Mathematical model of estimation of technical condition and prediction of emergency modes of power equipment of power plants using example of power transformer

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Abstract. This paper analyzes the existing regulatory indicators of the technical condition of power transformers. Causal relationships between measurable parameters and defects in the transformer have been studied to identify vulnerabilities and likely scenarios for an emergency. The technical condition of the transformer was assessed using the method of pairing comparisons. The probability of trouble-free operation of functional nodes and transformer in general has been determined. The impact on all transformer systems in determining its lifespan of congestion and short-circuit currents by introducing congestion ratios has been taken into account.

Introduction

Damage to power transformers in power plants and substations has a significant impact on the reliability of power supply in general. Therefore, the timely detection of developing defects in power transformers is an important task and can be used in modern monitoring systems for indicators of the technical condition of electrical equipment.

Currently, a continuous assessment of the technical condition of power transformers is carried out according to a set of monitored indicators and their normalized values, fixed in RD 34.45-51.300-97 Scope and standards of electrical equipment testing [1]. These measures showed quite good efficiency when used in the process of periodic and scheduled tests during operation of power plant equipment. In this case, the most promising from the point of view of increasing the efficiency of the repair process is the optimization of the overhaul interval. This task is relevant not only in the case of equipment operating within the normal service life, but even more so for worn-out equipment, when the probability of damage to it increases. In addition, in conditions when the equipment is operating at the limit of its service life, non-standard situations may arise associated with the simultaneous occurrence of several damages. In this case, the personnel need to quickly respond to the situation and adequately decide on the need for a preventive or other type of repair. It should be understood that personnel have to work fundamentally in non-standard or even critical conditions in the presence of uncertainty in the initial information to assess the causes and nodes that have suffered damage. It is possible to use expert assessments, but it is not always possible to attract experts from outside, and the number of universal highly qualified specialists who are able to obtain a solution quickly and efficiently based on the available information, unfortunately, is steadily decreasing. that personnel have to work fundamentally in non-standard or even critical conditions in the presence of uncertainty in the source information to assess the causes and nodes that have suffered damage. It is possible to use expert assessments, but it is not always possible to attract experts from outside, and the number of universal highly qualified specialists who are able to obtain a solution quickly and efficiently based on
the available information, unfortunately, is steadily decreasing. That personnel have to work fundamentally in non-standard or even critical conditions in the presence of uncertainty in the source information to assess the causes and nodes that have suffered damage. It is possible to use expert assessments, but it is not always possible to attract experts from outside, and the number of universal highly qualified specialists who are able to obtain a solution quickly and efficiently based on the available information, unfortunately, is steadily decreasing.

In this case, it becomes relevant to install continuous diagnostics systems on the main equipment of power plants and substations, which allow not only to monitor the current state of the equipment by taking the main parameters, but also to take on the main routine of primary processing of the measured results, up to its storage, comparison with regulatory or passport parameters for this equipment. As a result of such diagnostics, it becomes possible to carry out preventive repairs as necessary, which directly affects the reliability of electrical equipment and corresponds to the maintenance strategy for the actual condition.

Recently, a directly related to this strategy is the task of assessing the residual resource of electrical equipment, promising from the point of view of increasing the reliability of its operation. This task is complicated by the fact that, on the one hand, it is impossible to carry out type tests on working equipment in the full scope that is fixed by RD 34.45-51.300-97, on the other hand, even if we assume that this has become possible, the task of simultaneous analysis arises a large amount of information at each current point in time. In addition, it should be noted that since objects such as transformers are complex systems, it is therefore difficult to determine a clear causal relationship between the readings and possible damage that may arise.

Based on the foregoing, the objectives of this study are: to study the causal relationship between the measured parameters and defects in the transformer to identify vulnerabilities and possible scenarios for the development of an emergency, and then on this basis the construction of a mathematical model that allows the formation of an intelligent expert system of functional diagnostics and assess the degree of damage to equipment.

To identify the cause-effect relationship between the processes occurring in the transformer, it was divided into functional subsystems, in each of which the main nodes were identified. The processes occurring in these nodes were considered, not only from the point of view of the internal functional relationship between the individual elements, but also the physical phenomena during operation were taken into account, as well as the influence of external factors on the development of the emergency. As a result of the analysis, fault trees of the main functional subsystems of the transformer were built: the main conductive system - windings (Figure 1), oil supply and insulation system (Figure 2), magnetic circuit (Figure. 3), on-load tap-changer system (Figure 4), inputs with solid insulation (Figure 5), a cooling system (Figure 6), and separately, an oil damage system, i.e.
A characteristic feature of the constructed trees is that not only individual nodes were introduced into the system, affecting the performance of the subsystem as a whole, but also physical processes connecting them together, for example, electrodynamic loads, the appearance of circulating currents. In addition, on the same trees, one can trace the influence of external factors, such as the effect on the windings of overload currents or emergency short-circuit currents, the occurrence of asymmetric operating modes. The dynamics of the development of an emergency can be traced by enhancing
individual impacts during the development of the defect, which is reflected by the introduction of positive feedback branches.

