Expert system for predicting the state of transformers based on fuzzy logic

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Abstract. The article examines methods for monitoring the operation of oil-filled transformers and identifies methods for evaluating the state of the transformer using a fuzzy logic device. Solutions for remote analysis of transformer operation have been formed. The methods that were used for diagnostics are presented. Conclusions are drawn on which equipment is more effective for diagnostics of power transformers.

1. Introduction
Currently, substations use physically and morally outdated equipment, which can lead to failures and loss of electricity for consumers. One of the most important basic elements of TP electrical equipment is a power transformer. Its repair in case of damage is associated with a large expenditure of labor and money. Emergency foci occur primarily due to long-term operating time and significant physical wear and tear.

2. Materials and methods
An expert system for predicting the state of transformers based on fuzzy logic should solve a number of tasks aimed at improving the accuracy of the diagnostic result. The sequence of actions of the system is presented as follows:

- Processing of the survey results;
- Comparison procedure with the results of previous diagnostics in different operating modes;
- The calculation procedure of the fuzzy data in numerical format;
- The final output.

One of the main advantages of an expert system based on fuzzy logic is the ability to represent the knowledge base using a linguistic language. Thus, the database can be supplemented, expanded, and edited by a human expert without appropriate programming training. The introduction of additional characteristics, of course, will require special knowledge in this area, but working with existing characteristics is possible at a simpler level [1-2]. Based on the results of the system, a report is generated that describes each analyzed situation from the fuzzy knowledge base, shows the results of mathematical processing of diagnostic data, and
indicates the numerical values of the degree of confidence for each answer to the questions asked to the system.

Because the diagnostic features are random, the system uses modified functions based on the Gaussian membership function:

$$\mu(u) = \exp \left( - \frac{(u - b)^2}{2c^2} \right)$$

where: \(u\) is the abscissa, \(b\) is the maximum coordinate, and \(c\) is the concentration coefficient.

The degrees of significance of various parameters obtained in the table for evaluating the state of transformers already allow the expert to draw conclusions about the state of transformers, but it is possible to get a much more accurate expert assessment based on fuzzy logic methods. To develop such a system, we chose the SciLab software.

SciLab has a special Fuzzy Logic Toolbox add-on for working with fuzzy logic tools.

For the features highlighted in the table, we will set the linguistic values of variables corresponding to the degree of overheating according to thermal imaging data, the moisture content in the oil, the flash point, and the pH factor of the oil. Additionally, to improve the accuracy of evaluating the state of transformers, we will re-evaluate these characteristics on a 10-point scale.

When assessing the condition of equipment by excess temperature, the following areas are distinguished by the degree of malfunction:

- Excessive temperature - (5...10) °C. With a mean initial degree of fault that should be kept under control and take steps to eliminate it during repairs, scheduled according to the schedule. Excessive temperature – (10...30) °C, indicates a developed defect. In this case, it is necessary to take measures to eliminate the fault when the electrical equipment is taken out of operation as soon as possible.
- Excessive temperature - more than 30°C means an emergency defect. Requires an immediate solution.

Because of the analysis of table 1, the transformer membership functions were obtained and entered into SciLab. Similarly, we will identify the linguistic rules.

### 3. Results

For oil-filled transformers, these rules will be as follows:

- Degree of overheating according to thermal monitoring data: initial degree, developed defect, emergency defect;
- Oil moisture concentration – acceptable, risk area, unacceptable;
- Flash point – acceptable and unacceptable;
- pH factor of the oil – acceptable and unacceptable.

Figures 1-2 show the appearance of these functions for the various variables considered in the table. The type of selected function is trapezoidal.

![Figure 1. Fuzzy sets for the variable "Flash temperature".](image)
Figure 2. Fuzzy sets for the "pH factor" variable.

Based on the specified input functions, the membership functions for the output were formed. The type of selected function – Gaussian – emphasizes the probabilistic nature of the decision about the state of the transformer. In fact, this is the probability of its replacement, expressed as a percentage (figure 3).

Figure 3. Output accessory functions that reflect the state of the transformer.

In the first case, we selected only the first two characteristics from the table in Appendix A, so it is possible to visualize the input state using the built-in SciLab graphical tools. Figure 4 shows a surface that reflects the state of the fuzzifier output depending on the input values.

Figure 4. Function of dependence of the output state on the input values.
For the other two characteristics that reflect the features detected during transformer diagnostics, membership functions were also compiled. Their views are presented in figures 19-20. Figure 5-6 on the y-axis shows the weight of input status of fuzzifier. Comparing them with the previous ones, you can notice the appearance of the third state.

**Figure 5.** Fuzzy sets for the variable "Degree of overheating".

**Figure 6.** Fuzzy sets for the variable "Oil moisture concentration".

The membership functions for the output were set as in the previous case using Gaussian functions. The surface of possible solutions is shown in figure 7. On the graph, you can see 4 characteristic plateaus that reflect the state of the transformers [3-6].

**Figure 7.** Function of dependence of the output state on the input values.
4. Discussion

After entering all the necessary data and setting the rules that connect the inputs and outputs, it is possible to perform aggregation and defuzzification to obtain an accurate value for the probability of replacing the transformer.

Aggregation is a procedure for determining the degree of truth of conditions for each of the rules of the fuzzy inference system. In this case, the values of the membership functions of the terms of linguistic variables that make up the above-mentioned conditions (antecedents) of the cores of fuzzy production rules obtained at the fuzzification stage are used [7-8].

Currently, the following algorithms are most used in fuzzy inference systems.

The Mamdani algorithm found application in the first fuzzy automatic control systems. It was proposed in 1975 by the English mathematician E. Mamdani to control a steam engine.

Defuzzification is performed using the center of gravity or center of area method. Defuzzification using the center of gravity method is described by the following formula:

\[
\frac{\sum_{i=1}^{k} u_i \mu_A(u_i)}{\sum_{i=1}^{k} \mu_A(u_i)}
\]

In our case, this method was used.

Figure 8 shows a view of the function of aggregated output values and a clear value of the probability of replacing the transformer in the case when the expert entered 2 and 4 ratings for mechanical damage and discharge density, respectively, in the system.

![Figure 8. View of the function of aggregated output values and a clear value of the probability of replacing the transformer in the first case for the values of inputs 2 and 3.](image)

Further, the expert evaluation method consists in applying the received values of the probability of transformer failure to the input of a new fuzzifier and obtaining one value for the state of the transformers based on four input data. The fuzzifier inputs are configured as Gaussian functions. In this case, the information is no longer entered as an estimate on a scale from 1 to 10, but as a
percentage of the probability of finding the transformer in a particular state. The outputs of the final solution fuzzifier also have Gaussian membership functions, and the set of final solutions can be represented as a 3D graph [9-10].

5. Conclusion
The technical condition of the power transformer is characterized by a large number of parameters. With a large number of different data, the assessment of the technical condition of the power transformer is much more complicated. To solve this problem, you can use a fuzzy logic device. In this paper, based on a mathematical model, a method is developed for evaluating the technical condition of power transformers. This mathematical model is based on fuzzy logic, which can be trained using genetic algorithms. Using the device based on a fuzzy model of the technical condition of the power transformer will improve the quality of the assessment of the technical condition of the equipment by excluding a person when analyzing data. In addition, this will allow us to develop a number of similar programs for complex diagnostics, covering the entire range of electrical equipment of transformer substations, as well as to develop a program for predicting the remaining life, based on the assessment of a comprehensive analysis of the technical condition of electrical equipment of transformer substations.

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