

The approach has been developed to determining the numerical value of a failure probability and to forecasting the resource of an instrument transformer cell at the time of observation. Underlying a given approach is the control over the main parameters that affect the technical condition (TC) of an instrument transformer cell in the distributing device of high voltage (DDHV). To determine a TC of the devices, a mathematical method of fuzzy modeling has been applied, which makes it possible to integrate the diagnostic parameters that are different in their nature. Building a fuzzy model involved the experience of experts in the relevant industry.

The relevance of the development of a given approach is predetermined by the functional importance of a current transformer. Its performance affects the accuracy of triggering the relay protection devices, as well as the accounting of electrical energy. Precise accounting of electric energy implies minimizing its losses and shows the path to energy savings. A special feature of this approach is that it takes into consideration the influence of TC of each piece of cell equipment on the probability of its failure in general. To account for the factors of random disturbances, an expert fuzzy model is refined by the probabilistic-statistical method.

An example of the DDHV instrument transformer cell in an electric-energy system has been used to substantiate the advantage of a given approach over the existing methods to control the technical condition of electrical equipment. The error in predicting the cell resource based on one parameter (thermal imaging examination) was $\Delta_{f(D-02)} = 1 - Q_{D-02} = 0.364$, or 36.4%. When applying an expert-statistical model for determining the probability of a cell failure, the error was $\Delta_{f(D-02)} = 1 - Q_{apost} = 0.034$, or 3.4%. The application of a given approach has produced a more reliable estimate of the probability of cell failure.

Implementing the developed approach in the field of electrical equipment diagnosing could improve the reliability level of forecasting results. The constructed model could be applied in the automated systems that diagnose "on-line" the DDHV electric devices

Keywords: current transformer, disconnecter, cell, fuzzy model, technical condition, failure probability

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ESTIMATING THE FAILURE PROBABILITY OF AN INSTRUMENT TRANSFORMER CELL IN THE HIGH VOLTAGE DISTRIBUTING DEVICE USING AN EXPERT-STATISTICAL METHOD

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1. Introduction

The degradation of insulation, of structural elements in electrical devices, caused by aging, requires more careful control over the operational reliability of electrical equipment. These circumstances gave rise to the notion of reliability of machines and other technical means in science. One of the indicators of electrical equipment reliable operation implies determining a failure probability. The other issue is predetermined by the fact the development of science leads to the more complicated equipment and its structural elements. Therefore, it is a relevant task for modern science to create new methods and models for determining the probability of electrical equipment failure.

The main criterion that defines the probability of electrical equipment failure is the condition of the main insulation

and current conductive parts. The introduction of new types of insulation and structural materials requires constant revision of the approaches to assessing the TC of electrical equipment. Under these conditions, it is important to determine those diagnosing parameters that characterize the reliability of electrical equipment operation. In practice, this would reduce the occurrence of accidents and, as a consequence, ensure better power supply to consumers.

A significant quantity of power supply network equipment has exceeded its predefined calendar resource but the actual resource in most of this equipment has not expired yet. Under such conditions, it is very important to construct mathematical models for diagnosing and forecasting the TC of DDHV equipment under an "on-line" mode. Current instrument transformers (CTrs) with paper-oil main insulation is one of the most hazardous types of DDHV equipment.

CTrs are located in electric cells, which are separated by disconnectors, which is why the failure of a CTr or disconnector leads to failure of the entire cell, so it is advisable to assess the technical condition of the entire cell rather than separate devices.

2. Literature review and problem statement

The global nature of the issues related to energy security raises the question of improving the existing approaches to control the reliable operation of power equipment, in particular the equipment of power supply systems. Thus, works [1, 2] report the results of studying the method improvement and the measurement devices that control insulation under a working voltage. However, the issue of the comprehensive evaluation of the investigated apparatus remained unresolved. The reason for this is that the authors paid attention to only one parameter of insulation condition – dielectric losses. Papers [3, 4] partly resolved the issue of the comprehensive assessment but failed to take into consideration the device temperature parameters. In addition, a neural-network model created in [3] requires a reliable sample of a large number of investigated equipment. Studies [5, 6] explore the technologies, procedures, and algorithms to estimate the condition of CTr basic insulation under a working voltage for determining the worked-out resource; however, the issue of the comprehensive estimation of the TC of instrument transformers remained unresolved, which makes the research not objective enough. Paper [7] identified and categorized electrical measuring devices with a high level of failure but failed to reveal any functional dependence of failure probability on calendar resource. Works [8, 9] address the method of estimation based only on determining the metrological characteristics of instrument transformers, as well as the problems of modernization of the CTr structural elements for operation in a power supply network of rectified current. Much to our regret, the high-voltage DC power supply networks have not been widely used up to now. Somewhat less attention is paid to the TC of disconnectors but there are studies into determining the degree of wear of separate nodes in the machine. For example, papers [10, 11] proposed monitoring the state of a disconnector drive by controlling the motor currents during the mechanical operations involving the device. In addition, work [10] suggested controlling the thermal condition of contact connections. However, the hardware base for the application of this method is quite expensive. Given a large number of disconnectors in the total volume of DDHV equipment, this method is not financially justified. Papers [12–15] addressed the diagnosing methods based on the drive engine's current by the acoustic vibration method, ultrasound diagnosing, by measuring voltage-deformation, measuring the electromagnetic fields. Works [16, 17] proposed the generalized models for estimating a failure probability of electric power systems' equipment, disregarding the type of equipment. That does not make it possible to apply them in practice to the specific elements of a distributing device, without adapting them to the particular functioning of specific types of devices.

Under continuous modes of diagnosing the equipment and diagnosing under a working voltage, it is not possible to use many of these methods. One can conclude that the methods that diagnose the TC of instrument transformers and disconnectors provide information for the local parameter,

or are rather costly in the implementation. Therefore, it is a relevant task to devise new approaches to control the cells of instrument transformers.

Estimating the failure probability of an instrument transformer cell is complicated by the heterogeneity of input diagnostic parameters describing the current state of a device and by the absence of analytical interrelations, as well as incomplete or distorted retrospective data on device functioning. Available literary sources mostly employ the generalized statistics on the functioning of electrical devices. Our analysis of studies [1–6, 10, 11] has revealed that the proposed diagnosing methods could not provide an integrated determination of the technical condition of a current instrument transformer's cell. Diagnosing is based on the condition of individual devices; such an approach complicates the assessment of the operational reliability of a power supply network.

Therefore, it is promising to devise new approaches and methods for estimating the worked-out resource of an instrument transformer cell in DDHV.

3. The aim and objectives of the study

The purpose of this work is to improve the approach to forecasting the resource of electrical equipment, namely the cells of instrument transformers in DDHV. Underlying it is the combination of a method of expert evaluation of the current TC based on the diagnostic parameters and a probability-statistical method. In addition, a given approach takes into consideration the influence of a TC of each cell unit on the probability of its failure. This could make it possible to improve the level of reliability in forecasting the resource of electrical equipment in the DDHV of power supply systems.

