil-filled equipment, it is necessary to use of monitoring system with a limited functional set. When selecting emergency assistance methods, it is also necessary to take into account the design features of electrical equipment and pursue the goals of reducing failure accidents. The studies carried out confirm the presence of high-frequency overvoltages (Fig. 4) on the buses of high-voltage distribution devices, which, when using an isolating transformer with a high input resistance, can create overvoltages dangerous for the insulation of the devices (Fig. 3), as a result, a modernization of the obligatory transformer bushing insulation diagnostic is proposed, which does not need such an isolating transformer (Fig. 7), and can also have a number of advantages in comparison with the scheme widely used at this stage. During the diagnostic of capacitor-type insulation it should also be taken into account that only an increase in capacitance is a criterion for partial insulation breakdown. Decrease in capacitance can only be caused by a partial short circuit of the leakage current through parasitic shunts (bypassing the control circuit) or by distortion of the reference signal (i. e. not by the state of the insulation itself). It should also be taken into account that after a partial breakdown of one layer, the device, as a rule, can operate for several more days, and this time is sufficient for decommission of the equipment (Fig. 10). Thus, obligatory transformer bushing insulation diagnostic scheme can be realized cheaper and more reliable.

Water presence in insulation leads to accelerated wear of the insulation resource, while a high value of relative moisture saturation leads to a decrease in the dielectric characteristics of the insulating structure. So, it is possible to prevent insulation breakdown due to free water appearance in the equipment by using low-cost thin-filmed capacitive sensors, without absolute water content estimation, which should be a part of complex offline laboratory tests, but not of online monitoring. When installing such sensors, it is necessary to take into account the presence of oil circulation in the place of immersion of the sensor, as well as the possibility of distortion of the results due to dehydrators or other design features of the monitored equipment. The most suitable place for installing the sensor on the tank, in order to obtain the closest absolute moisture

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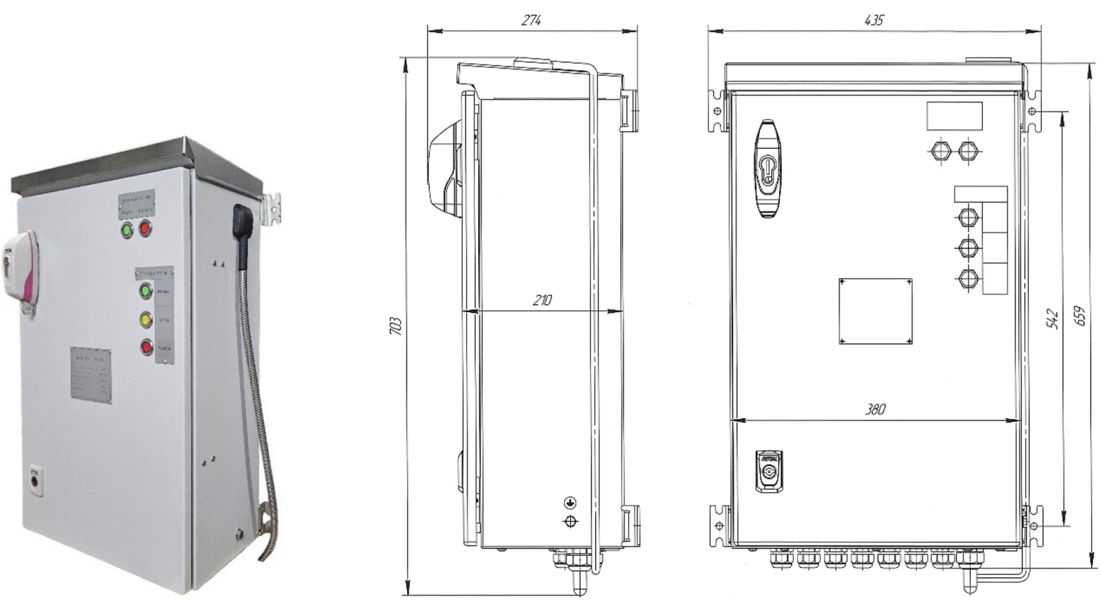
content to the laboratory result, is the area of the upper layers of oil, due to the higher oil temperature. It should be taken into account that the places of the highest saturation are in the coldest points of the insulation, respectively, to control the formation of emulsion (which is the most important task in operational control) the sensor should be placed in the lower part of the tank. So for the different purposes (failure preventions or residual life calculation) it is necessary to choose correct location (for the big-volume equipment, it may be necessary to install several sensors).

When selecting a gasses monitor, it should be taken into account that operational measurement of gas content is a complex task and one should not expect complete convergence with laboratory measurements by a chromatograph from such devices, especially if they are not chromatograph, as described in [23]. When organizing continuous control of gas concentrations, its purpose is to track the changes in the concentration of gas or the sum of gases, and not to measure them accurately. A sudden increase in the rate of gas recorded by the monitoring device is a signal for unscheduled manual sampling for chromatographic analysis of DGA in laboratory conditions.

