**Evaluation of Power Transformer No-Load Energy Efficiency Using Fuzzy Inference Models**

Dostonbek Abdurakhimov1, a), Mukhаmmаdyusuf Mukhаmmаdjоnоv1, b),   
Dilmurod Yusupov2, c), Odiljon Kutbidinov3, d), Anvar Norboev4, e),   
Aloviddin Sadullaev4, f) andOtabek Babaev4, g)

1Fergana State Technical University, Fergana 150107, Uzbekistan  
2Institute of Energy Problems, Academy of Sciences of the Republic of Uzbekistan, Tashkent 100095, Uzbekistan  
3Tashkent State Transport University, 1 Temiryulchilar St., Tashkent 100167, Uzbekistan  
4Karshi State Technical University, Karshi 180100, Uzbekistan

*a)* [*abduraximovdoston2@gmail.com*](mailto:abduraximovdoston2@gmail.com) *b)* [*mrmuhаmmаdyusuf0013@gmаil.cоm*](mailto:mrmuhаmmаdyusuf0013@gmаil.cоm) *c)* [*dilmurоd85@list.ru*](mailto:dilmurоd85@list.ru) *d) Corresponding author: [odiljon.qutbidinov@bk.ru](mailto:odiljon.qutbidinov@bk.ru)  
 e)* [*a\_norboyev@list.ru*](mailto:a_norboyev@list.ru) *f)* [*aloviddinsadullayev@gmail.com*](mailto:aloviddinsadullayev@gmail.com) *g)* [*otabekelmurodovich5100@gmail.com*](mailto:otabekelmurodovich5100@gmail.com)

**Abstract.** In this study, a mathematical model has been developed using a fuzzy logic approach to evaluate the energy efficiency of power transformers in no-load operation mode. In the proposed model, power losses and acoustic noise levels during transformer no-load operation were selected as the primary input parameters, and their impact on efficiency was assessed using a Sugeno-type inference mechanism. The modeling results indicate that a methodological solution has been proposed, allowing for a highly accurate and adaptable assessment of transformer efficiency.

**Keywords:** fuzzy logic, no-load losses, acoustic noise, power transformer, Sugeno model, energy efficiency, diagnostic model, mathematical modeling, transformer evaluation, linguistic variables, efficiency assessment, inference system

**INTRODUCTION**

Improving energy efficiency in modern electric power systems remains a pressing issue [1]. In particular, energy losses occurring during the operation of power transformers, which are widely used in distribution networks, significantly affect the overall system efficiency [2, 3]. Although most attention is focused on operating modes under load, power losses in no-load conditions also deserve serious consideration [4]. These losses are mainly caused by hysteresis and eddy currents arising in the magnetic core [5].

In addition, the level of acoustic sound arising from the operation of the transformer is structurally related to energy losses, and this parameter also indirectly affects the efficiency indicator [6]. Assessing these factors based on traditional statistical or deterministic models presents difficulties [7, 8, 9]. Therefore, in this study, an evaluation model based on fuzzy logic theory was developed and proposed as an approach that allows for a qualitative and accurate classification of transformer efficiency [10].

**LITERATURE REVIEW**

International standards (e.g., IEC 60076 series and IEC/TS 60076-20) define how unloaded losses (P0) and efficiency are measured: the core is charged with a secondary opening at nominal voltage; the results are adjusted to the corresponding recording temperature and crane condition; and indices such as Peak Efficiency Index (PEI) have been reported [1, 2, 3]. However, these documents stop with deterministic formulas and do not establish a smart, multi-criteria sum of electrical, acoustic, and thermal indicators in a single performance rating.

Loadless losses are mainly caused by hysteresis and vortex flows in nuclear steel. Magnetostriction causes vibration and audible noise, which is related to the density of the nuclear flux and therefore to P0. Many studies consider acoustic level (L\_A) and vibrational spectra as indirect indicators of ground state and energy efficiency in unloaded excitation [4, 5, 6].

This encourages combining electrical losses with acoustic (and possibly thermal) properties to assess richer efficiency.

Analytic expressions (Steinmetz-type formulas) predict the main losses, but struggle with the nonlinearities of the real world (harmonics, aging effects). In recent works, data-driven models - Adaptive Neuro-Turbid Inference Systems (ANFIS), regression trees, and light neural networks - are used to assess the main losses with high accuracy and fewer tests [7, 8, 9]. Such surrogates perform "whatever happens" analysis by flow levels, materials, and distorted waveforms.