To accomplish the aim, the following tasks have been set:

- to build the fuzzy mathematical models of an instrument transformer cell's devices to determine a failure probability, whose construction is based on data acquired from the survey of experts in the relevant industry and further processing of expert information;
- to improve the expert model by correcting it with statistical data on the functioning of a particular type of equipment, and to determine a failure probability for a cell of the DDHV instrument transformer taking into consideration possible external disturbances.

4. Construction of mathematical models to estimate a failure probability for the equipment in an instrument transformer cell

The models were constructed on the basis of fuzzy modeling methods [18], which is due to the following:

- the evaluation is possible based only on the information available for observation and measurement (limiting the possibility of data acquisition during device operation);
- the measurement and observation of processes imply a certain degree of reliability (errors could reach 20 %);
- the absence of analytical dependences of the mutual influence exerted by the diagnostic parameters in assessing the failure probability of an electrical device.

According to [18], a device can be regarded as an object that has n elements with input attributes and one output:

$$T \cdot dz / dt = f(z, V(t, \varepsilon), P(t)), \tag{1}$$

where $z=(z_1\dots z_n)^T$ is the vector of state variables (phase coordinates), which are determined on the basis of electrical, mechanical, chemical laws, typical for each element of the object;

$P(t)$ is the vector of parameters of object elements, which changes over time due to aging, wear, structural features of the object;

T is the vector of time constants of the object elements;

$V(t, \varepsilon)$ is the external disturbances;

ε is the case predetermined by an operation mode, the influence of meteorological conditions, and personnel.

To determine the failure probability of an electrical device, based on the current values of the components of the state variable vector, we applied a method of fuzzy modeling, which allows the integrated assessment of the state of the object according to the diagnostic attributes that are different in nature. To implement this problem, a Mamdani fuzzy model was applied [18], which has the following structure:

$$S = F(\mu(P), R(W), M, D, A), \tag{2}$$

where $\mu(P)$ is the membership functions of terms of the input and output linguistic variables;

$R(W)$ is the basis of fuzzy rules “IF–THEN” with weight coefficients W ;

M is the mechanism of fuzzy derivation, which implements logical operations and uses rules “IF–THEN” to reflect the input linguistic variables into an output linguistic variable;

D is the defuzzification method;

A is the input linguistic variable;

S is the output linguistic variable.

The main tasks in building a fuzzy model are to determine the number of terms, the membership degree $\mu(P)$ of linguistic variables to the corresponding term sets. The membership functions (MF) are given in a parametric form, that is, the construction is reduced to determining the function parameters. When the initial and permissible value is known, MFs have a triangular and trapezoidal shape. The forms of MFs [19] are shown in Fig. 1.

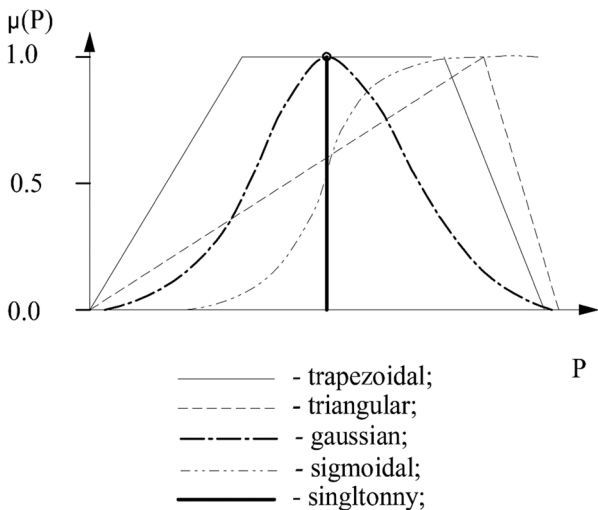


Fig. 1. Diagrams of the most widespread MFs

The MF parameters of the input linguistic variables are determined based on the weight coefficients, with a linear approximation. The evaluation of the advantage of one element over another employs a Saaty method of paired comparisons. Paired comparisons are recorded as the matrix $\Lambda=[a_{nm}]$. The membership degrees are accepted to equal the appropriate coordinates of the eigenvector $\omega=(\omega_1, \omega_2,\dots,\omega_n)^T$ of the matrix of paired comparisons Λ [20].

The eigenvector is determined from the system of equations:

$$\begin{cases} a_{11}\omega_1 + a_{12}\omega_2 + \dots + a_{1m}\omega_m = 0, \\ a_{21}\omega_1 + a_{22}\omega_2 + \dots + a_{2m}\omega_m = 0, \\ \dots \\ a_{n1}\omega_1 + a_{n2}\omega_2 + \dots + a_{nm}\omega_m = 0, \\ \omega_1 + \omega_2 + \dots + \omega_m = 1, \end{cases} \tag{3}$$

where a_{nm} is the level of superiority of the n -th element over the m -th element, $a_{nm}=1/a_{mn}$, $a_{nn}=1$; ω are the weight coefficients of the significance criteria.

The matrix eigenvalue is determined from the following equation:

$$(\Lambda - \lambda E) \cdot \omega = 0; \tag{4}$$

where λ is the largest matrix Λ eigenvalue; E is the identity matrix of dimensionality $(n \times n)$.

The assessment of advantage of one criterion (term) of the diagnostic parameter over another criterion was performed using a 9-point relationship scale [20]. The evaluation was carried out by a group of experts (9 experts with practical experience in the diagnosing services of electrical equipment at the following enterprises – Ukrainian hydro-power company, the State Enterprise National Energy Company, Zaporizhzhya Regional Power Company). An example: m experts determined the membership of an interval criterion to the set of an input variable, n experts determined that it does not belong to the interval, then the advantage of one criterion over another was determined $m-n$, at $m+n=9$. An example of the questionnaire is given in Table 1.

Table 1

Expert questionnaire

Respondents	Criterion (term)	0.0 (min)	...	1.0 (max)
Expert 1	P_1	1	1	0
	P_i	0	0	1
.....
Expert 9	P_1	1	0	0
	P_i	0	1	1

The MF parameters of the output linguistic variables were determined using a Harrington desirability scale, calculated on the basis of the statistical analysis of large data array with the universal application [18].

The defuzzification is based on the center of gravity method [19]. The approximate modification of the center of gravity:

$$S = \frac{\sum_{i=1}^m \mu_i(s) \cdot s_i}{\sum_{i=1}^m \mu_i(s)}. \tag{5}$$

The obtained quantity S , based on the constructed fuzzy model, quantitatively characterizes the failure probability of the electrical device, which is part of the cell.

To determine the failure probability of an instrument transformer cell, we chose, in accordance with normative documents [21, 22], the diagnostic parameters that could be measured directly or indirectly, without disabling the equipment. For CTR: insulation resistance, the tangent of dielectric loss angle, a change in insulation capacitance, data from infrared thermography. For disconnector: the number of worked operational cycles (enable-arbitrary pause-disable), data from infrared thermography. The set of the selected parameters corresponds to the normative documentation and makes it possible to identify defects in the main CTR insulation in the early stages of development. Such defects are the partial breakdown of the CTR main insulation, the poor state of contact joints in the disconnector, the presence of thermal defects, short-circuited contours.

Based on the selected diagnostic parameters, the following input linguistic variables were assigned for CTR:

- A_1 ="Insulation resistance";
- A_2 ="Dielectric losses";
- A_3 ="Capacitance deviation";
- A_4 ="Boundary temperature difference".