Figure 3. Transformer Magnet Failure Tree

It should also be noted that all the trees are interconnected to a greater or lesser extent, which, in turn, shows the complexity of the processes and their interdependence. For example, the trees in Figures 1 and 2 are interconnected by elements that take into account the processes of gas evolution in the oil, overheating of the winding, damage (violation) of the chemical composition of the oil. The
trees in Figures 2 and 6 are interconnected by elements that take into account overheating and damage to the chemical composition of the oil, overheating of the winding, damage to the heat exchange of the radiator tubes and slowing down the circulation of oil. Thus, in almost every functional unit, intensively proceeding processes arising due to the rapidly developing emergency scenario can be distinguished. In a conductive system (windings) and transformer inputs, these are processes due to overload and short circuit. In the transformer magnetic circuit, these are the processes of dynamic action on the fastening elements during the flow of short circuit currents. In the on-load tap-changer system, these are processes associated with mechanical damage to the contacts and violation of the insulating properties of the oil.

![Fault Tree](image)

**Figure 4. Transformer on-load tap-changer system fault tree**

To assess the technical condition of the functional subsystems and the transformer as a whole, there is a set of performance criteria that are obtained by calculation and are compared with the results obtained for the corresponding parameters of the controlled subsystems as a result of monitoring. These key indicators include the index of the technical condition of the functional unit and the index of the technical condition of the equipment [2].
Each functional unit in the device in question has its own significance or relative importance in the composition of the equipment in question, which, in turn, can be estimated by the weight coefficient. The weight coefficient for each group of measured or calculated parameters can vary from 0 to 1. We define it by the method of analysis of hierarchies.

To obtain a strictly mathematically sound value of the weighting coefficients, we will use their choice based on pairwise comparison. The ranking of the criteria can be linear when the compared criteria $K_2, K_3, \ldots K_n$ are aligned with respect to the most important criterion $K_1$ according to the degree of importance in accordance with the inequality:

$$K_1 > K_2 > K_3 > \ldots > K_n.$$  \hspace{1cm} (1)

A partially linear ranking option is also possible, when some of the criteria have the same importance indicator, i.e. are related:

$$K_1 > K_2 = K_3 > K_4 > \ldots > K_n.$$  \hspace{1cm} (2)

According to [3], various approaches to calculating the weighting coefficients of the criteria are possible when using the conditions with the floating preference approach. To do this, calculate the importance indicators of each of the criteria $K_i$ in relation to the criterion $K_j$: 

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**Figure 5.** Fault Tree Input System with Solid Transformer Insulation
\[ K_i = \sum_{j=1}^{n} K_{ij}, \]  

where \( i = 1, 2, ..., n; j = 1, 2, ..., n. \)

Then calculate the total indicator of the importance of all the criteria:

\[ K_\Sigma = \sum_{i=1}^{n} K_i \]  

and weighting criteria:

\[ \alpha_i = \frac{K_i}{K_\Sigma}. \]  

then check the condition for normalizing the criteria by the formula:

\[ \sum_{i=1}^{n} \alpha_i = 1. \]  

Figure 6. Transformer Cooling System Failure Tree
We will complete the pairwise comparison matrix using a universal approach based on a weak preference for criteria. When using this approach to a pairwise comparison of criteria, all diagonal elements of the matrix should be equal to unity, and the remaining elements of the matrix should be assigned the values of $K_{ij}$ as follows:

$$K_{ij} = \begin{cases} 1 + h, & \text{if } K_i \text{ is more important than } K_j \\ 1 - h, & \text{if } K_i \text{ is more important than } K_j \\ 1, & \text{if } K_i \text{ and } K_j \text{ are equally important} \end{cases} \quad (7)$$

In this case, the condition $K_{ij} + K_{ji} = 2$ at $i \neq j$ and $0 < h < 1$.

As a result, criteria importance indicators $K_i$ are members of arithmetic progression in increments $\Delta = h - (-h) = 2h$. Using the exponent $h$, one can establish a fixed, constant difference between the preference indices of the criteria of a linearly ranked series. Depending on the value of $h$, this difference can be: very weak, weak, moderate, noticeable, strong, very strong. We select a weak preference for the criteria, the calculation results are entered in table 1.

Table 1. The values of the weights of the functional subsystems of the transformer, obtained by the method of weak preference criteria

| Name of the functional subsystems of the transformer | Linear ranking | Weights according to the weak criteria preference method |
|-----------------------------------------------------|----------------|--------------------------------------------------------|
| Oil                                                 | 7              | 0.2381                                                 |
| Oil supply system and insulation system             | 6              | 0.2064                                                 |
| Inputs                                              | 5              | 0.1746                                                 |
| ConductiveWindingSystem                             | 4              | 0.1428                                                 |
| On-loadtap-changer                                  | 3              | 0.1111                                                 |
| Coolingsystem                                       | 2              | 0.0794                                                 |
| Magnetic core                                       | 1              | 0.0476                                                 |

