Early Fault Detection of High-Voltage Bushings Based on Curve Recognition Methods

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Abstract. The aim of this study is the early detection of developing insulation defects in high-voltage oil-filled bushings based on the analysis of the temporal behavior of diagnostic indicators rather than only their comparison with threshold values. To achieve this aim, insulation indicators are interpreted as time curves, and data processing is performed using curve recognition methods that identify characteristic patterns of parameter variation. The most important results demonstrate stable differences between different technical conditions. Serviceable bushings are characterized by the absence of a statistically significant relationship with service duration while maintaining consistent internal dependencies and a high similarity of time curves on adjacent phases caused by common operating conditions. For defective bushings, statistically significant relationships between individual indicators and service duration are identified, changes in the internal correlation structure are observed, and similarity with the indicators of neighbouring serviceable bushings is absent. Based on the recognition of the shapes and mutual consistency of time curves, a decision rule is formulated: a defect is diagnosed when correlation with time and internal correlations are present, while cross-phase correlation is simultaneously absent. The significance of the obtained results lies in the fact that the application of curve recognition methods enables the detection of developing defects before the indicators exceed threshold values, reduces the probability of erroneous rejection, and increases the reliability of bushing condition assessment under various network operating modes. The proposed approach can be used in technical condition monitoring systems to improve the efficiency of operational maintenance of high-voltage equipment, leading to reduced failure risks and more justified maintenance planning.

***Keywords*:** high-voltage bushings, diagnostics, insulation indicators, tangent of the dielectric loss angle, capacitance, measuring terminal resistance, correlation, curve recognition.

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Detectarea timpurie a defecțiunilor izolatoarelor de înaltă tensiune bazată pe metode de recunoaștere a curbelor

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Rezumat. Scopul lucrării constă în depistarea timpurie a defectelor de izolație în curs de apariție la intrările de înaltă tensiune umplute cu ulei, pe baza analizei comportamentului temporal al indicatorilor de diagnostic, mai degrabă decât doar a comparației lor cu valorile prag. Pentru a atinge acest obiectiv, indicatorii de izolație sunt interpretați ca și curbe temporale, iar prelucrarea datelor se efectuează folosind metode de recunoaștere a curbelor care identifică modele caracteristice de variație a parametrilor. Cele mai importante rezultate demonstrează diferențe stabile între diferite condiții tehnice. Trecerile izolatoare funcționale se caracterizează prin absența unei relații semnificative statistic cu durata de funcționare, menținând în același timp dependențe interne consistente și o similaritate ridicată a curbelor temporale pe fazele adiacente cauzate de condițiile comune de funcționare. Pentru trecerile izolatoare defecte, se identifică relații semnificative statistic între indicatorii individuali și durata de funcționare, se observă modificări ale structurii de corelație internă și lipsește similaritatea cu indicatorii trecerilor izolatoare funcționale vecine. Pe baza recunoașterii formelor și a consistenței reciproce a curbelor temporale, se formulează o regulă de decizie: un defect este diagnosticat atunci când este prezentă corelația cu timpul și corelațiile interne, în timp ce corelația între faze este simultan absentă. Semnificația rezultatelor obținute constă în faptul că aplicarea metodelor de recunoaștere a curbelor permite detectarea defectelor în curs de dezvoltare înainte ca indicatorii să depășească valorile prag, reduce probabilitatea de respingere eronată și crește fiabilitatea evaluării stării izolațiilor izolatoare în diferite moduri de funcționare a rețelei. Abordarea propusă poate fi utilizată în sistemele de monitorizare a stării tehnice pentru a îmbunătăți eficiența mentenanței operaționale a echipamentelor de înaltă tensiune, ducând la reducerea riscurilor de defecțiune și la o planificare mai justificată a mentenanței.

***Cuvinte-cheie*:** intrare de înaltă tensiune, diagnosticare, indicatori de izolație, tangenta unghiului de pierdere dielectrică, capacitate, măsurarea rezistenței terminalelor, corelație, recunoașterea curbelor.

Раннее обнаружение неисправностей высоковольтных вводов на основе методов распознавания кривых

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Аннотация. Цель работы состоит в раннем выявлении развивающихся дефектов изоляции высоковольтных маслонаполненных вводов на основе анализа временного поведения диагностических показателей, а не только их сравнения с предельными значениями. Для достижения цели показатели изоляции трактуются как временные кривые, а обработка данных выполняется с использованием методов распознавания кривых, позволяющих выделять характерные паттерны изменения параметров. В исследовании проанализированы результаты периодических испытаний 113 исправных вводов, эксплуатируемых в четырёх регионах Украины, и 28 дефектных вводов; оценены три группы зависимостей: связь показателей с длительностью эксплуатации, внутренние корреляции между показателями одного ввода и корреляции с показателями вводов соседних фаз. Наиболее важные результаты демонстрируют устойчивые различия для разных технических состояний. Для исправных вводов характерны отсутствие статистически значимой связи с длительностью эксплуатации при сохранении согласованных внутренних зависимостей и высокой похожести временных кривых на соседних фазах, обусловленной общими условиями работы. Для дефектных вводов выявлены статистически значимые связи отдельных показателей с длительностью эксплуатации, изменение внутренней корреляционной взаимосвязи и отсутствие сходства с показателями соседних исправных вводов. На основе распознавания форм и взаимосогласованности временных кривых сформулировано правило принятия решения: дефект фиксируется при наличии корреляции с временем и внутренних корреляций при одновременном отсутствии межфазной корреляции. Значимость полученных результатов состоит в том, что применение методов распознавания кривых обеспечивает обнаружение развивающихся дефектов до выхода показателей за предельные значения, уменьшает вероятность ошибочного выбраковки и повышает надёжность оценки состояния вводов в различных режимах работы сети. Предложенный подход может быть использован в системах мониторинга технического состояния для повышения эффективности эксплуатационного обслуживания высоковольтного оборудования. Это приводит к снижению аварийных рисков, оптимизации ремонтных стратегий и более обоснованного планирования технического обслуживания оборудования.

