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Analysis of artificial neural network applications for assessing the technical condition of traction transformers in electric locomotives

O.R. Khamidov¹, Sh.A. Samatov¹, B.I. Gayratov¹, A.K. Djuraev¹

¹Tashkent state transport university, Tashkent, Uzbekistan

Abstract:

This paper presents a critical and systematic analysis of the scientific literature on assessing the technical condition of traction transformers of electric locomotives using artificial neural networks (ANN). Unlike earlier descriptive reviews, the analysis was carried out in three stages: chronological evolution of the directly relevant studies, classification of existing approaches according to Dasarathy's data fusion taxonomy, and critical evaluation of each study's methodological strengths and limitations, including constraints acknowledged by the original authors themselves. Nine studies dedicated directly to traction transformers of electric locomotives were identified. All of them operate within a single physical-domain parameter group and a single data-fusion level; their datasets are limited to one institution or one train type and are not publicly available. It is shown, both empirically and theoretically, that no existing approach fuses heterogeneous thermal, insulation, mechanical and electrical parameters at a level higher than single-domain feature fusion. The results provide a methodological foundation for developing a multi-parameter hybrid neural network model for traction transformer diagnostics.

Keywords:

traction transformer, electric locomotive, artificial neural network, technical diagnostics, data fusion, condition assessment, dissolved gas analysis, vibration diagnostics, multi-parameter model

1. Introduction

Modernization of railway transport in the Republic of Uzbekistan is one of the priority areas of state policy. Traction transformers of electric locomotives are among the most important and expensive components of rolling stock, and their unexpected failure may lead to disruption of train schedules and a reduction in operational safety. Conventional diagnostic methods are performed according to fixed schedules regardless of the actual technical condition of the transformer, which increases the need for intelligent diagnostics based on artificial neural networks (ANN).

For a deeper theoretical understanding of the problem, it is appropriate to consider it from the perspective of data fusion theory. According to the taxonomy proposed by Dasarathy [10], fusion processes are divided into data, feature, and decision levels depending on the input–output abstraction level. Assessing the condition of a traction transformer using sources with fundamentally different physical characteristics and sampling frequencies, such as thermal, insulation, mechanical, and electrical parameters, is not simply a matter of adding more inputs; rather, it is a theoretically complex fusion problem that requires the integration of heterogeneous data.

The aim of this paper is to systematically analyze studies in which ANNs have been applied to traction transformer diagnostics, classify them according to the Dasarathy taxonomy, and substantiate the existing research gap from both theoretical and empirical perspectives.

2. Research methodology

The literature search was conducted in IEEE Xplore, MDPI, Springer, ScienceDirect, and Google Scholar databases, covering

the period from 2014 to 2024. The inclusion criteria were: the study had to focus directly on traction transformers, employ an artificial intelligence method, and be published in a peer-reviewed source. Initially, 18 candidate publications were identified; one was excluded from the analysis because it was officially retracted in 2025 due to unauthorized use of third-party data, while nine publications concerned stationary transformers and were therefore mentioned only briefly as general context. The final in-depth analysis included nine studies directly related to traction transformers.

3. Results and Discussion

Ordering the selected studies by publication year reveals a clear evolutionary trend (Fig. 1). The early studies of 2014–2015 (Zhu et al.) employed relatively simple architectures, including wavelet neural networks and Gaussian-PSO. By 2021–2022, more sophisticated hybrid models, such as kernel PCA and multi-stage optimization (ISOA-SVM), had emerged. From 2023 onward, the research direction changed qualitatively, with a shift toward multi-label classification (Li et al.) and comprehensive reviews covering the entire traction system.

Classification based on the Dasarathy taxonomy (Table 1) shows that all four studies by the Zhu group [1–4] implement feature-level fusion (FEI-FEO); however, all input data belong to the same physical domain (thermal-chemical). The study by Li et al. [5] combines feature and decision levels, whereas the study by Lukovenko [9] represents the simplest case, directly combining two parameters at the data level. An important finding is that none of the analyzed studies integrates four parameter groups with fundamentally different physical characteristics at the feature or decision level.

