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Energy Efficiency Assessment of Long-Life Power Transformers Using Fuzzy Logic Method

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ABSTRACT: This article proposes using a fuzzy logic method to assess the energy efficiency of oil-immersed power transformers. The model takes power loss, load factor, and service life as input parameters and determines the efficiency class based on the Mamdani method. The obtained results allow for a more accurate assessment of the transformer's energy efficiency.

KEY WORDS: oil power transformer, assesment energy efficiency, fuzzy logic, Mamdani, power losses, membership functions.

I. INTRODUCTION

The energy efficiency assessment of oil-immersed power transformers is determined based on the energy loss indicators of the transformers, based on current regulatory and technical documents. Technical standards for energy efficiency classes of oil-immersed power transformers are given in normative documents [3] and [4]. The main indicator determining the energy efficiency of oil-immersed power transformers is the power loss values in no-load and load operating modes [3]. The process of assessing the energy efficiency of oil-immersed power transformers was carried out by dividing these main indicators into energy efficiency classes [4]. In practice, the energy efficiency of transformers is determined by the value of power losses in no-load and load operating modes based on the passport data of the transformers. If the determined values of power losses are within the maximum permissible limits established by [3], [4] or other regulatory documents, the transformers are evaluated according to the energy efficiency criterion.

The literature [3] provides technical specifications for most oil power transformers in the power supply system of the Republic of Uzbekistan, but these documents do not contain information about oil power transformers with capacities of 25, 40, and 63 kVA, which are widely used in regional power grids. Therefore, [3] using the technical data presented in Tables 2 and 3, mathematical models were developed based on the regression analysis method for determining power losses in unloaded and loaded operating modes for oil power transformers with operating capacities of 25, 40, and 63 kVA, as well as for assessing energy efficiency classes.

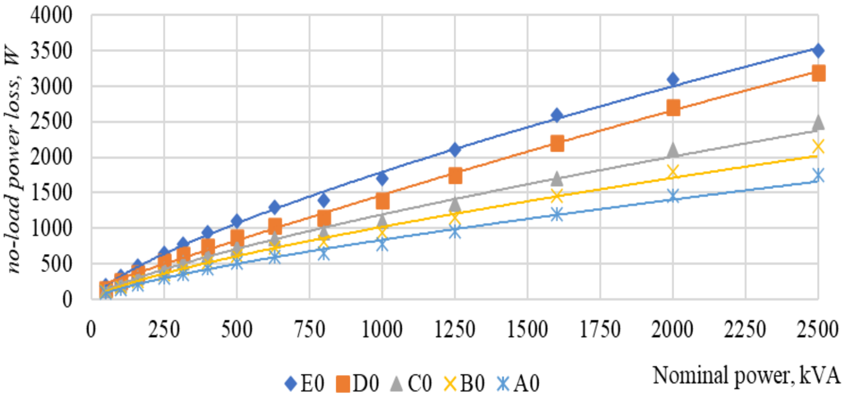

Figure 1. Graph of the dependence of no-load power losses on nominal power for each energy efficiency class

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Table 1 presents mathematical models for determining the energy efficiency class of oil-immersed power transformers in no-load and load operating modes.

Table 1. Mathematical models for determining the energy efficiency class of oil-immersed power transformers in no-load and full-load operating modes

Energy Efficiency Class	Unloaded mode	Loaded mode
A	$P_{A_{SI}} = 4{,}7138 \cdot S_{nom}{}^{0{,}7493}$	$P_{A_{QT}} = 7{,}2378 S_{nom} + 397{,}62$
B	$P_{B_{SI}} = 5{,}7839 \cdot S_{nom}{}^{0{,}7484}$	$P_{B_{QT}} = 8{,}6053 S_{nom} + 411{,}82$
C	$P_{C_{SI}} = 6{,}5996 \cdot S_{nom}{}^{0{,}7522}$	$P_{C_{QT}} = 10{,}292 S_{nom} + 494{,}85$
D	$P_{D_{SI}} = 7{,}2282 \cdot S_{nom}{}^{0{,}7727}$	$P_{D_{QT}} = 12{,}329 S_{nom} + 888{,}53$
E	$P_{E_{SI}} = 10{,}506 \cdot S_{nom}{}^{0{,}7438}$	

Through the mathematical models obtained on the basis of the above mathematical models (Table 1), it was possible to determine the indicator values of energy efficiency classes in no-load operation for oil-immersed power transformers with a capacity of 25, 40 and 63 kVA (Table 2).