Ключевые слова: высоковольтные вводы, диагностика, показатели изоляции, тангенс угла диэлектрических потерь, емкость, измерительное сопротивление выводов, корреляция, распознавание кривых.

INTRODUCTION.

The conventional approach to assessing the technical condition of high-voltage equipment in power networks is primarily based on comparing periodically measured insulation indicators with predefined threshold values. However, as noted in [1], such an approach does not always ensure the timely detection of developing faults. As a consequence, latent defects may remain unnoticed until they evolve into failures, leading to substantial economic losses and reduced system reliability.

In this paper, high-voltage bushings-one of the most failure-prone components of power transformers, shunt reactors, and circuit breakers [2]-are used as a representative ex-ample to introduce an alternative diagnostic concept.

The proposed approach shifts the focus from the analysis of individual parameter values to the examination of their temporal behavior. By applying curve recognition principles to insulation indicators, the method makes it possible to identify characteristic pat-terns in the evolution of diagnostic parameters that are indicative of emerging defects.

As a result, the developed methodology provides a basis for early fault detection in high-voltage bushings and contributes to improving the operational reliability of high-voltage equipment.

PUBLICATION ANALYSIS AND RESEARCH AGENDA

According to existing international and national standards [3–5], one of the principal criteria for assessing the insulation condition of high-voltage bushings is the comparison of measured indicators with their prescribed limit values. Our earlier studies showed that refinement of permissible levels for diagnostic parameters can significantly reduce the risk of overlooking developing defects; however, such an approach does not allow defects to be detected at an early stage.

At present, intensive research efforts are directed toward the development of advanced diagnostic techniques capable of improving the reliability and sensitivity of insulation condition assessment.

In particular, works [6–7] present a comprehensive analysis of the most typical failure mechanisms of high-voltage bushings and review the most promising methods for evaluating their technical state.

The application of frequency response analysis (FRA) for diagnosing both high-voltage bushings and power cables is proposed in [8], while study [9] recommends the combined use of frequency response analysis (FRA) and dissolved gas analysis (DGA) to enhance the diagnostic reliability for bushing insulation.

In studies [10–13], frequency domain spectroscopy (FDS) is employed as a tool for evaluating the dielectric condition of bushing insulation, providing insight into aging, moisture ingress, and structural changes in oil–paper systems.

Additionally, the return voltage measurement (RVM) technique is suggested in [14] as an effective method for assessing the state of condenser-type bushing insulation.

A considerable number of publications [15–17] are also devoted to the development of online and off-line monitoring systems aimed at continuous supervision of high-voltage bushing insulation condition.

However, despite the extensive body of existing research, the problem of early detection of bushing defects based specifically on the results of periodic diagnostic testing has not been sufficiently investigated.

Moreover, the time-dependent behavior of insulation indicators as a function of operating duration remains largely unexplored in the literature.

These unresolved issues form the primary motivation for the present study and define the direction of the research presented in this article.

THE STUDY MATERIALS AND METHODS

Our previous investigations indicate the presence of significant differences in the nature of the relationships between insulation indicators and service life for serviceable and defective high-voltage oil-filled bushings. In particular, for both sealed and unsealed bushings with developing defects, a pronounced systematic component appears in the time dependencies of insulation indicators, which is not characteristic of serviceable bushings.

The identified differences in the structure of the time-dependent curves describing the insulation indicators make it possible to approach the diagnostic problem in a different way. In this case, the condition of the bushing is evaluated not only by individual numerical values of the parameters, but also by the nature of their variation over time. It is precisely these features of the shape and behavior of the curves that are used to recognize the technical condition. In this context, the insulation condition of a bushing is determined not by the absolute value of a parameter at a particular time instant, but by the form, trend, and mutual consistency of its time-dependent curve. The proposed approach is based on the concept of curve recognition, according to which the technical condition of equipment is determined from the shape, trend, and characteristic features of the function x(t) describing the temporal evolution of diagnostic parameters over time.

In practical diagnostics, information about the equipment condition is usually presented in the form of sequences of measurements or deviations from a reference level at discrete time instants [18]. Such data may be interpreted either as continuous curves x(t) or as discrete time series $\{x(t_i)\}$. The development of a defect may manifest itself in the form of systematic trends, monotonic increase or decrease, as well as the appearance of regular components in the temporal behavior of diagnostic indicators. Therefore, within the framework of curve recognition, the key diagnostic task is to establish a correspondence between the shape of the curve x(t) and the actual technical condition of the equipment.

From the standpoint of technical diagnostics, two fundamental questions arise [18]: (i) whether the observed changes in x(t) are caused by random, insignificant fluctuations or by physically meaningful degradation processes; and (ii) which specific equipment states correspond to the detected changes in the curve structure. When assessing the technical condition of equipment installed at the same substation using a set of diagnostic indicators, two additional questions should be considered in addition to those listed above: whether different diagnostic indicators evolve coherently due to a common physical process, and whether the detected temporal patterns are unique to the object under study or are also observed in adjacent equipment operating under comparable conditions.

One of the ways to obtain this information is the analysis of correlation relationships. In the proposed approach, curve recognition is implemented by analyzing: (i) the correlation between insulation indicators and operating time in order to identify systematic trends in individual curves; (ii) the correlation between different indicators within a single bushing to assess the internal consistency of parameter evolution; and (iii) the correlation between indicators of bushings installed on neighboring phases in order to distinguish local defects from common external influences.