Dirty logic (Mamdani, Sugeno) is widely used to combine heterogeneous indicators of transformer state - DGA patterns, moisture content, insulation health - composite health or risk indices [8, 9, 10].

Linguistic variables ("low loss," "high noise") and membership functions naturally encompass uncertainty. Sugeno-type FIS, with linear/constant results, is easy to calculate and ideal for optimization and built-in applications.

Researchers increasingly associate FIS with Bayesian inference, rough sets, genetic algorithms, or neural networks to improve diagnostic reliability in high-dimensional spaces [4, 5, 6, 7]. Most hybrids focus on identifying defects rather than comparing effectiveness. Nevertheless, the same architectures can be re-parameterized: inputs become P0, L\_A, ∆T\_core, the PEI space, etc.; results become "performance levels" instead of "fault classes."

Turbidity-based transformer research rarely considers unloaded energy efficiency as the primary product; they focus on errors or overall health.

Acoustic/vibrational indicators are rarely combined with electrical loss indicators in a combined fuzzy efficiency system.

The standards define how to measure P0, but not how to rationally combine multi-mode indicators into a flexible performance index.

Many ANFIS/FIS models are trained in laboratory datasets; testing under operating conditions (voltage disturbances, core aging, temperature fluctuations) remains limited.

This article that addresses these gaps:

Develops a Sugeno-type fuzzy inference model that includes unloaded electrical losses (P0), acoustic noise level, and (optional) ground temperature to derive an unloaded energy efficiency index expressed in linguistic terms ("Very efficient...", "Useless").

Confirms the model with experimental data and compares it with traditional deterministic estimates.

Hybrid architecture (FIS + NN/Bayesian) discusses increasing confidence in extension prediction and optimizing the life cycle.

**MATERIAL AND METHODS**

Fuzzy logic theory was proposed by Lotfi Zade in 1965 and began to be widely used in technical and management fields in subsequent decades. This approach takes into account not only traditional "yes-no" decisions, but also intermediate values. This approach to assessing transformers provides the following advantages:

* consideration of parameter uncertainty;
* qualitative classification based on expert opinions;
* does not require a linear model;
* a sensitive and flexible approach to small changes.

The BS EN 50464-1:2007 standard specifies the permissible power loss values under no-load conditions for three-phase oil transformers with nominal voltages up to 36 kV, operating at 50 Hz frequency (ranging from 50 kVA to 2500 kVA), as well as their classification according to energy efficiency classes. Based on this standard, two main input parameters were selected to assess the energy efficiency of power transformers in no-load mode:

* **P₀** – no-load power losses, Vt;
* **LwA** – noise level, dB(A).

The energy efficiency of the transformer (η, %) was taken as the output parameter. Each input parameter is divided into linguistic categories (low, medium, high), and each category is represented by triangular membership functions.

For each input parameter, three linguistic categories were identified, and their triangular membership functions (trimph) were expressed as follows:

**No-load power losses P₀:**

* Low: [90, 200, 300]
* Avarage: [300, 375, 460]
* High: [460, 900, 1300]

**Noise level LwA:**

* Low: [39, 45, 52]
* Avarage: [52, 56, 60]
* High: [60, 65, 70]

Efficiency **η:**

* Low: 30%
* Avarage: 60%
* High: 90%

The membership function for the “Low” level of is:

The base of fuzzy rules, formed on the basis of expert knowledge, was formed as follows:

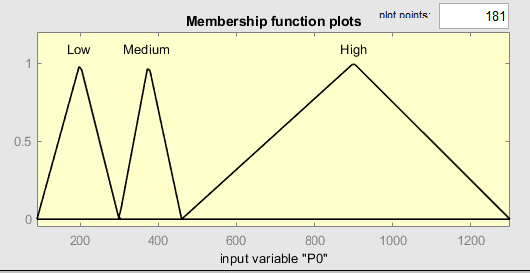
**TABLE 1.** Developed rule base

|  |  |  |  |
| --- | --- | --- | --- |
| Rules | P₀ | LwA | η |
| R1 | LOW | LOW | HIGH (90%) |
| R2 | LOW | LOW | HIGH (90%) |
| R3 | AVARAGE | AVARAGE | AVARAGE (60%) |
| R4 | HIGH | HIGH | LOW (30%) |

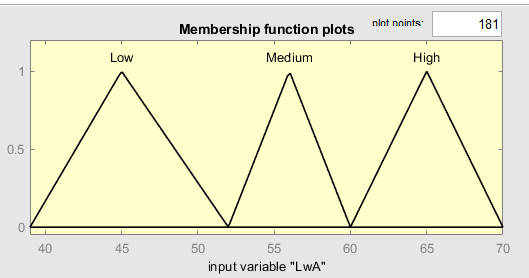
In the model, the mechanism of Sugeno method output is expressed as follows:

where: – i-rule activity level; – i-rule output value (z₁ = z₂ = 90; z₃ = 60; z₄ = 30).

