Development of a power transformer residual life diagnostic system based on fuzzy logic methods

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Abstract. The existing methods of diagnostics and control of a power transformer residual life have been studied. The results of developing a new diagnostic system, which is introduced into a tree structure of the automated system for monitoring and control of transformers and implemented via the data mining of errors based on fuzzy logic, are presented. Operating with fuzzy sets and introducing linguistic variables, an algorithm was created using a tree structure, which is translated into a program code. The system operation principle is shown using the selected diagnostic parameters of a power oil transformer.

1. Introduction
The economic feasibility and performance reliability of the electrical network, power plants and power-supply systems to a greater extent depend on the operation of power transformers [1, 2]. Failures during operation or emergency shutdowns of power transformers result to financial losses, associated both with the need to restore the transformer, and with an interruption in the power supply to consumers [3–5]. Currently, there are hardware and software complexes, by virtue of which unit transformers testing is carried out, thereby it is possible to adjust the routine inspection schedule [6, 7].

From structural standpoint, the complexes are represented by the following levels:
- level 1 (information collection level) – the executors are primary sensors and measuring systems, located on transformer equipment with various types of interfaces and protocols;
- level 2 (primary information processing level) – formation of control commands of the cooling system, data exchange with higher storage levels using a PLC;
- level 3 (consolidation, storage and visual inspection of data) – is an automated workplace of the operator, providing the implementation of the following functions: mathematical transformation and integrated transfer of information to other automated control systems of the power facility, remote control of the object, visual inspection of the calculated and observable parameters of the transformer system, controlling work with the information collected in log books and archives.

Currently, two main types of power transformers faults can be specified: electrical damage and mechanical defects [8, 9]. The first type of faults includes inter-winding faults, lamination insulation breakdown, damage to the circuit of the transformer core, etc. The following can be referred to mechanical defects: damage to the housing, mechanical wear, fatigue processes, loosening of bolted connections, seal failure of the cooling system, breakdown of the fan or cooling pump, sludge formation and oil contamination in the overflow tank, etc.

In [10] it is discussed that in the absence of applying equipment diagnostics, the probability of an increase in the number of failures runs up to 20% instead of 1% and even less, as far as it can be stated...
to date. The purpose of equipment technical condition diagnostics can be divided into three types of tasks. The most commonly used type of task is determining the technical condition of the system as of specific moment of time. The second type of task is forecasting, calculating the technical condition for the future. The third type (genesis) involves determining the technical condition for the time interval from the past.

2. Algorithm of a transformer diagnostic system based on fuzzy logic
The authors consider the algorithm for processing signals from the sensors of the transformer TDTN-63000/110. The state of the power transformer is controlled according to 16 parameters (Table 1). Figure 1 shows a diagram of diagnostic algorithm for detecting a defect. The use of conditions within blocks allows determining, to which range the value of one or another parameters belongs to. According to the flow diagram, testing for compliance with the operating state range begins upon completion of the parameters measurement. In case of incompliance, the defect is determined during further testing of this parameter. In case of compliance with the range of operating technical condition of the parameters, the next parameter is processed.

![Flowchart of data processing algorithm](image)

**Figure 1.** Data processing algorithm
The proposed diagnostic system is implemented with data mining of errors when diagnosing a transformer, using the rule base of implicit logic. The algorithm of this type involves operands of fuzzy sets, introduces linguistic variables, following that, the data presentation is translated into a program code for processing incoming data.

Implicit set $A$ has implicit boundaries of its membership area. When $x$ goes from one set to another, the membership changes smoothly.

The implicit set is determined through paired aggregates and is defined by formula

$$A = \frac{\mu_A \cdot x}{x}$$  \hspace{1cm} (1)

The characteristic function $\mu_A \cdot x$, equals to 1, when the characteristic attribute $R$ refers to $x$, and 0 in the opposite case, if $x$ does not satisfy this property. The membership function $\mu_A$ expresses (from 0 to 1) to what extent the element $x$ belongs to the subset $A$.

When building a graph to implement an implicit algorithm, the following rules were established. Lines denote portions of a fuzzy algorithm that do not contain conditional implicit operators, and nodes in the algorithm to which arcs are connected, denote conditional implicit operators. The beginning of each algorithm comprises a node that gives rise to the arc, wherein it does not include other arcs.

Each branch emerged from the node, is limited by a new conditional operator, obtaining control from the previous branch operator, or by the end of the algorithm. Such an implicit operator generates a new branch after processing the previous incoming ones. When branches move off the first node, they are limited by the next conditional operator, which performs the functions from two incoming ones and generates a new branch, or ends the algorithm [11–13].