The developed method occupies a distinct position among time-series analysis tools by shifting the diagnostic focus from static threshold-based assessment to the recognition of characteristic patterns in the temporal evolution of insulation parameters. This makes it possible to identify incipient defects before the monitored indicators exceed their prescribed limit values. The principal requirement for the input data is a discrete sequence of measurements obtained under identical operating conditions for a group of bushings installed within the same unit. The main limitation of the proposed approach is the impossibility of extrapolating the identified correlation relationships to similar equipment installed on adjacent transformers, which confirms the individual nature of defect evolution for each separate unit.

For the quantitative assessment of these relationships, the Pearson pairwise correlation coefficient is used:

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 (y_i - \bar{y})^2}}, \qquad (1)$$

where r – is the sample value of the Pearson correlation coefficient; x_i, y_i – are the values of the analyzed random variables; $\bar{x}, \bar{y}$ – are the sample means of the random variables; n – is the sample size.

The presence of a statistically significant correlation was assumed when the calculated value of the pairwise correlation coefficient exceeded the critical value $rcrit$ for n-2 degrees of freedom at a confidence level of p = 0.95. To establish the relationship between the form of temporal variations of insulation indicators (based on correlation analysis) and the actual insulation condition, the results of periodic tests of 113 serviceable high-voltage bushings operated in four regions of Ukraine were examined. Among the analyzed units, 87 bushings had a rated voltage of 110 kV (68 of sealed design and 19 of unsealed design), 12 bushings were rated at 220 kV (6 sealed and 6 unsealed), and 14 bushings were rated at 330 kV (11 sealed and 3 unsealed). In addition, the temporal behavior of insulation indicators was studied for 28 defective sealed bushings with a rated voltage of 110 kV.

The insulation condition of high-voltage oil-filled bushings was evaluated using the following diagnostic parameters: the dielectric loss tangent of the main insulation (tgδ1), the capacitance of the main insulation (C1), the dielectric loss tangent of the measuring capacitor insulation (tgδ2), the capacitance of the measuring capacitor (C2), and the insulation resistance of the measuring tap (R).

The performed analysis demonstrates that, irrespective of voltage class and design type, serviceable bushings generally do not exhibit a statistically significant correlation between operating time and the values of insulation indicators, indicating the absence of a persistent directional trend in their temporal behavior.

At the same time, statistically significant correlations–both positive and negative-are observed between individual parameters, reflecting their internally coordinated but non-monotonic variations. Importantly, a pronounced positive correlation is also detected between corresponding insulation indicators of bushings installed on neighboring phases, which suggests the influence of common external operating factors rather than the presence of localized defects.

As an illustrative example, Table I summarizes the results of the correlation analysis for serviceable unsealed bushings of the 330 kV class (type БМТП-330). As can be seen from Table I, for all five analyzed parameters and for all three phases, no statistically significant correlation is observed between the parameter values and the duration of operation. This conclusion is further supported by the time dependencies of the insulation indicators presented in Fig. 1, where the curves exhibit non-monotonic behavior, i.e., during operation the parameter values both increase and decrease. At the same time, the analysis of the complete dataset of 113 serviceable bushings did not reveal any systematic patterns in the occurrence of local maxima or minima in the parameter dependencies.

At the same time, Table 1 clearly indicates the presence of statistically significant correlations between individual insulation indicators in serviceable bushings, which characterizes the internal consistency of their temporal evolution. In particular, for the high-voltage bushing installed on phase A, significant correlations were identified for the following indicator pairs: tgδ1–tgδ2, tgδ1–C2, tgδ2–C2. For the bushing installed on phase B, statistically significant correlations were observed for tgδ1–tgδ2, tgδ1–R, tgδ2 – C1, tgδ2–C2, tgδ2–R, and C1–C2. In the bushing installed on phase C, significant correlations were found for tgδ1–R, tgδ2–C1, tgδ2–C2, and C1–C2.

The obtained results indicate that, in serviceable bushings, variations of individual insulation indicators are statistically interrelated, reflecting coordinated changes of the diagnostic parameters. However, since similar correlation patterns are simultaneously observed in bushings installed on adjacent phases, it is reasonable to conclude that these parameter variations are driven by common external influences rather than by defect related processes. This inference is fully supported by the results of the correlation analysis be-tween insulation indicators of bushings installed on neighboring phases of the transformer, as presented in Table 2.

Table 1

Results of the correlation analysis between insulation indicators values and duration of operation, and between insulation indicators for of the serviceable high-voltage bushings БМТП-330

Insulation indicators	**Duration of operation**	***tgδ_1***	***tgδ_2***	***C_1***	***C_2***		***R***
	***Phase A*, *n*=11, $r_{\text{crit, 9, 0.95}}$=0.602**						
tgδ_1	-0.206		**-0.695**	0.185	**0.677**		-0.399
tgδ_2	0.471	**-0.695**		-0.453	**-0.878**		0.516
C_1	0.062	0.185	-0.453		0.601		-0.204
C_2	-0.324	**0.677**	**-0.878**	0.601			-0.451
R	0.148	-0.399	0.516	-0.204	-0.451		
	***Phase B*, *n*=11, $r_{\text{crit, 9, 0.95}}$=0.602**						
Insulation indicators	**Duration of operation**	***tgδ_1***	***tgδ_2***	***C_1***	***C_2***		***R***
tgδ_1	-0.040		**-0.765**	0.429	0.560		**-0.746**
tgδ_2	0.402	**-0.765**		**-0.657**	**-0.746**		**0.762**
C_1	0.001	0.429	**-0.657**		**0.955**		-0.434
C_2	-0.139	0.560	**-0.746**	**0.955**			-0.493
R	0.1	**-0.746**	**0.762**	-0.434	-0.493		
	***Phase C*, *n*=11, $r_{\text{crit, 9, 0,95}}$=0.602**						
Insulation indicators	**Duration of operation**	***tgδ_1***	***tgδ_2***	***C_1***	***C_2***		***R***
tgδ_1	-0.057		-0.567	0.258	0.422		**-0.622**
tgδ_2	0.317	-0.567		**-0.628**	**-0.809**		0.556
C_1	-0.007	0.258	**-0.628**		**0.834**		-0.127
C_2	-0.490	0.422	**-0.809**	**0.834**			-0.378
R	0.087	**-0.622**	0.556	-0.127	-0.378		

As shown in Table 2, all insulation indicators of bushings installed on adjacent phases of the transformer exhibit statistically significant correlations. This demonstrates that the temporal variations of the parameters in all three phase bushings are governed by a common influencing factor.