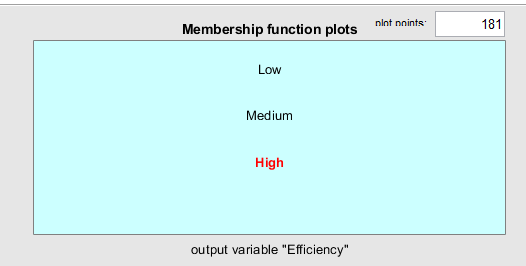
**A fuzzy logic (fuzzy logic) simulation model was developed to assess the efficiency of power transformers operating in no-load mode using the MATLAB environment.**



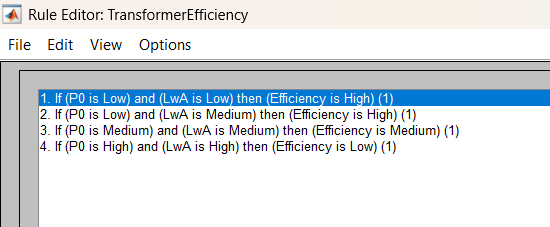
**FIGURE 1.** Membership functions of the input variable P₀ (no-load losses)



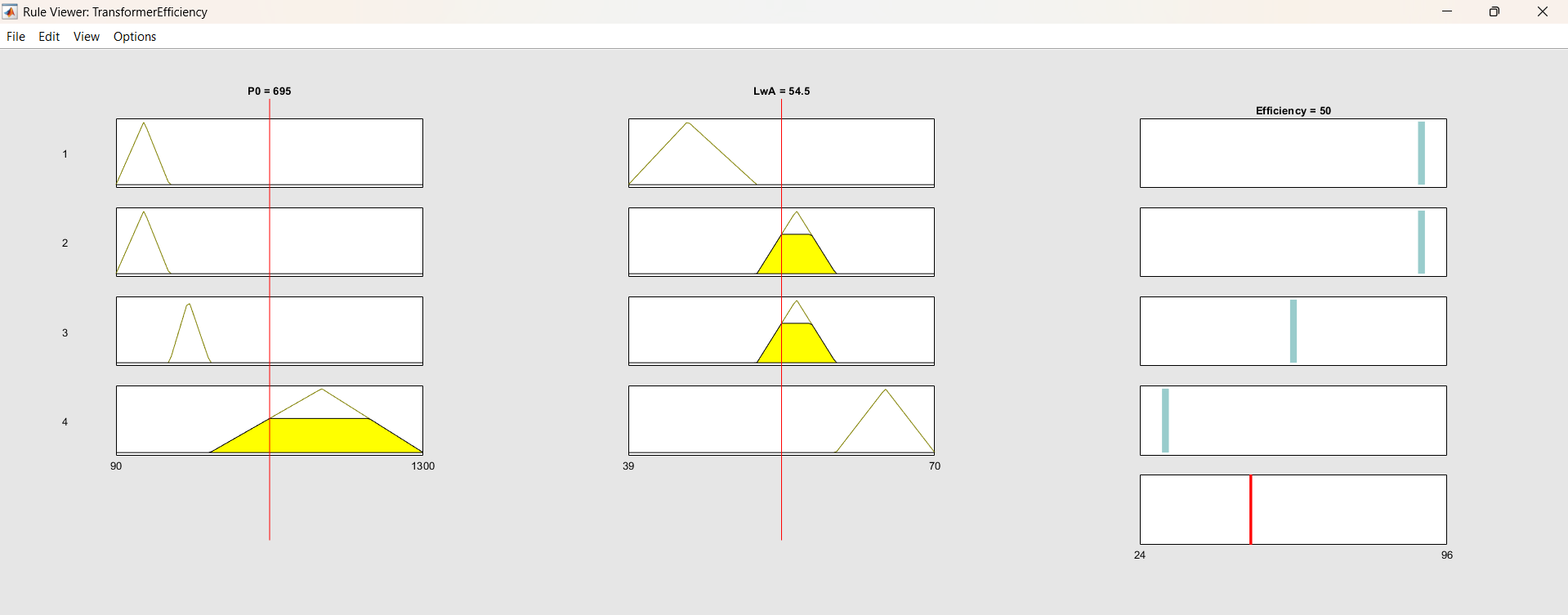
**FIGURE 2.** Membership functions of the input variable LwA (acoustic power level)