Table 2. Values of energy efficiency class indicators in no-load operation mode for oil-immersed power transformers with a capacity of 25, 40 and 63 kVA

S_{nom} kVA	E_{SI} Vt	D_{SI} Vt	C_{SI} Vt	B_{SI} Vt	A_{SI} Vt
25	115	90	75	65	55
40	165	125	105	90	75
63	230	180	150	130	105

II. SIGNIFICANCE OF THE SYSTEM

This approach does not determine the extent to which power losses have increased or decreased, and whether there is a possibility of improving these indicators in terms of increasing energy efficiency. Therefore, when assessing the energy efficiency of a transformer, it is necessary to compare the power losses determined with the normative values, and also analyze the degree of their increase and the quantitative expression of the resulting decrease in efficiency. This approach allows, based on the current technical condition of the transformer, to develop measures to optimize it, that is, to reduce energy losses

III. LITERATURE SURVEY

Taking into account the above shortcomings, in order to eliminate them, we change the evaluation criteria (A (very high), B (high), C (average), D (below average), E low) taking into account the input variables [1]. To determine these criteria, we use input ratios in the fuzzy logic method. Table 3 presents the energy efficiency evaluation indicators for the input variables [2].

Table 3. Table for assessing the state of input variables

Input variable	E (low)	D (below average)	C (average)	B (high)	A (very high)
X_1	$A > X_1$	$A \le X_1 \le B$	$B < X_1 \le C$	$C < X_1 \le E$	$X_1 > E$
…	…	…	…	…	…

To form an uncertain subset, the proportion given in expression (1) is used, which converts the set value of the input parameter into the corresponding element of $u^* \in [0,1]$according to Figure 2 [1, 6].

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$$\frac{(x_{pi}-x_{ki})}{(1-0)} = \frac{(x_i^*-x_{pi})}{(u^*-0)} \quad (1)$$

Based on the above formulas, we can establish the following rules for evaluating the energy efficiency of oil-immersed power transformers under long-term operation conditions according to 5 linguistic criteria [1, 3, 7]. Norms are established for each input variable.

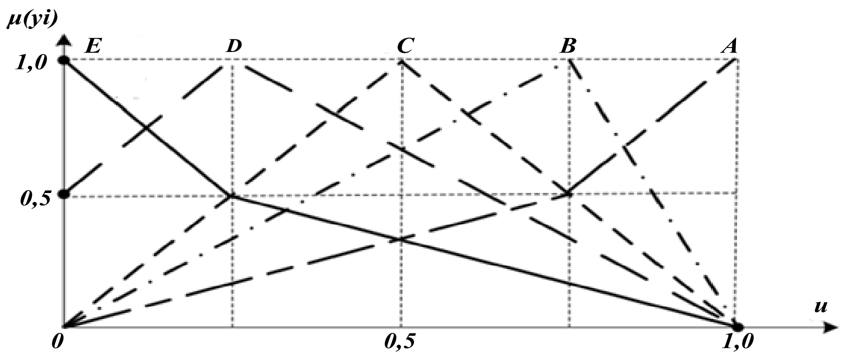

Figure 2. Graphic representation of the terms: A-very high, B-high, C-average, D-below average, E-low