Considering that the simultaneous development of independent defects in all three bushings is highly improbable, the presence of strong correlations between their insulation indicators - even when individual parameters exceed the specified threshold values - should be interpreted as evidence of a serviceable condition rather than as an indication of local damage. In this way, the proposed approach reduces the probability of a Type I error (false rejection of equipment), which may arise from systematic measurement inaccuracies.

An examination of the dependencies presented in Fig.1 shows that the absolute values of insulation indicators in serviceable bushings installed on different phases are not identical. Such differences may result in increased unbalance current when the condition of bushings is continuously monitored using the unbalanced–compensated method [19].

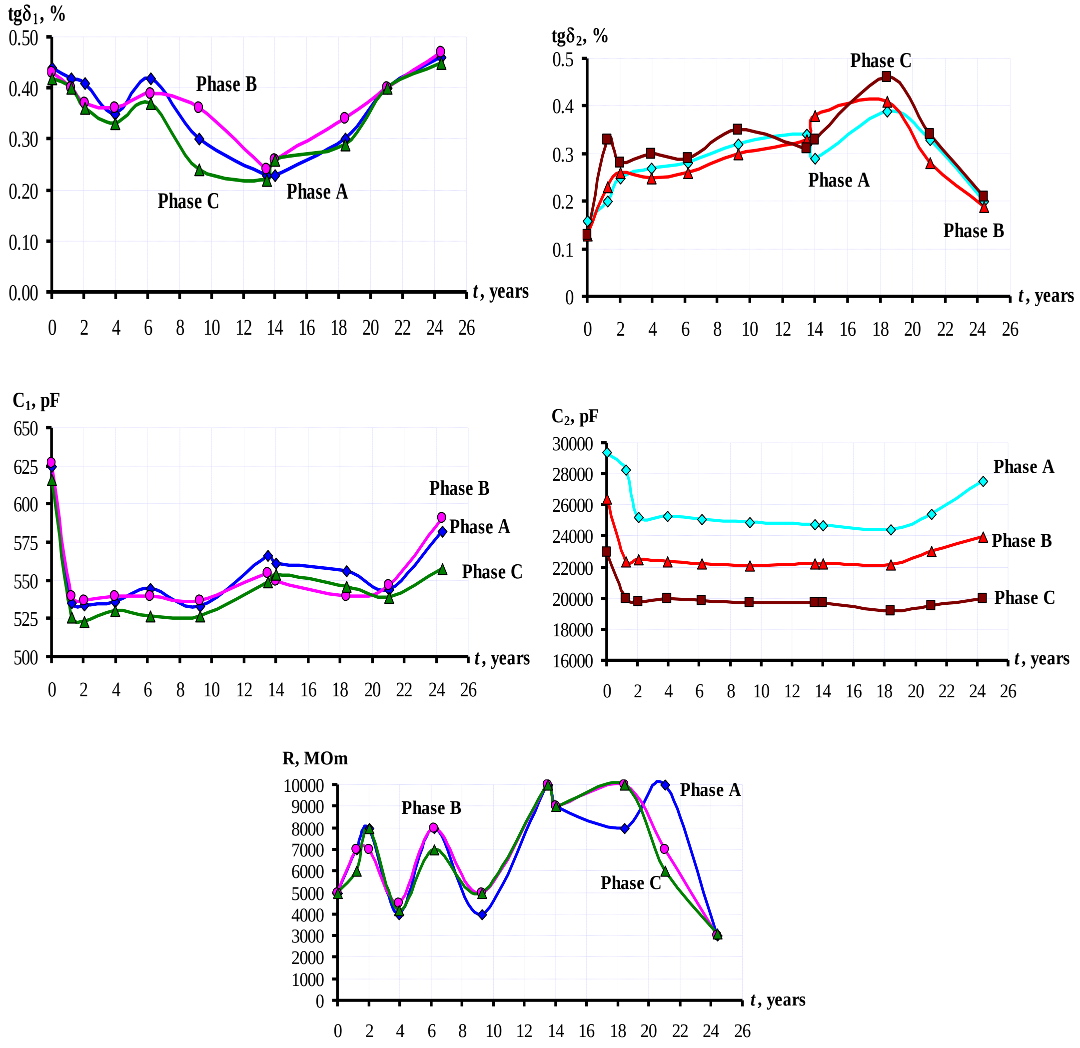

Fig. 1. The dependence of insulation indicators of the serviceable БМТП-330 kV high-voltage bushings on the duration of operation.

However, the application of correlation anaysis makes it possible to separate variations caused by common external operating conditions from those associated with actual insulation degradation. As a result, the insulation condition of high-voltage bushings can be determined with higher reliability even under asymmetric or otherwise non-standard operating conditions of the power system. The analysis further indicates that, although significant correlations are observed between the insulation indicators of serviceable bushings mounted on neighboring phases of the same transformer, similar correlations between bushings installed on adjacent transformers at the same substation are practically absent. This confirms that correlated temporal behavior is characteristic only of bushings operating within a single unit under identical external influences.