Thus, a compact monitoring unit (Fig. 13) in combination with a set of sensors (for example: H_2, relative water saturation, insulation leakage currents, temperature, electrical loads), can provide effective monitoring of the technical condition. It can be used for three-phase power transformer, autotransformer, shunt reactor or a three-phase group of such devices, a three-phase group of measuring transformers. Such monitoring unit can be used instead of old electromechanical devices such as KIV-500 (750) with ТПС-0,66, to increase diagnostic abilities to solve current and future problems of increasing the reliability of the power supply system. Such monitoring unit, with limited list of diagnostic parameters, compare to "full-range" online monitoring systems (examples are in the Fig. 1) have compact size and are much cost-effective (in price, installation work and operation). It allows covering by online monitoring more critical-important equipment when the electric-energy facilities become as military targets.

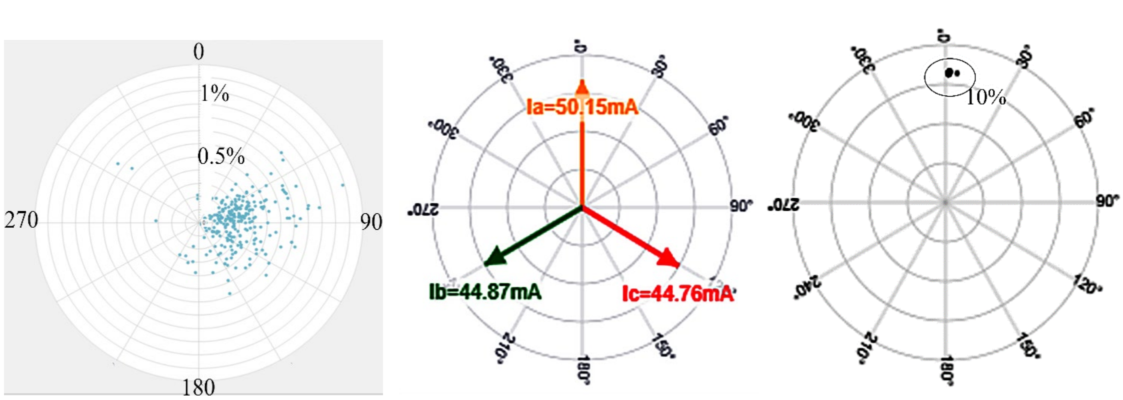
Such a monitoring unit is a fully autonomous system of automated diagnostics of equipment under operating voltage and is equipped by both: local signaling and visualization of the state of the monitored equipment, as well as remote notification and diagnostic data transmission subsystems. The cost of such unit is several times lower than the cost of a fully functional system, with the provision of the most important diagnostic functions (Fig. 14).

The presented results can be used in the production of domestic systems for monitoring the technical condition of high-voltage equipment and protective devices for high-voltage bushings from accidents in accordance with the requirement of 3.2.60 of PUE.



a *b*

Fig. 13. The example of the monitoring unit, which can provide the necessary diagnostic level to decrease number of failures of high-voltage oil-filled equipment: *a* – photo, *b* – sketch



a *b* *c*

Fig. 14. Example diagnostic results from real OMS: *a* – polar graph of unbalance vector for normal insulation (remote software); *b* – vector diagram of leakage currents with failure in phase "A" (local web-server); *c* – polar graph of unbalance current in case of failure in phase "A" as shown at *b* (local web-server)

Online monitoring systems are powerful diagnostic tools and are one of the ways to reduce the risks of accidents and unplanned interruptions in power supply to consumers, which is especially important in military conditions. However, in such conditions, the primary task of diagnostics under operating voltage is precisely the prevention of emergency cases. Main reasons of such case are: deterioration of the technical condition due to unpredictable exhaustion of the resource, accelerated development of hidden defects due to damage to the electric power infrastructure of Ukraine as a result of military actions.

The presented results are intended for the creation of automated systems and equipment primarily to reduce the risk of accidents associated with the presence of hidden defects or unpredictable depletion of the resource. The results cannot be applied in cases where extended monitoring is needed to identify defects in equipment at an early stage of their occurrence.

This research is especially relevant during the war, when electric-power facilities became as military targets. The presented results are aimed at improving the reliability of electric-power system in conditions of limited funding and unpredictable impact on the residual life of high-voltage equipment due to military actions. Prospects for further research include the development of mathematical models and algorithms for diagnosing the condition of high-voltage equipment based on a limited list of diagnostic parameters and control methods.

4. Conclusions

The paper considers the cost-effective approach for online condition monitoring of power and measurement oil-filled transformers. As the research result, the using of a limited number of monitoring methods was proposed. Such approach provides the ability to identify most often defects, that can cause an accident with equipment, but reduces the costs of implementing monitoring of the technical condition of equipment while maintaining its high efficiency in identifying dangerous defects.

First of all, the research is focused on diagnostics of the state of the main insulation of electrical equipment with capacitor-type insulation (bushings, measuring current transformers, measuring capacitive voltage transformers) namely on insulation's partial breakdown monitoring. Such monitoring proposed with simplification of its implementation, but in accordance with the requirements of regulatory documents (according paragraph 3.2.60 [13]). Namely modernized obligatory transformer bushing insulation diagnostic method was proposed, which differ by absence of isolation transformer ТПС-0,66, but with pass-through miniature transformers and microprocessor main device instead. The approach is also including highly efficient diagnostic methods like: monitoring of the relative moisture content and dissolved gases content of oil.

The proposed approach to organizing monitoring of the technical condition under operating voltage should ensure the costs of its implementation at the level of 3–5 % of the cost of the monitored equipment itself.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

Manuscript has no associated data.

Use of artificial intelligence

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

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