The following fuzzy terms were defined for the linguistic variables:

- A_1 : N_1 ="Normal", M_1 ="Acceptable", FL_1 ="Emergency low";
- A_2 : N_2 ="Normal", M_2 ="Acceptable", FH_2 ="Emergency high";
- A_3 : M_3 ="Acceptable", FH_3 ="Emergency high";
- A_4 : I_4 ="Initial", D_4 ="Developed".

Based on the selected diagnostic parameters, the following input linguistic variables were assigned for the disconnector:

- A_5 ="Mechanical resource";
- A_6 ="Boundary temperature difference".

The following fuzzy terms were defined for the linguistic variables:

- A_5 : L_1 ="Usable", M_1 ="Acceptable", B_1 ="Used";
- A_6 : I_2 ="Initial", D_2 ="Developed".

The output set of the probability of events S is described by the linguistic variable "Failure probability". The terms for the output variable and their intervals were determined according to standard points along a Harrington verbal-numerical scale:

- VB ="Very high failure probability" (0.80; 1.00];
- B ="High failure probability" (0.63; 0.80];
- M ="Medium failure probability" (0.37; 0.63];
- L ="Low failure probability" (0.20; 0.37];
- VL ="Very low failure probability" [0.00; 0.20].

The rule bases for assessing the failure probability of a cell's devices were formed on the basis of expert knowledge of the structure, characteristics, and processes of the examined object (the knowledge of 9 experts). Thus, we obtained a set of 36 and 6 producing rules of the following type:

- for CTR - "IF insulation resistance $A_1=\{FL_1, M_1, N_1\}$ AND dielectric losses $A_2=\{N_2, M_2, FH_2\}$ AND capacitance deviation $A_3=\{M_3, FH_3\}$ AND boundary temperature difference $A_4=\{I_4, D_4\}$, THEN failure probability $S=\{VB, B, M, L, VL\}$;

- for the disconnector - "IF mechanical resource $A_1=\{L_1, M_1, B_1\}$ AND boundary temperature difference $A_2=\{I_2, D_2\}$, THEN failure probability $S=\{VB, B, M, L, VL\}$ ".

General rule bases for assessing the failure probability of devices are given in Tables 2, 3; the structural patterns of the models are shown in Fig. 2, 3.

Table 2

Rule base for estimating the probability of a CTR failure

A_4	I_4				D_4			
A_3								
M_3	A_2	N_2	M_2	FH_2	A_2	N_2	M_2	FH_2
	A_1				A_1			
	N_1	L	L	B	N_1	L	L	B
	M_1	L	VL	VB	M_1	L	L	VB
	FL_1	B	B	VB	FL_1	B	B	VB
FH_3	A_2	N_2	M_2	FH_2	A_2	N_2	M_2	FH_2
	A_1				A_1			
	N_1	M	M	VB	N_1	B	B	VB
	M_1	M	L	VB	M_1	M	M	VB
	FL_1	B	VB	VB	FL_1	B	VB	VB

Table 3

Rule base for estimating the probability of a disconnector failure

A_6	I_2	D_2
A_5		
L_1	VL	B
M_1	M	VB
B_1	B	VB

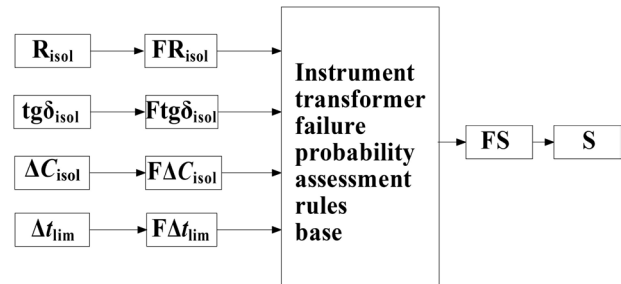


Fig. 2. Fuzzy model to assess the probability of a CTR failure

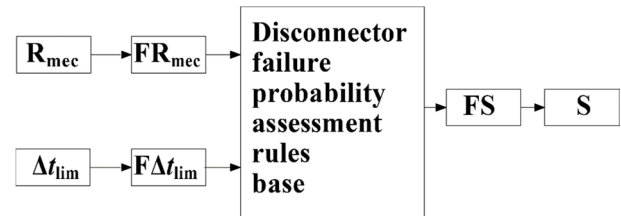


Fig. 3. Fuzzy model to assess the probability of a disconnector failure

According to (3), let us define the degree of belonging of the values of the input linguistic variables to the fuzzy terms. The calculation results are summarized in Tables 4–9.

The graphical representation of the MFs of the fuzzy terms of the input linguistic variables is shown in Fig. 4–10.

Table 4

Degrees of belonging of the values of the input quantity "Insulation resistance" to the fuzzy terms

R_{isol}	0.00	0.20	0.40	0.60	0.80	1.00
μ_N	1.000	0.886	0.000	0.000	0.000	0.000
μ_M	0.000	0.114	1.000	0.555	0.113	0.000
μ_{FL}	0.000	0.000	0.000	0.445	0.887	1.000

Table 5

Degrees of belonging of the values of the input quantity "Dielectric losses" to the fuzzy terms

$tg\delta_{isol}$	>0.00	0.20	0.40	0.60	0.80	1.00
μ_N	1.000	1.000	0.665	0.000	0.000	0.000
μ_M	0.000	0.000	0.335	1.000	0.114	0.000
μ_{FH}	0.000	0.000	0.000	0.000	0.886	1.000

Table 6

Degrees of belonging of the values of the input quantity "Capacitance deviation" to the fuzzy terms

$\pm\Delta C_{isol}$	0.00	0.20	0.40	0.60	0.80	1.00
μ_M	1.000	1.000	0.555	0.000	0.000	0.000
μ_{FH}	0.000	0.000	0.445	1.000	1.000	1.000

Table 7

Degrees of belonging of the values of the input quantity "Boundary temperature difference" to the fuzzy terms

Δt_{lim}	0.00	0.20	0.40	0.60	0.80	1.00
μ_I	1.000	1.000	1.000	0.224	0.000	0.000
μ_D	0.000	0.000	0.000	0.776	1.000	1.000

Table 8

Degrees of belonging of the values of the input quantity "Mechanical resource" to the fuzzy terms

R_{mec}	0.00	0.20	0.40	0.60	0.80	1.00
μ_L	1.000	0.777	0.000	0.000	0.000	0.000
μ_M	0.000	0.223	1.000	1.000	0.665	0.000
μ_B	0.000	0.000	0.000	0.000	0.335	1.000

Table 9

Degrees of belonging of the values of the input quantity "Boundary temperature difference" to the fuzzy terms

Δt_{lim}	0.00	0.20	0.40	0.60	0.80	1.00
μ_I	1.000	1.000	1.000	0.336	0.000	0.000
μ_D	0.000	0.000	0.000	0.664	1.000	1.000