Table 2

Results of the analysis of the correlation between the insulation indicators of the serviceable бмтп-

330 kv high-voltage bushings installed on adjacent phases of the transformer

Phase	$tg\delta_1/tg\delta_1$	$tg\delta_2/tg\delta_2$	C_1/C_1	C_2/C_2	R/R
n=11, $r_{\text{crit, 9, 0,95}}$=0.602					
A-B	0.940	0.882	0.958	0.796	0.872
A-C	0.951	0.843	0.976	0.774	0.812
B-C	0.895	0.873	0.934	0.912	0.966

Table 3

Results of the analysis of the correlation between the values of insulation indicators and the duration of operation, as well as between individual parameters for serviceable bushings ГТТБ 60-110-800-У1

Insulation indicators	**Duration of operation**	$tg\delta_1$	$tg\delta_2$	C_1	C_2	R
T-1, Phase A, **n=6, $r_{\text{crit,4, 0.95}}$=0.811**						
$tg\delta_1$	0.100		**-0.843**	**0.899**	0.705	-0.525
$tg\delta_2$	-0.058	**-0.843**		**-0.950**	-0.571	0.598
C_1	-0.107	**0.899**	**-0.950**		0.604	-0.643
C_2	0.262	0.705	-0.571	0.604		0.106
R	0.558	-0.525	0.598	-0.643	0.106	
T-1, Phase B, **n=6, $r_{\text{crit,4, 0.95}}$=0.811**						
Insulation indicators	**Duration of operation**	$tg\delta_1$	$tg\delta_2$	C_1	C_2	R
$tg\delta_1$	-0.272		**-0.896**	**0.976**	0.111	-0.792
$tg\delta_2$	0.113	**-0.896**		**-0.962**	-0.042	0.670
C_1	-0.259	**0.976**	**-0.962**		0.084	-0.748
C_2	0.543	0.111	-0.042	0.084		0.464
R	0.490	-0.792	0.670	-0.748	0.464	
T-1, Phase C, **n=6, $r_{\text{crit,4, 0.95}}$=0.811**						
Insulation indicators	**Duration of operation**	$tg\delta_1$	$tg\delta_2$	C_1	C_2	R
$tg\delta_1$	-0.358		**-0.881**	**-0.958**	0.063	0.260
$tg\delta_2$	0.445	**-0.881**		**-0.910**	0.080	-0.199
C_1	-0.232	**-0.958**	**-0.910**		0.087	0.363
C_2	0.533	0.063	0.080	0.087		0.606
R	0.002	0.260	-0.199	0.363	0.606	
T-2, Phase A, **n=6, $r_{\text{crit,4, 0.95}}$=0.811**						
Insulation indicators	**Duration of operation**	$tg\delta_1$	$tg\delta_2$	C_1	C_2	R
$tg\delta_1$	-0.646		0.392	**0.963**	-0.091	0.189
$tg\delta_2$	-0.769	0.392		0.444	-0.402	0.380
C_1	-0.626	**0.963**	0.444		0.006	0.167
C_2	0.725	-0.091	-0.402	0.006		-0.623
R	-0.674	0.189	0.380	0.167	-0.623	
T-2, Phase B, **n=6, $r_{\text{crit,4, 0.95}}$=0.811**						
Insulation indicators	**Duration of operation**	$tg\delta_1$	$tg\delta_2$	C_1	C_2	R
$tg\delta_1$	-0.650		0.254	**0.965**	-0.353	0.198
$tg\delta_2$	-0.659	0.254		0.306	0.110	0.436
C_1	-0.600	**0.965**	0.306		-0.189	0.143
C_2	0.611	-0.353	0.110	-0.189		-0.393
R	-0.674	0.198	0.436	0.143	-0.393	
T-2, Phase C, **n=6, $r_{\text{crit,4, 0.95}}$=0.811**						
Insulation indicators	**Duration of operation**	$tg\delta_1$	$tg\delta_2$	C_1	C_2	R
$tg\delta_1$	-0.568		0.248	**0.948**	-0.413	0.186

$tg\delta_2$	-0.803	0.248		0.369	-0.240	0.341
C_1	-0.612	**0.948**	0.369		-0.238	0.221
C_2	0.625	-0.413	-0.240	-0.238		-0.451
R	-0.703	0.186	0.341	0.221	-0.451	

Although statistically significant correlations in dissolved gas concentrations had previously been observed for adjacent serviceable transformers, the results of the present study indicate a fundamentally different pattern in the temporal behavior of insulation indicators of high-voltage bushings. for insulation indicators of high-voltage bushings. As an illustration, Table 3 summarizes the results of the correlation analysis between insulation indicators and operating time, as well as between insulation indicators of serviceable sealed-type bushings (ГТТБ 60–110) installed on two adjacent transformers at the substation.

As follows from Table 3, for all analyzed bushings no statistically significant correlation is observed between the values of insulation indicators and the duration of operation. The corresponding time dependencies of the insulation indicators for high-voltage bushings installed on adjacent transformers are presented in Fig. 2.

For the high-voltage bushings mounted on the three phases of transformer T-1, statistically significant correlations were identified for the following indicator pairs: tgδ1–tgδ2, tgδ1–C1, and tgδ2–C1. In contrast, for the bushings installed on the three phases of transformer T-2, a significant correlation was found only for tgδ1–C1. These results indicate that the temporal behavior of insulation indicators is not identical for different transformers, even when they operate at the same substation.