In order to assess the technical condition of the transformer, it is necessary to obtain the results of a diagnostic study of the functional units under consideration, which are evaluated on a 100-point scale, and based on it, calculate the technical condition index (ITS) of the equipment of both individual nodes (Table 2) and the entire device in whole:

$$\text{ITS} = 20 \times 0.2381 + 16 \times 0.2064 + 12 \times 0.1746 + 8 \times 0.1428 + 8 \times 0.1111 + 5 \times 0.0794 + 5 \times 0.0476 = 76.2705$$ \quad (8)

Table 2. Indices of technical condition for functional subsystems and the entire transformer as a whole

| Name of the functional subsystems of the transformer | Rating state of functional units, score | Weights | Index of the technical condition of the functional units of the transformer, score |
|-----------------------------------------------------|----------------------------------------|----------|----------------------------------------------------------------------------------|
| Butter                                              | 85                                     | 0.2381   | $85 \times 0.2381 = 20.2385$                                                    |
| Oil supply system and insulation system             | 80                                     | 0.2064   | $80 \times 0.2064 = 16.512$                                                     |
| Inputs                                              | 70                                     | 0.1746   | $70 \times 0.1746 = 12.222$                                                     |
| ConductiveWindingSystem                             | 60                                     | 0.1428   | $60 \times 0.1428 = 8.568$                                                      |
| On-loadtap-changer                                  | 80                                     | 0.1111   | $80 \times 0.1111 = 8.888$                                                      |
| Coolingsystem                                       | 70                                     | 0.0794   | $70 \times 0.0794 = 5.558$                                                      |
| Magnetic core                                       | 90                                     | 0.0476   | $90 \times 0.0476 = 4.284$                                                      |
According to the results of calculations of the ITS obtained in table 2, in accordance with the methodology [2], the condition of the transformer under consideration is assessed as good.

The calculation of the reliability of the transformer, allowing to assess the likelihood of its failure-free operation, can also be performed using the weight coefficients obtained in the calculation of ITS. Considering that in the reliability structural diagram all the nodes of the subsystem are connected in parallel and contribute to the reliability of the functional node in accordance with their weight coefficient, we obtain an expression for the probabilities of failure-free operation of the i-th functional node and the transformer as a whole:

\[ P_{FUi} = e^{-\lambda_i \alpha_i t} \]  \hspace{1cm} (9)

\[ P_T = e^{-\lambda_T \Sigma \alpha_i t} \]  \hspace{1cm} (10)

where \( P_{FUi} \), \( P_T \) - the probability of failure-free operation of the i-th functional unit and the transformer as a whole;

\( \lambda_T = 2.3 \times 10^{-6} \text{ h}^{-1} = 0.02 \text{ g}^{-1} \text{ const} \) is the failure rate of the transformer [4];

\( \alpha_i \) - weight coefficient of the i-th functional unit; \( \Sigma \alpha_i = 1 \);
\( t = 8760 \text{ h} \) - the considered period of time.

The results of the calculation of reliability taking into account weight indicators are presented in Table 3.

| Name of the functional subsystems of the transformer | Weights \( \lambda_i \times a_i \times 10^{-6} \text{ h}^3 \) | Uptime probability of function node | Transformer uptime probability |
|--------------------------------------------------|------------------------------------------------|-------------------------------------|-------------------------------|
| Butter                                           | 0.2381                                          | 0.9952                             |                               |
| Oil supply system and insulation system           | 0.2064                                          | 0.9958                             |                               |
| Inputs                                           | 0.1746                                          | 0.9965                             |                               |
| Conductive Winding System                        | 0.1428                                          | 0.9971                             | 0.98                          |
| On-loadtap-changer                               | 0.1111                                          | 0.9978                             |                               |
| Coolingsystem                                    | 0.0794                                          | 0.9984                             |                               |
| Magnetic core                                    | 0.0476                                          | 0.99904                            |                               |

**Conclusions.** In this paper, we analyze the existing normatively fixed indicators of the technical condition of power transformers, on the basis of which failure trees are constructed that allow us to consider the processes occurring in the transformer nodes, not only from the point of view of the internal functional relationship between the individual elements, but also taking into account the physical phenomena occurring in system during its operation, as well as the influence of external factors on the development of an emergency. The technical condition of the transformer was evaluated using a specific example using the method of pairwise comparisons. The probability of failure-free operation of functional units and a transformer for a year of operation is determined. As follows from the analysis, the most significant influence on all transformer systems is overload and short circuit currents.

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**References**

[1] STO 34.01-23.1-001-2017 Scope and standards of testing of electrical equipment Organization standard.

[2] The methodology for assessing the technical condition of the main technological equipment and power lines of electric stations and electric networks, approved by orderMinistry of Energy of Russia07/26/2017 N 676.

[3] Spiridonov SB, Bulatova I.G., Postnikov V.M. Analysis of approaches to the selection of weighting coefficients of criteria by the method of pairwise comparison of criteria // Internet journal "SCIENCE" Volume 9, No 6 (2017) https://naukovedenie.ru/PDF/16TVN617.pdf (free access).

[4] M. A. Baydyuk, G. V. Komarova Assessment of the technical condition and reliability of electric machines.News SPbGETU "LETI" No. 3/2019.