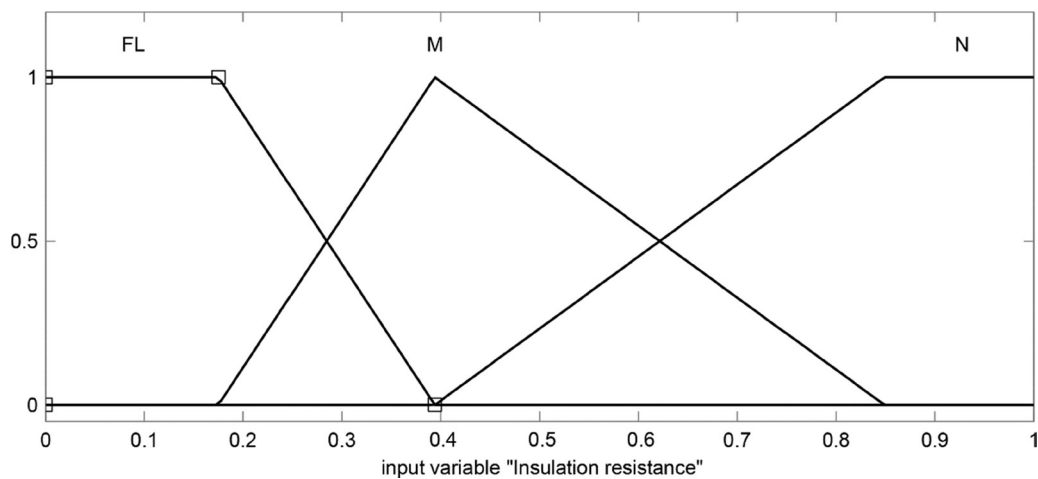


Fig. 4. MF of the terms of the linguistic variable "Insulation resistance"

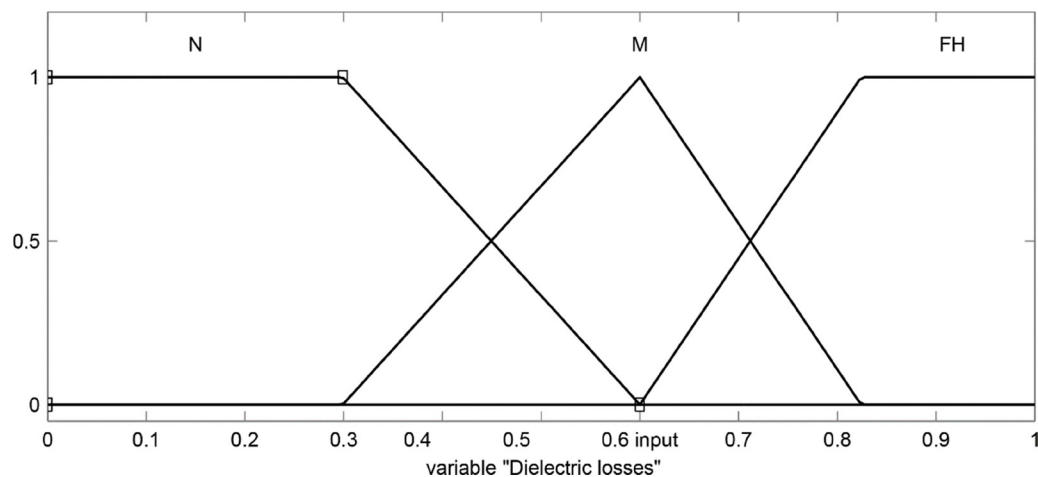


Fig. 5. MF of the terms of the linguistic variable "Dielectric losses"

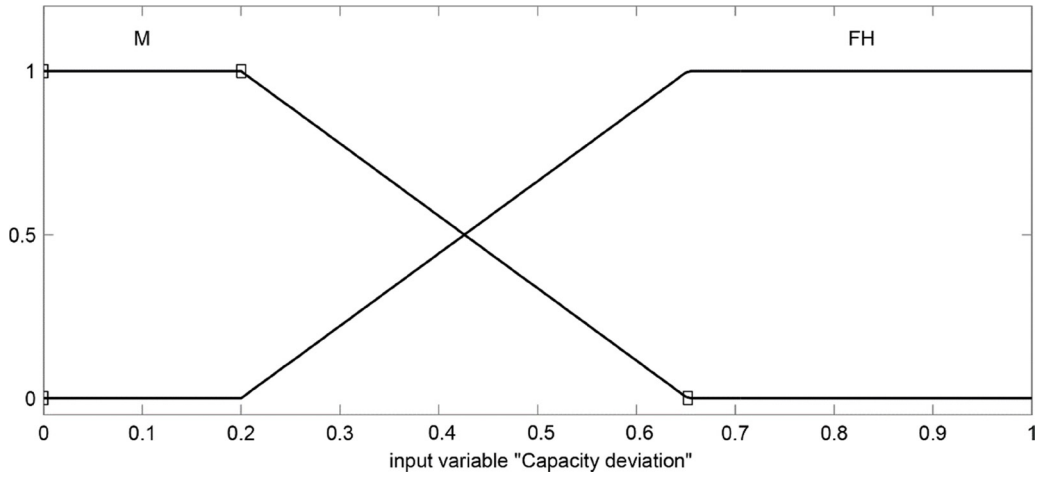


Fig. 6. MF of the terms of the linguistic variable “Capacitance deviation”

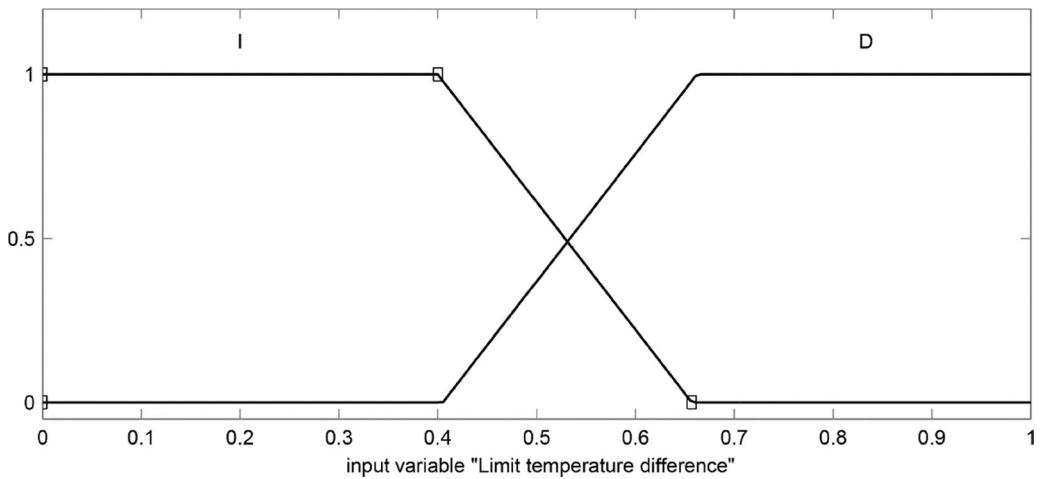


Fig. 7. MF of the terms of the linguistic variable “Boundary temperature difference”