Table 4

Results of the analysis of the correlation between the insulation indicators of serviceable high-voltage bushings гттб 60-110-800-у1 installed on adjacent phases of transformers

Phase	$tg\delta_1/tg\delta_1$	$tg\delta_2/tg\delta_2$	C_1/C_1	C_2/C_2	R/R
T-1, n=6, $r_{\text{crit},4,\ 0.95}$=0.811					
A-B	0.904	0.950	0.986	0.842	0.994
A-C	0.884	0.854	0.990	0.846	0.295
B-C	0.992	0.855	0.999	0.936	0.597
T-2 n=6, $r_{\text{крит},4,\ 0.95}$=0.811					
A-B	0.999	0.950	0.999	0.836	1.000
A-C	0.989	0.978	0.997	0.840	0.990
B-C	0.986	0.916	0.998	1.000	0.990

This conclusion is further supported by the dta in Table 4, where statistically significant correlations are observed for almost all insulation indicators for bushings installed on the three phases of transformer T-1 (which is consistent with the results of our previous studies) and for the bushings installed on the three phases of transformer T-2. In other words, the time evolution of the indicators is internally consistent for bushings operating on different phases of the same transformer.

At the same time, the results presented in Table V demonstrate the practical absence of statistically significant correlations between the insulation indicators of bushings installed on adjacent transformers at the same substation. As can be seen from the table, out of the five analyzed indicators, a significant correlation-indicating similarity in temporal behavior-was observed only for the measuring tap capacitance C2. For all other parameters, the character of the time dependencies does not coincide, which is also confirmed by the curves shown in Fig.2.

The obtained results therefore indicate that the nature of the time dependencies of insulation indicators for high-voltage bushings installed on different transformers is fundamentally different. That is, the temporal evolution of indicators for bushings operating on the same transformer is unit-specific and cannot be generalized to adjacent transformers. This circumstance precludes the application of the trajectory method [20] for predicting the values of insulation indicators of bushings.

In contrast, for high-voltage bushings in which defects have been detected, the temporal behavior of the indicators changes substantially. In particular, the analysis shows that defect development is accompanied by the appearance of a statistically significant correlation between individual insulation indicators and operating time (which is consistent with the results reported in [20]), by the presence of strong correlations among the indicators of the defective bushing, and by the absence of significant correlations between the insulation indicators of bushings installed on adjacent phases of the transformer.

As an illustrative case, Table 6 summarizes the results of the correlation analysis between insulation indicators and operating time, as well as the mutual correlations between insulation indicators for a defective high-voltage bushing of type ГБМВ-110 installed on phase A and the serviceable bushings of the same type installed on phases B and C. The bushing on phase A was diagnosed as overheated to a temperature of 300–700 °C due to the presence of a short-circuited loop.

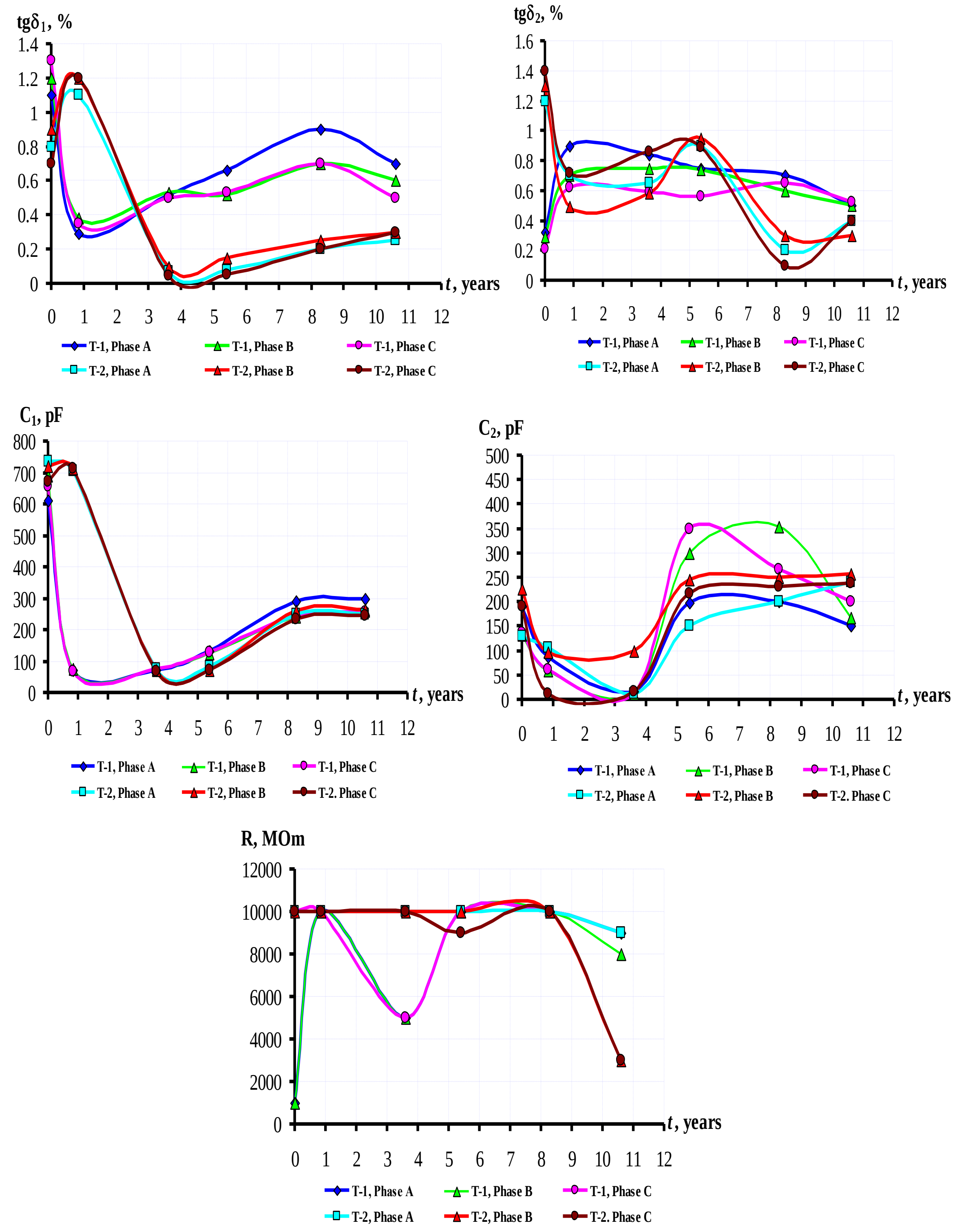

Fig.2. Dependence of the insulation indicators of the serviceable ГТТБ 60-110 high-voltage bushings installed on adjacent transformers of the substation on the duration of operation.