To assess the energy efficiency of oil-immersed power transformers under long-term operating conditions, a mathematical model was developed based on fuzzy logic to classify the energy efficiency of transformers into classes A, B, C, D, and E.
It is convenient to use the "if-then" rule to assess the energy efficiency of oil-immersed power transformers in operation using key indicators [1]. The indicators defining such a state are given in numerical values, and several rules are used to convert them into linguistic indicators [2.]. Fuzzy logic is one of such methods [2].
The energy efficiency class (Class) is selected as the output parameter, which takes a value in the range [0, 100] and is divided into the following sets (Table 4):

Table 4. Energy efficiency class

Energy efficiency class	Classification	Function type	Output parameter range
A	very high efficiency	Linzmf (Z-shakl)	[0, 20)
B	high efficiency	Trapmf (trapetsiya)	[20, 40)
C	average efficiency	Trapmf (trapetsiya)	[40, 60)
D	below average efficiency	Trapmf (trapetsiya)	[60, 80)
E	low efficiency	Linsmf (S-shakl)	[80, 100]

IV. METHODOLOGY

This fuzzy logic allows us to determine the value of the output variable based on the value of the input parameters. Inference using fuzzy logic is carried out in three stages (Figure 3.10): Stage 1: Fuzzification (transition from certainty to uncertainty), Stage 2: establishment of rules, Stage 3: Defuzzification (transition from uncertainty to certainty) [5].

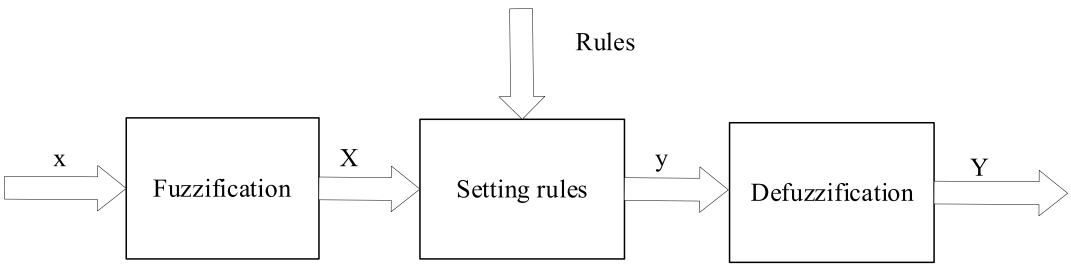

Figure 3. Structural diagram of fuzzy logic [5]

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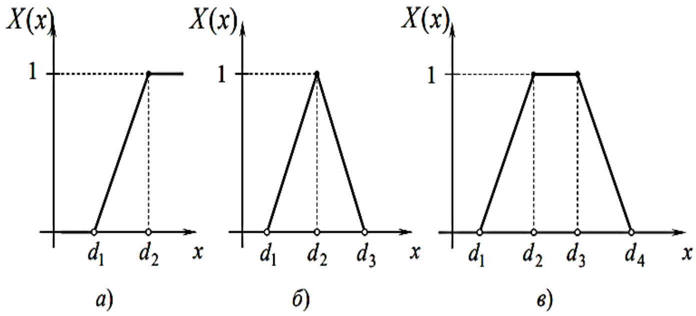

Figure 4. Membership functions [6; p. 105, 7; p. 440]

The piecewise linear membership function is described by an expression of the form (Figure 5):

$$f(x) = \begin{cases} o, x \in (-\infty, d_1], \\ \frac{x-d_1}{d_2-d_1}, x \in (d_1, d_2], \\ 1, x \in (d_2, +\infty) \end{cases} \tag{3}$$

The connection points of the linear segments d_1, d_2 [12]
The linear membership function is expressed as follows [12]

$$f(x) = \begin{cases} o, (-\infty, d_1] \\ \frac{x-d_1}{d_2-d_1}, x \in (d_1, d_2], \\ \frac{d_3-x}{d_3-d_2}, x \in (d_2, d_3), \\ 0, x \in [d_3, +\infty) \end{cases} \tag{4}$$

where, d_1, d_3 are the left and right boundary points of the membership function, d_2 is the height coordinate [5,6].