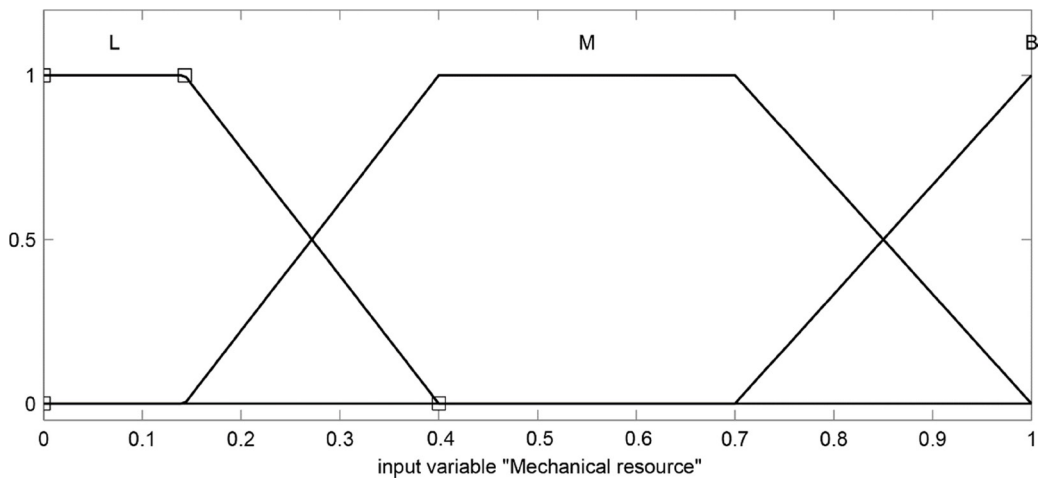


Fig. 8. MF of the terms of the linguistic variable “Mechanical resource”

We tested the model adequacy using the following practical example: at a Switchgear of 330 kV, the cell's devices were checked (CTr, disconnector D-01, disconnector D-02)

by means of infrared equipment. The examination result detected the heating of the device clamping and the disconnector's jaws (Fig. 11).

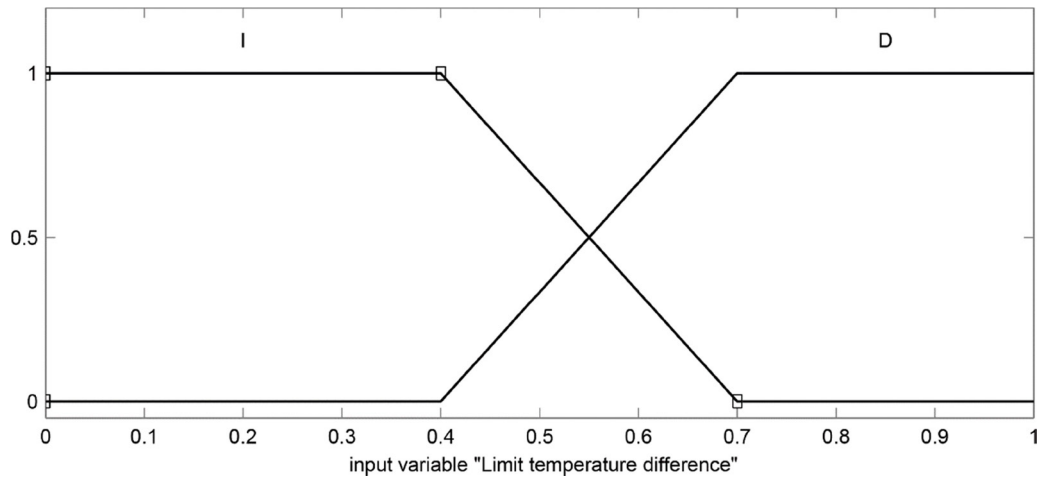


Fig. 9. MF of the terms of the linguistic variable “Boundary temperature difference”

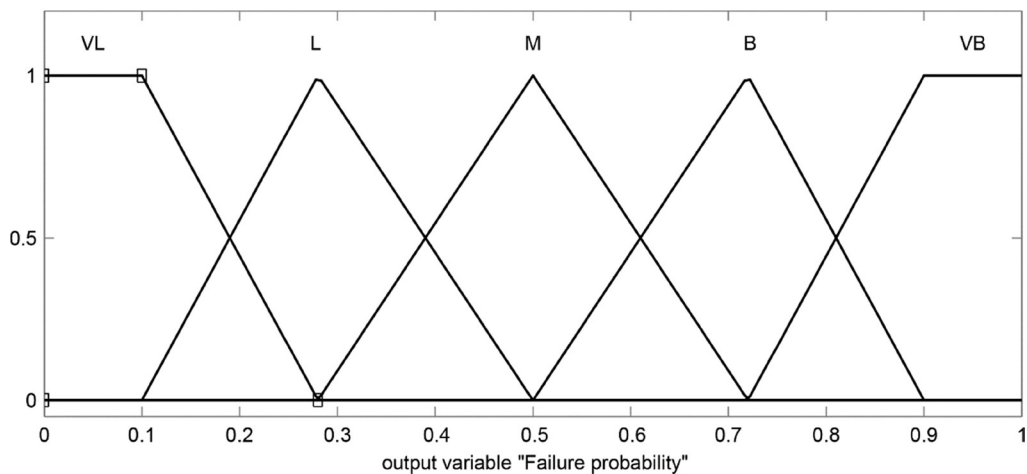


Fig. 10. MF of the terms of the linguistic variable “Failure probability”

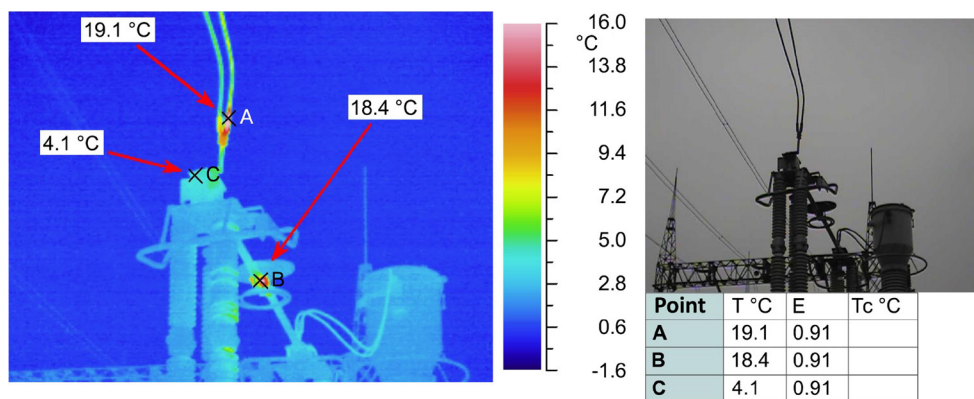


Fig. 11. Thermogram of the disconnector RNDZ–330U/3200

In the calculation, we used the parameter values obtained from the test data and preventive observations. The parameters are given in Tables 10, 11. The probability of a cell failure was calculated on the basis of the developed fuzzy model, implemented in the programming environment MATLAB Fuzzy Logic Toolbox; the results are shown in Fig. 1–14, and given in Table 12.