As shown in Table 6, among the five analyzed indicators, three-tgδ1, tgδ2, and C1-exhibit a statistically significant correlation with operating time for the defective bushing. Moreover, both tgδ1 and tgδ2 demonstrate a monotonic increase with service duration, which reflects the development of the defect. In contrast, for the serviceable bushings installed on phases B and C, no statistically significant correlation between the insulation indicators and operating time is observed.

Further analysis of the correlation structure presented in Table VI reveals that, for the defective bushing, statistically significant relationships exist between the following indicator pairs: tgδ1–tgδ2, tgδ1–C1, tgδ1–R, tgδ2–C1, tgδ2–R, C1–R, and C2–R. For the serviceable bushings, significant correlations were identified for tgδ1–C2, tgδ1–R, C1–C2, C1–R, and C2–R. Thus, with the exception of relationships involving the resistance of the measuring tap, the sets of correlated indicators differ markedly between the defective and serviceable bushings.

These results demonstrate that, in the presence of a defect, not only do individual insulation indicators acquire a pronounced time dependence, but the internal correlation structure of the parameters also changes. Consequently, deviations in both the temporal behavior of individual curves and the pattern of mutual correlations provide reliable diagnostic features for identifying defective high-voltage bushings.

Table 7 summarizes the results of the correlation analysis between insulation indicators of bushings installed on adjacent phases of the transformer. As follows from the data, statistically significant correlations between the indicators are observed only for the serviceable bushings mounted on phases B and C.

At the same time, the temporal behavior of the indicators for the defective bushing differs fundamentally from that of the serviceable units. This difference is confirmed both by the values of the correlation coefficients presented in Table VII and by the time dependencies of the insulation indicators shown in Fig.3. Thus, while the serviceable bushings exhibit mutually consistent parameter variations, the defective bushing is characterized by a distinct pattern of indicator evolution, which provides an additional diagnostic criterion for identifying insulation faults.

Table 5

Results of the analysis of correlation between the insulation indicators of serviceable high-voltage bushings installed on different phases of adjacent transformers

Transformers / Phase	$tg\delta_1/tg\delta_1$	$tg\delta_2/tg\delta_2$	C_1/C_1	C_2/C_2	R/R
n=6, $r_{\text{crit},4,\ 0.95}$=0.811					
T-1/A-T-2/A	-0.155	-0.339	0.481	0.754	-0.197
T-1/A-T-2/B	-0.142	-0.467	0.472	0.894	-0.197
T-1/A-T-2/C	-0.265	-0.336	0.421	0.887	-0.249
T-1/B-T-2/B	0.188	-0.428	0.532	0.811	-0.089
T-1/B-T-2/C	0.048	-0.337	0.485	0.812	-0.142
T-1/C-T-2/C	0.072	-0.766	0.463	0.843	0.300

Table 6

Results of the correlation analysis between insulation indicators and service life, and between individual parameters for the defective bushing гбмв-110 (phase a), and serviceable high-voltage -110 bushings гбмв-110 installed on phases *b* and *c*

Insulation indicators	**Duration of operation**	$tg\delta_1$	$tg\delta_2$	C_1	C_2	R
***Phase A*, n=10, $r_{\text{crit},\ 8,\ 0.95}$=0.632**						
tgδ$_1$	**0.732**		**-0.964**	**-0.945**	0.455	**-0.934**
tgδ$_2$	**0.704**	**0.964**		**-0.905**	0.421	**-0.893**
C$_1$	**-0.880**	**-0.945**	**-0.905**		-0.217	**0.817**
C$_2$	-0.002	0.455	0.421	-0.217		**-0.675**
R	-0.604	**-0.934**	**-0.893**	**0.817**	**-0.675**	
***Phase B*, n=10, $r_{\text{crit},\ 8,\ 0.95}$=0.632**						
Insulation indicators	**Duration of operation**	$tg\delta_1$	$tg\delta_2$	C_1	C_2	R

tgδ₁	-0.511		0.130	0.580	**0.896**	**-0.905**
tgδ₂	-0.162	0.130		0.416	0.225	-0.249
C₁	-0.223	0.580	0.416		**0.799**	**-0.822**
C₂	-0.580	**0.896**	0.225	**0.799**		**-0.994**
R	0.501	**-0.905**	-0.249	**-0.822**	**-0.994**	
***Phase C, n*=10, *r*$_{crit, 8, 0.95}$=0.632**						
Insulation indicators	**Duration of operation**	***tgδ₁***	***tgδ₂***	***C₁***	***C₂***	***R***
tgδ₁	-0.630		-0.240	0.624	**0.722**	**-0.693**
tgδ₂	-0.064	-0.240		0.116	0.337	-0.344
C₁	-0.313	0.624	0.116		**0.822**	**-0.786**
C₂	-0.576	**0.722**	0.337	**0.822**		**-0.976**
R	0.427	**-0.693**	-0.344	**-0.786**	**-0.976**	

Table 7

Results of the correlation analysis between the insulation indicators of the defective bushing (phase a) and the serviceable гбмв-110 bushings installed on phases b and c of the transformer

Phase	***tgδ₁/tgδ₁***	***tgδ₂/tgδ₂***	***C₁/C₁***	***C₂/C₂***	***R/R***
***T-1, n*=10, *r*$_{crit, 8, 0.95}$=0.632**					
A-B	-0.132	0.029	0.133	0.335	0.077
A-C	-0.394	0.218	0.241	0.335	0.101
B-C	**0.880**	**0.878**	**0.667**	**1.000**	**0.992**

A fundamentally important fact is that for slowly developing defects of high-voltage bushings, such as overheating in the range of low and medium temperatures, a change in the nature of the temporal dependencies of the indicators is observed even before the values of the indicators exceed the threshold values (in this example, one year before detection).