3. Using Matlab software and fuzzy inference result processing

The authors designate 16 sensor parameters to control the state of the transformer TDTN-63000/110 and build a tree structure for the power transformer. For input, let us express the vector $x$ of diagnostic features as follows:

$$x = [x_1, x_2, \ldots, x_n]$$  \hspace{1cm} (2)

Designations, diagnostic parameters and measurement ranges for the vector $x$ are given in table 1.

![Figure 2. Structural hierarchy diagram of fuzzy inference for a power transformer; $x_1$–$x_{16}$ - input diagnostic factors of the system; $y_1$ - intermediate parameters; Q - system output](image)

**Table 1.** Selection of parameters for calculating the residual life of a power transformer
| Designation | Diagnostic parameters | Measurement ranges of input values |
|-------------|-----------------------|------------------------------------|
| $x_1$       | Insulation idling current, % of rate | 0 - 0.3 |
| $x_2$       | Idling losses, kW | 0 - 0.15 |
| $x_3$       | Turn insulation wear coefficient | 0 - 1 |
| $x_4$       | Generalized diagnostic parameter of turn insulation | 0 - 0.1 |
| $x_5$       | Turn insulation idling losses, kW | 0 - 0.5 |
| $x_6$       | Insulation resistance of the winding relative to the housing, MOhm | 0 - 1 |
| $x_7$       | Temperature of the most heated point of winding insulation, °C | 0 - 140 |
| $x_8$       | Oil temperature, °C | 0 - 140 |
| $x_9$       | Oil pressure, kPa | 1 - 1.2 |
| $x_{10}$    | Ohmic resistance of contacts, MOhm | 0 - 0.025 |
| $x_{11}$    | Contact pressure, kgf | 4 - 7.5 |
| $x_{12}$    | The presence of defects and damage to the tank | 0 - 1 |
| $x_{13}$    | Capacitive input current, A | 0 - 1 |
| $x_{14}$    | Input insulation resistance, MOhm | 0 - 500 (500 low level of damage) |
| $x_{15}$    | Input temperature, °C | 95 - 140 |
| $x_{16}$    | Input temperature, °C | 60 - 95 |
| $y_1, y_2, y_3, y_4, y_5,$ | Enlarged influencing factors |
| $y_6, y_7, y_8, q_1, q_2,$ |
| $q_3, q_4, q_5, q_6$ |
| $Q$         | Tree root |

To determine the residual life of a power transformer using fuzzy logic, let us apply the MatLab Fuzzy Logic Toolbox software environment. By virtue of the tree branches, connected according to the hierarchy, the implicit output of the result is performed. The function starts by calling 16 inputs with discrete values, the parameters $x_1$-$x_{16}$ acquire the specified values. The values of the factors from $x_1$ to $x_{16}$ can be presented as a term: 'H' - low; 'HC' - below average; 'C' - medium; 'BC' - above average; 'B' - high. The operation in the graph node is performed by the Gaussian membership function when a logical inference emerges with implicit input data. Next, the assessment of the membership of one implicit subset to others is determined.

Figure 3 presents a sample of the working window of the knowledge base compilation using Fuzzy Logic Toolbox.

In the created program, it is possible to consider any number of input factors to determine the residual life of a power transformer. Figure 4 presents a preliminary result of the operation of a fuzzy simulation system of the residual life of a power transformer depending on influencing factors over time.

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Figure 3. Fuzzy knowledge base for $y_8$ and Rule Editor knowledge base of fuzzy system for $y_8$

Figure 4. Change in the residual life of a power transformer over time

4. Conclusion
The main results of the work:
1. The main types of faults and failures for a three-phase power transformer have been considered.
2. Based on the analysis of faults and failures, diagnostic features were selected and the list of monitored parameters was prepared. The schemes of cause-and-effect relations of faults, diagnostic features and parameters were constructed.
3. The principle of constructing a graph model for determining the state of a power transformer has been developed.
4. A methodology for assessing the residual life of a power transformer has been developed.
5. The examples of the practical application of the methodology for assessing the state of a transformer have been presented. The result is represented in the form of the dependence of the change in residual life on the selected parameters.

The algorithm based on fuzzy logic allows processing data from sql-file of data on the operation of a transformer over some time [14]. The time interval of unstable operation of a power transformer is allocated; the data from the period are used to build a model of an artificial neural network using the Matlab software: data collection, preliminary processing (normalization and randomization), network
build-out, its training and performance testing. This network is applied for diagnostics and predicting the values of the parameters and technical condition of the transformer.

The analysis of the diagnostic tools and the determination of the residual hours of a power transformer allows the conclusion that the existing techniques are aimed at identifying the defect that has already arisen. The proposed methodology allows the implementation of an automated system for predicting the occurrence of a defect and breakdown of a power transformer in the future.

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