Table 10

Results of CTr tests

Value of insulation resistance, MOhm		Value of dielectric losses, %		Capacitance deviation, %		Excess temperature difference, °C	
Measured	Rated	Measured	Rated	Measured	Rated	Measured	Rated
8.5×10^4	10^4	0.18	≤ 0.6	1.2	$5 \pm$	0.5	2

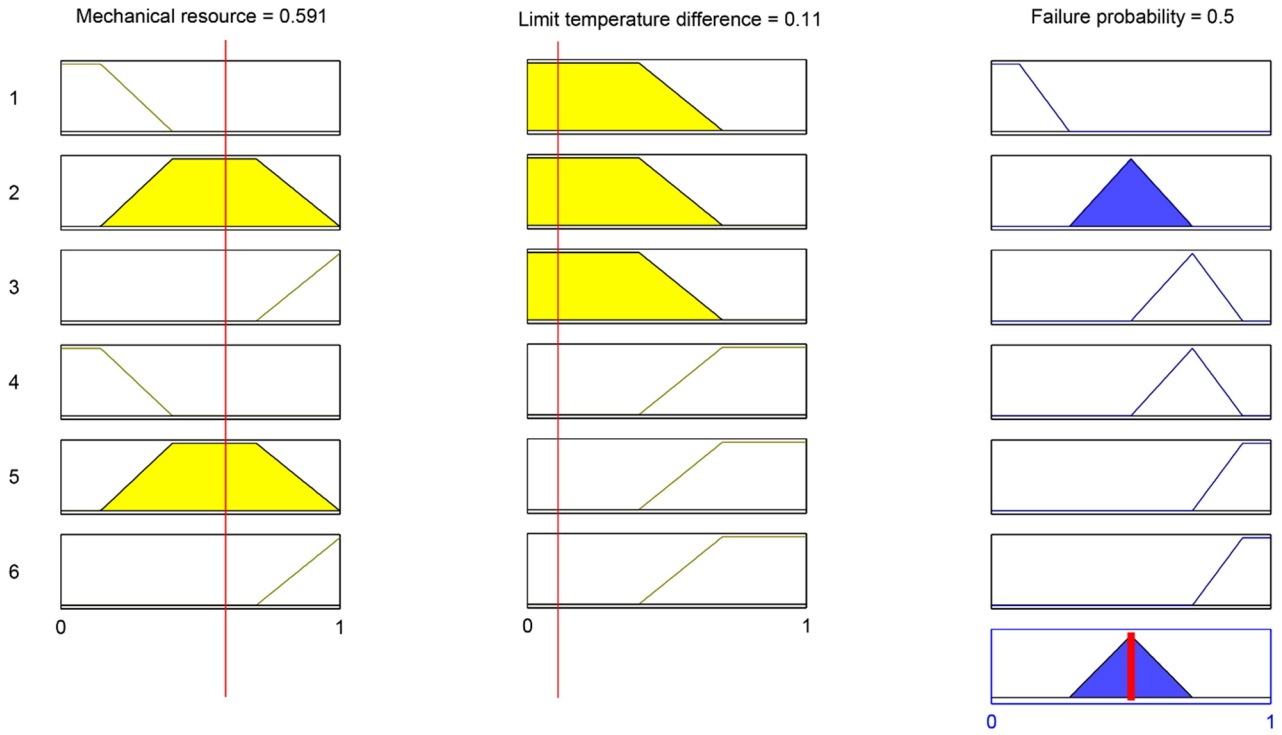


Fig. 12. Estimation of failure probability for disconnector D-01

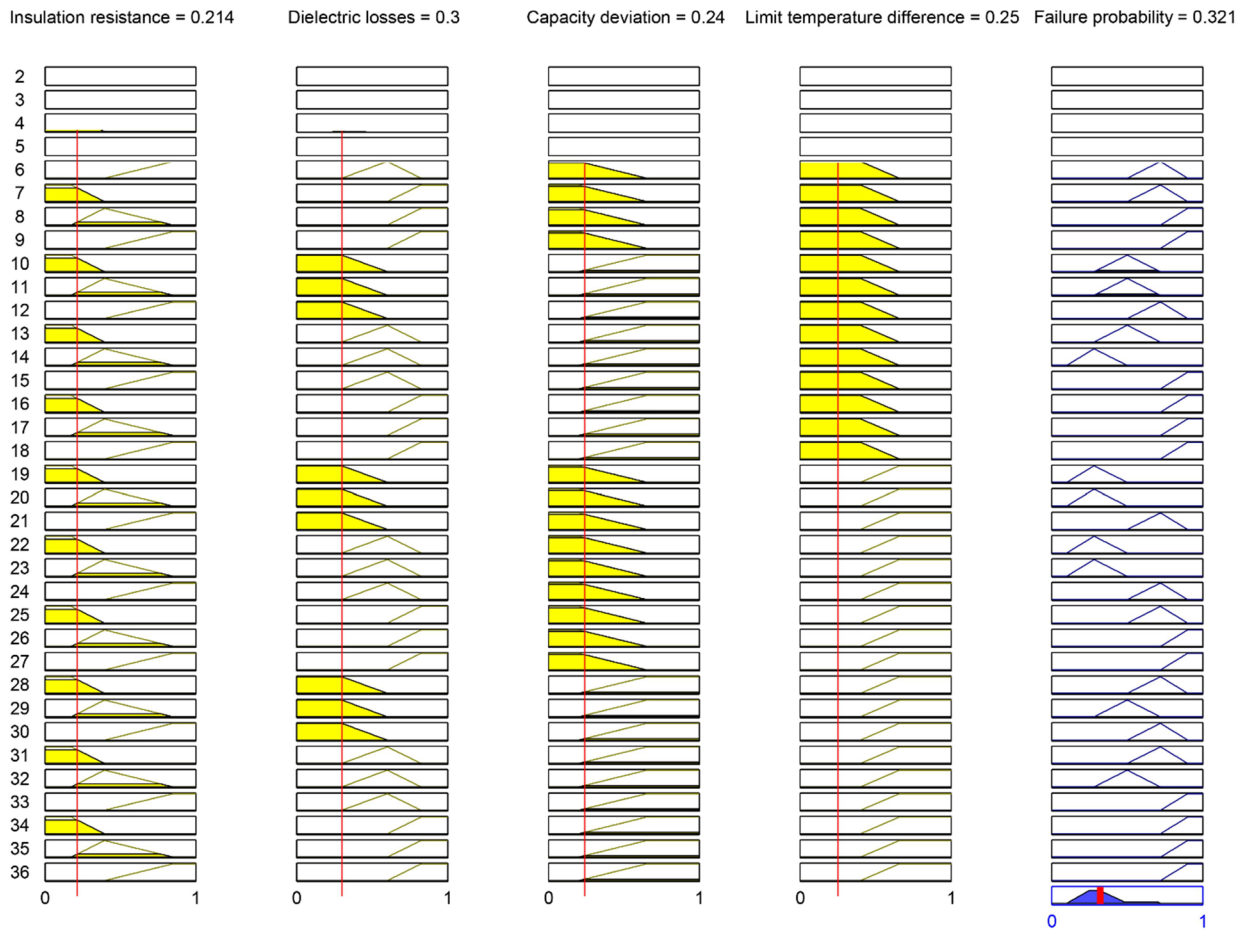


Fig. 13. Estimation of failure probability for CT

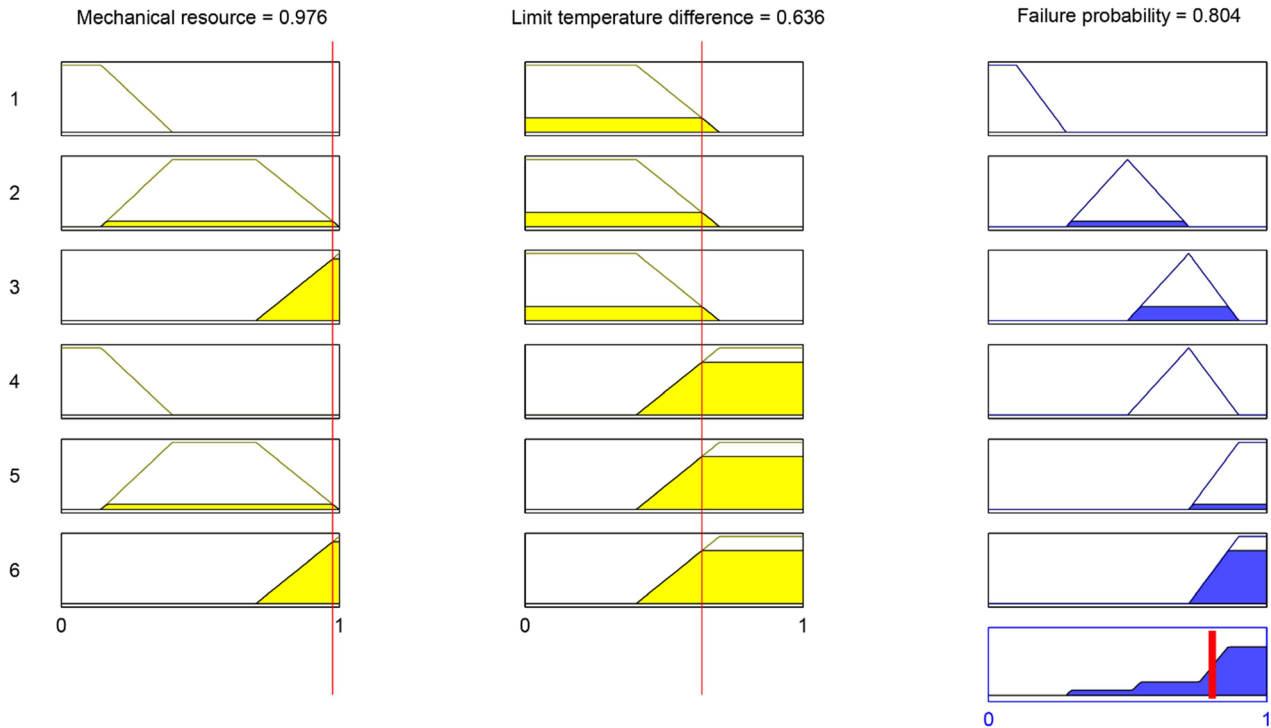


Fig. 14. Estimation of failure probability for disconnector D-02

Table 11

Results of disconnector observations

Disconnector D-01			
Used mechanical resource, units		Excess temperature difference, °C	
Measured	Rated	Measured	Rated
591	1,000	3.2	<30
Disconnector D-02			
Used mechanical resource, units		Excess temperature difference, °C	
Measured	Rated	Measured	Rated
976	1,000	19.1	<30

Table 12

Numerical values for a failure probability of CTr, disconnector D-01, disconnector D-02

S_{CTr}	S_{D-01}	S_{D-02}
0.321	0.5	0.804

Based on the developed fuzzy models, the following numerical values of the input and output variables were derived:

For CTr: insulation resistance – 0.214, dielectric losses – 0.3, capacitance deviation – 0.24, boundary temperature difference – 0.25, failure probability – 0.321.

For D-01: mechanical resource – 0.591; boundary temperature difference – 0.11; failure probability – 0.5.

For D-02: mechanical resource – 0.976; boundary temperature difference – 0.636; failure probability – 0.804.

5. Improvement of the expert model of determining a failure probability for an instrument transformer cell

The expert method produces an estimate only of the current TC of the investigated electrical equipment but it cannot

take into consideration the influence of such operational factors as the human factor, influence of meteorological conditions, the modes of a power system, etc. Such factors are accounted for by the statistical method of assessing the probability of electrical equipment failure based on the totality of all factors but it ignores the current state of the examined unit. Therefore, it is reasonable to combine these methods when studying the failure probability of an instrument transformer cell.