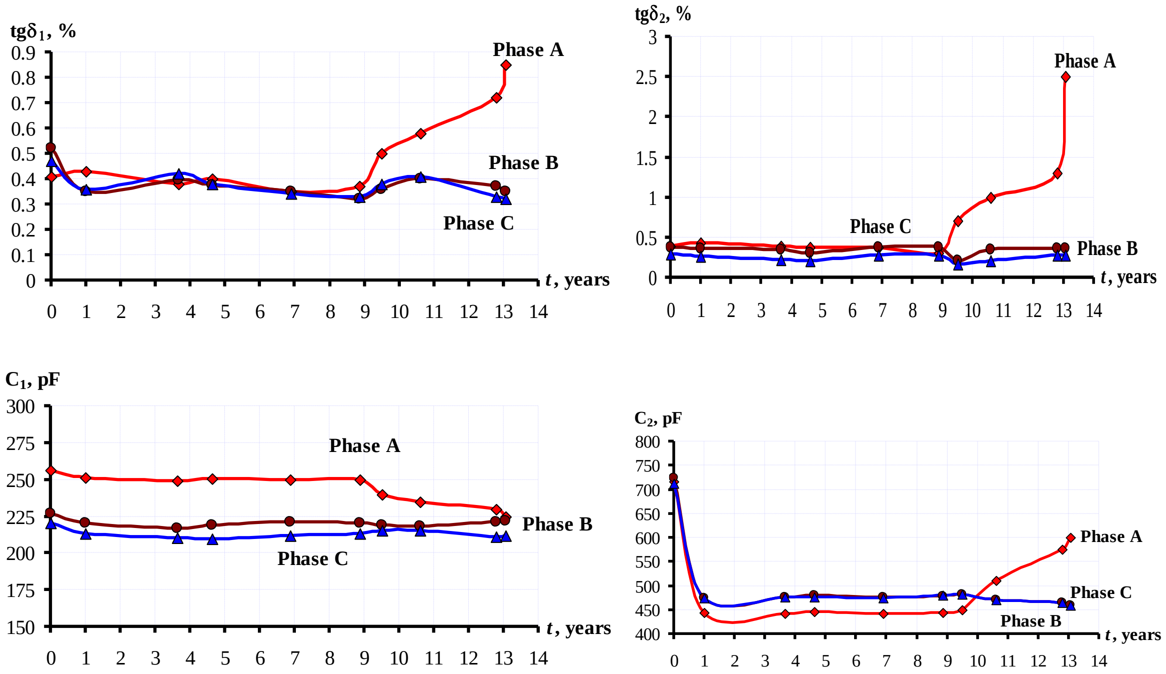

Fig.3. Bushing (phase A) and the serviceable bushings (phases B Dependence of insulation indicators on the duration of operation for the defective and C).

This approach makes it possible to identify such defects at an early stage of their development. At present, however, the limited volume of experimental data on defective high-voltage bushings does not yet permit a definitive association between specific defect types and particular sets of correlated indicators. Addressing this issue is therefore identified as a subject of further research.

The revealed differences in the temporal behavior of insulation indicators for bushings in different technical conditions have been formalized into a method for the early detection of bushing defects. Within this method, the presence of a defect is inferred when three criteria are simultaneously satisfied: (i) a statistically significant correlation is observed between at least one insulation indicator and operating time; (ii) statistically significant correlations exist among the insulation indicators of the bushing under investigation; and (iii) no statistically significant correlation is detected between the indicators of the analyzed bushing and those of bushings installed on adjacent phases.

The proposed method has been implemented as a dedicated module of the information-analytical system SIRENA, which is currently under development at the Department of Electric Power Transmission of NTU “KhPI”.

CONCLUSION

The results of this study demonstrate that the condition of high-voltage bushings is reflected not only in the absolute values of insulation indicators-which is a well-established and widely applied diagnostic approach-but also in the temporal behavior of these indicators. A pronounced difference in the dynamics of parameter changes over time is revealed for bushings operating in different technical states, and this difference can be effectively used for condition assessment.

For serviceable high-voltage bushings, the following features are characteristic: the absence of statistically significant correlations between insulation indicators and operating time; the presence of statistically significant correlations among the indicators themselves, with similar correlation patterns observed for corresponding parameters of bushings installed on all phases; and the existence of strong correlations between insulation indicators of bushings mounted on adjacent phases.

In contrast, for defective high-voltage bushings of both hermetic and non-hermetic designs, the temporal behavior of the indicators is fundamentally different. Such bushings are characterized by statistically significant correlations between insulation indicators and operating time, pronounced internal correlations among the indicators, and the absence of significant correlations between the indicators of defective bushings and those of serviceable bushings installed on adjacent phases.

Importantly, the identified differences in the structure and dynamics of the time-dependent relationships can be detected even before the indicator values exceed the prescribed threshold limits. Therefore, the proposed approach provides a reliable basis for the early detection of developing defects in high-voltage bushings.

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