**FIGURE 3.** Output membership functions for transformer efficiency η



**FIGURE 4.** Fuzzy rule base for transformer efficiency estimation



**FIGURE 5.** Rule Viewer window, displaying the graphical operation of fuzzy rules

**RESULTS AND DISCUSSION**

Experimental studies were conducted on power transformers used in power systems, and energy efficiency was assessed (Table 1).

* **P₀ = 300 Vt,**
* **LwA = 52 dB(A)**

**Based on these values, the values of the membership functions for each input variable were determined:**

In this case, it was found that only R1 and R2 rules are activated, and the resulting efficiency is equal to:

The result shows that the energy efficiency, assessed based on the selected no-load parameters of the transformer, is at a high level (90%).

**TABLE 2.** Model-based energy efficiency calculations

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| № | P₀ (Vt) | LwA (dB(A)) | Active rules |  |  | (%) |
| 1 | 300 | 52 | R1, R2 | 1.0, 1.0 | 90, 90 |  |
| 2 | 375 | 56 | R3 | 1.0 | 60 |  |
| 3 | 900 | 70 | R4 | 1.0 | 30 |  |
| 4 | 250 | 50 | R1, R2 | 0.5, 0.5 | 90, 90 |  |
| 5 | 600 | 68 | R4 | 0.8 | 30 |  |
| 6 | 350 | 53 | R3 | 0.67 | 60 |  |
| 7 | 1000 | 65 | R4 | 0.5 | 30 |  |

As can be seen from this table:

• In low P0 and low LwA cases, efficiency reaches up to 90%.

• At high values of P0 and LwA, efficiency decreases by up to 30%.

• Average values are estimated at around 60%.

The research results confirm that the evaluation model, built on fuzzy logic, allows one to accurately and qualitatively assess the efficiency of transformer unloading.

**CONCLUSION**

The evaluation model proposed in this article, based on the fuzzy logic approach, provides high accuracy and reliability in determining the efficiency of transformers operating without load. The model serves as an effective tool for assessing energy efficiency at the initial stages of transformer design, determining compliance with regulatory requirements, and making operational decisions.

**REFERENCES**

1. A. V. Varganova, V. R. Khramshin, and A. A. Radionov, “Improving efficiency of electric energy system and grid operating modes: Review of optimization techniques,” Energies **15**(19), 7177 (2022).
2. M. A. M. Khan, R. Haque, and A. Bajwa, “A systematic literature review on energy-efficient transformer design for smart grids,” Am. J. Scholarly Res. Innov. **1**(1), 186–219 (2022).
3. J. Wang, et al., “Review on evolution of intelligent algorithms for transformer condition assessment,” Front. Energy Res. **10**, 904109 (2022).
4. A. Esmaeili Nezhad and M. H. Samimi, “A review of the applications of machine learning in the condition monitoring of transformers,” Energy Syst. **15**(1), 463–493 (2024).
5. D. Rodriguez-Sotelo, et al., “Power losses models for magnetic cores: A review,” Micromachines **13**(3), 418 (2022).
6. R. Liao, et al., “An integrated decision-making model for condition assessment of power transformers using fuzzy approach and evidential reasoning,” IEEE Trans. Power Del. **26**(2), 1111–1118 (2011).
7. M. Arshad, S. M. Islam, and A. Khaliq, “Fuzzy logic approach in power transformers management and decision making,” IEEE Trans. Dielectr. Electr. Insul. **21**(5), 2343–2354 (2014).
8. K. Cao, T. Zhang, and J. Huang, “Advanced hybrid LSTM-transformer architecture for real-time multi-task prediction in engineering systems,” Sci. Rep. **14**(1), 4890 (2024).
9. D. Yusupov, et al., “Development of the algorithm of additional cooling process for oil power transformers with ONAN cooling system,” ICTEA: Int. Conf. Therm. Eng. **1**(1) (2024).
10. D. T. Yusupov, B. K. Avazov, O. M. Kutbidinov, and M. Bazarov, “Cleaning of transformer oils using the electric field,” IOP Conf. Ser.: Earth Environ. Sci. **1231**(1), 012024 (2023).