The probability of the occurrence of compliant events is determined as follows [23]:

$$Q\left(\sum_{i=1}^n A_i\right) = \sum_i Q(A_i) - \sum_{i,j} Q(A_i A_j) + \sum_{i,j,k} Q(A_i A_j A_k) - \dots + (-1)^{n-1} \sum_n Q(A_1 A_2 \dots A_n). \tag{6}$$

The probability of the occurrence of compatible events consisting of three elements is calculated as follows:

$$Q(A+B+C) = Q(A) + Q(B) + Q(C) - Q(AB) - Q(BC) - Q(AC) + Q(ABC), \tag{7}$$

where A is the probability of a CTr failure (S_{CTr});

B – a failure probability of disconnector D-01 (S_{D-01});

C – a failure probability of disconnector D-02 (S_{D-02}).

The value of a failure-free operation probability and a failure probability based on statistical data is determined according to [11]:

$$P(t) = \exp\left[-\int_0^t \lambda(t) dt\right], \tag{8}$$

where λ is the average failure intensity, year⁻¹; t is the disconnector work duration at the time of observation,

year; $P(t)$ is the value of an object's failure-free operation probability.

$$Q(t) = 1 - P(t), \tag{9}$$

where $Q(t)$ is the object's failure probability.

The failures of a CTr, the disconnectors D-01 and D-02 are the compatible events (one event does not exclude another), so the probability of a cell failure, based on the developed mathematical model, is equal to:

$$Q_{exp} = Q(A + B + C) = 0,933.$$

In order to determine the statistical probability of a CTr failure, we analyzed the fleet of current transformers of the following types: TFUM, TFKN, TRN, TFRM, with which the power system of Ukraine is equipped [24]. The analysis revealed that for the TFRM operated over 29 years, the value of a failure-free operation probability is 0.78. A diagram of the distribution of failure-free operation probabilities for a CTr of the TFRM type is shown in Fig. 15.