V. EXPERIMENTAL RESULTS

The fuzzy logic method was used to evaluate the energy efficiency of oil-immersed power transformers through energy losses in the no-load operating mode. In this case, the evaluation of power losses was determined using the π, L, γ - classes of the Mamdani membership function [7]. A simulation model for evaluating the energy efficiency of an oil-immersed power transformer through the amount of active power losses in the no-load operating mode was developed for an oil-immersed power transformer using the mathematical expression obtained using the Mamdani method above as follows[1, 8].
The following structural diagram presents a model for evaluating the energy efficiency of oil-immersed power transformers through no-load power losses. The model takes the membership functions of no-load energy losses as input parameters and reanalyzes them based on the rules, and the energy efficiency class membership functions are reflected as output parameters (Figure 5).

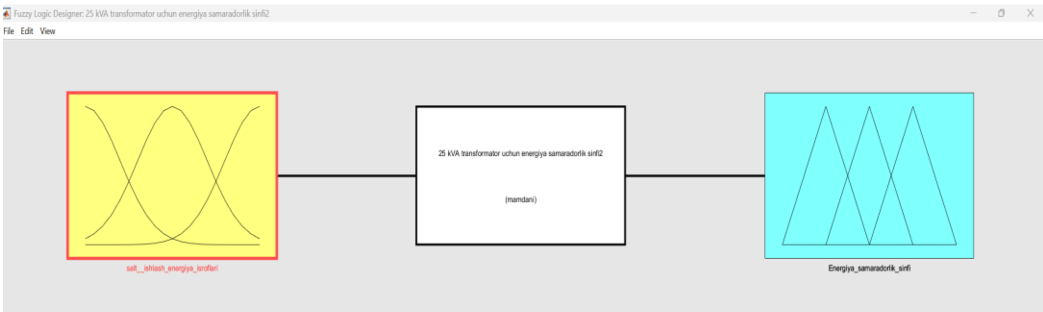

Figure 5. Model for assessing the energy efficiency of an oil-immersed power transformer through active power losses in no-load operation mode

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The output variable, "Energy Efficiency Class," is represented by trapezoidal/triangular membership functions for five linguistic criteria (A–E). This graph constitutes the basic output model for evaluating transformer efficiency based on fuzzy logic (Figure 6).

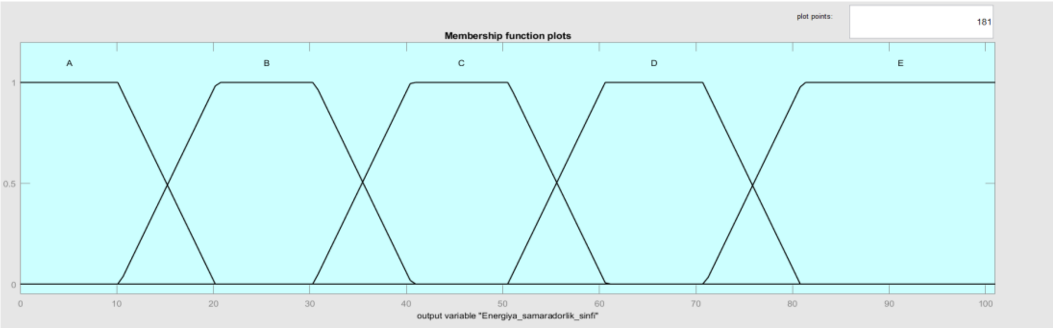

Figure 6. Output variable of an oil-immersed power transformer

VI. CONCLUSION AND FUTURE WORK

It was found that relying on passport indicators when assessing the energy efficiency of oil-immersed power transformers is insufficient. Because this method does not fully take into account the technical condition, service life and degree of degradation of the transformer. Therefore, a five-level (A–E) assessment model was developed based on the fuzzy logic method. The model takes into account parameters such as power losses, load factor and service life, and more accurately classifies efficiency. The proposed method serves to reduce energy losses of transformers and improve their performance.

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