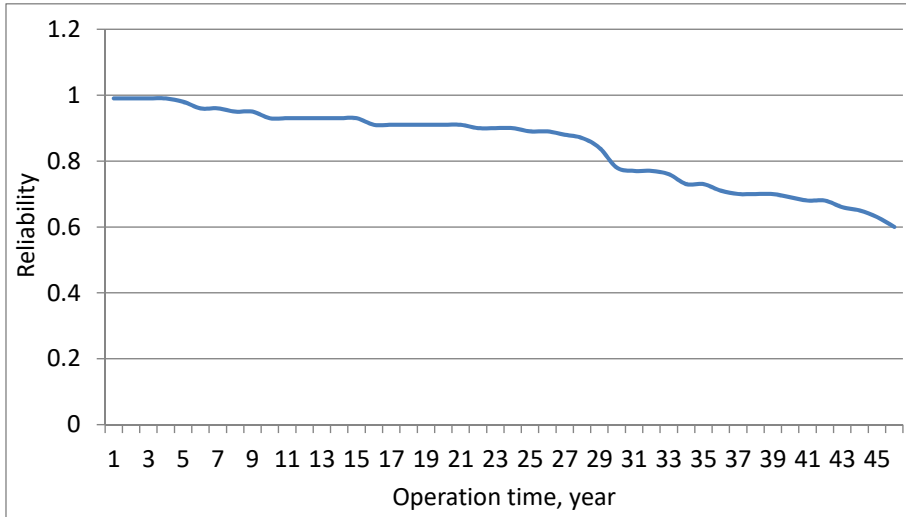


Fig. 15. Distribution of failure-free operation probabilities for a CTr of the TFRM type

A statistical failure probability for the disconnector RNDZ-330U/3200, in operation since 1993, is determined in accordance with (7, 8). According to [25], the average failure probability for disconnectors $\lambda = 0.0166 \text{ year}^{-1}$.

$$Q(t) = 1 - \exp\left[-\int_0^{t=26} 0.0166 dt\right] = 0.351.$$

The failure probability of an instrument transformer cell, based on statistics, is calculated as follows:

$$Q_{stat} = Q(A + B + C) = 0.672.$$

A posteriori failure probability of an instrument transformer cell under the conditions defined by the expert and statistical methods is determined from the Bayesian formula [26]:

$$Q_{apost} = \frac{Q_{stat} \cdot Q_{exp}}{Q_{stat} \cdot Q_{exp} + P_{stat} \cdot P_{exp}}, \tag{10}$$

where Q_{stat} is the value of *a priori* probability of a cell failure (determined by the statistical method);

P_{stat} is the value of *a priori* probability of a cell failure-free operation (determined by the statistical method);

Q_{exp} is the value of the relative probability of a cell failure (determined by the expert method);

P_{exp} is the value of the relative probability of a cell failure-free operation (determined by the expert method).

The results of calculations according to expressions (7) to (10) are given in Table 13.

Table 13

Results of calculating the failure probability of an instrument transformer cell

A priori probability		Conditional probability (based on the developed model)		A posteriori probability
P_{stat}	Q_{stat}	P_{exp}	Q_{exp}	Q_{apost}
0.328	0.672	0.067	0.933	0.966

The result of the calculations (Table 13) is the following derived values: based on statistical data, *a priori* failure probability (Q_{stat}) of the cell and a failure-free operation (P_{stat}) of the cell; based on the expert model, a conditional failure probability (Q_{exp}) of the cell and a failure-free operation (P_{exp}) of the cell; a corrected failure probability due to external disturbances (Q_{apost}).

6. Discussion of results of estimating the failure probability of an instrument transformer cell using an expert-statistical method

We have developed an expert-statistical method for estimating the failure probability of an instrument transformer cell.

According to [18], the object of our study was considered as a system with several inputs and one output. In addition, the method takes into consideration both the current vector of state variables and the influence of external disturbances. However, unlike the diagnostic parameters proposed in [18], underlying the control of a TC of electrical equipment, this paper considers the most informative ones [21, 22]. Although control over these parameters has already been implemented in the global electric power systems, there are no models of the comprehensive estimation of a TC of devices based on these parameters.

To solve the task of the comprehensive estimation of a TC of an instrument transformer cell's devices, we applied a method of fuzzy modeling engaging the expert knowledge. Based on the built fuzzy models (Fig. 12–14), according to (2) to (5), we have determined the numerical value of the failure probability for devices in the cell of one of the objects in a power supply system.

The expert fuzzy model has been improved by considering the influence of external disturbances. We have analyzed the retrospective information (Fig. 15) and reference data [25] on the operation of the appropriate type of elec-

trical equipment included in the cell. The numerical values of a failure probability considering the external disturbances have been derived. In contrast to existing methods that forecast the resource of electrical equipment, the developed model, according to (6), takes into consideration the influence of each device on the probability of a cell failure in general. Based on the derived numerical data (Table 12), and, according to (6) to (10), we have comprehensively determined the failure probability of an instrument transformer cell (Table 13).

The data from a periodic thermal imaging examination of the cell's devices at Switchgear 330 kV revealed the heating of the device clamp in a support column (Fig. 11) of disconnecter D-02, but the temperature value did not make it possible to disable the line for an emergency. According to the data from a periodic thermal imaging examination, based on normative documentation (Table 13), the probability of a cell failure at the time of observation was $Q_{D-02}=0.636$. At the same time, we estimated at Switchgear 330 kV the failure probability of an instrument transformer's cells according to the developed expert and statistical model. We acquired information about the diagnostic parameters of the devices (Tables 10, 11) in the examined cell. Based on these parameters, the failure probability was $Q_{apost}=0.966$, which meant the emergency state of the equipment. The results of the calculation were confirmed by further events: during the operative switching, the support column of disconnecter D-02 broke down causing damage to CTr. The accident resulted in that the cell and the line were disabled for the time of repair and equipment replacement.

As one can see from the example, an error in forecasting a cell resource based on a single parameter (thermal imaging) was $\Delta_{f(D-02)}=1-Q_{D-02}=0.364$, or 36.4 %. When applying the expert-statistical model for determining the probability of a cell failure, the error was $\Delta_{f(D-02)}=1-Q_{apost}=0.034$, or 3.4 %. The advantage of the developed model over those proposed in [1–6, 10–15] is predetermined by taking into consideration the influence of a TC of each piece of equipment of the cell on a failure probability, and by the integrated assessment of controlled diagnostic parameters that influence the TC. This leads to the higher accuracy of the forecast, in compar-

ison with existing methods of current control over the TC of electrical equipment.

A limitation of this study is that the construction of a fuzzy expert model requires the selection of specialists with a certain qualification, experience, knowledge in the field of diagnosing electrical equipment of the corresponding type. In addition, when improving a mathematical model, it is necessary to acquire reliable retrospective information, or reference data, about the operation of the devices of this type. It is advisable to use the retrospective information, if available, about the equipment of the power system being examined, to account for the patterns in local conditions.

7. Conclusions

1. We have improved an approach to forecasting the resource of electrical equipment using an example of instrument transformers' cells. The difference between the proposed approach and those existing ones is taking into consideration the influence of a TC of each piece of equipment, which is part of the cell, on the probability of its failure. To determine the TC of the cell's devices based on the main diagnostic parameters [21, 22], we have developed fuzzy mathematical models. A fuzzy model makes it possible to determine the failure probability of a device by integrating those diagnostic parameters that are different in nature (electrical, thermal, mechanical), which affect the TC of equipment. A special feature of fuzzy model development is to use the knowledge of experts of appropriate qualifications with certain experience in the field of electrical equipment diagnosing.

2. To account for external disturbances [18], the expert model was improved by correcting using statistical data on the functioning of a specific type of equipment of the cell. Approbation of the model when using actual electrical equipment of a power system has demonstrated the higher reliability of the resource forecast of DDHV cells. When examining the cell of an instrument transformer, the error from the developed model was 3.4 %, in contrast to the results of the current control, which was 36.4 %.

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