^a <https://orcid.org/0000-0003-0821-5754>

^b <https://orcid.org/0000-0002-4014-3845>
^c <https://orcid.org/0009-0005-3957-337X>



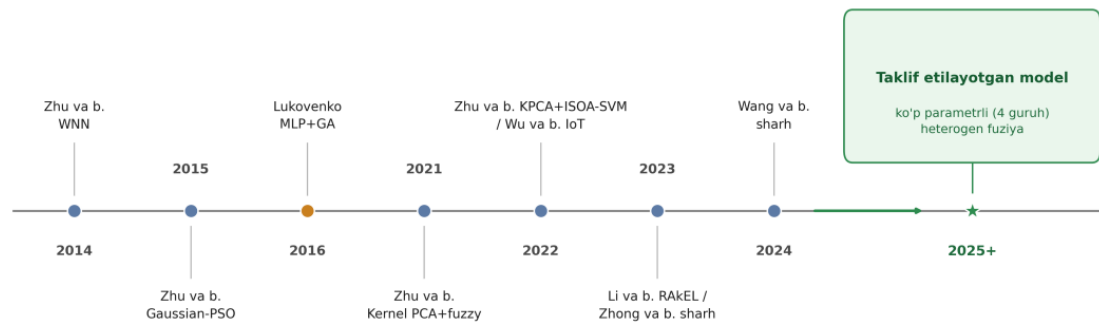


Fig. 1. Chronological evolution of ANN studies in traction transformer diagnostics

Table 1

Critical analysis of traction-transformer-related studies based on the Dasarathy taxonomy

No	Author, year	Method	Parameters	Results and limitations
1	Zhu et al., 2014 [1]	WNN	Diagnostic features	Demonstrated the feasibility of ANN for an onboard transformer; data source unclear
2	Zhu et al., 2015 [2]	Gaussian-PSO	Early fault indicators	Early-stage detection; dataset limited
3	Zhu et al., 2021 [3]	Kernel PCA + fuzzy	DGA, electrical tests	Nonlinear feature extraction; no publicly available data
4	Zhu et al., 2022 [4]	KPCA + ISOA-SVM	DGA, electrical parameters, oil quality	High accuracy; high computational complexity
5	Li et al., 2023 [5]	Improved RAKEL	BV, moisture, acidity, H ₂ , C ₂ H ₂	93.62% accuracy; low AP (0.304), CRH5 only
6	Wang, Zhong [6;7]	Review articles	—	Systematizes the field; does not propose a new model
7	Wu et al., 2022 [8]	IoT monitoring	Real-time telemetry	Addresses the infrastructure problem; ANN not applied
8	Lukovenko, 2016 [9]	MLP + GA	Insulation resistance, temperature	Demonstrated the effect of two parameters; stationary object



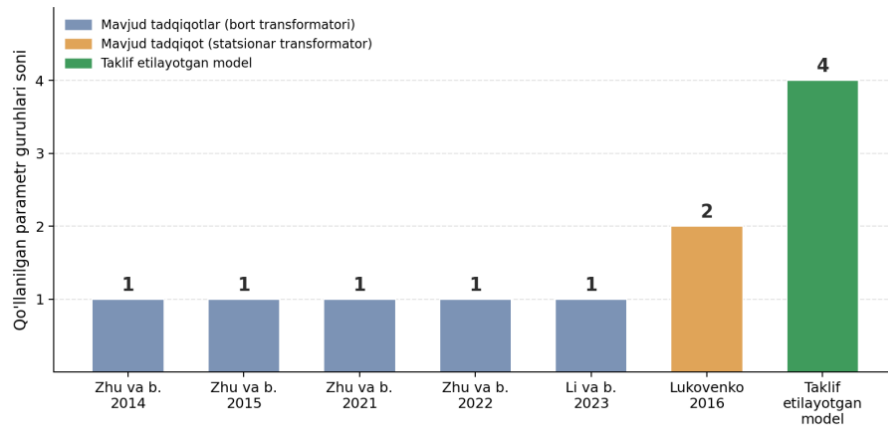


Fig. 2. Comparison of the number of parameter groups used

Table 2

Comparison of existing studies and the proposed approach

Aspect	Existing studies	Proposed model
Number of parameter groups	Maximum of 2	4 (thermal + insulation + mechanical + electrical)
Fusion level (Dasarathy)	Feature/data level, within the same domain	Feature + decision, across heterogeneous domains
Object	Mixed (some are stationary)	Onboard traction transformer only
Output format	Binary / multi-label indication	4-class condition + health index (HI)
Mathematical formalization	Limited or absent	Complete (27 equations)

Important methodological findings were also identified. Li et al. [5] explicitly acknowledge that the Average Precision of their models is relatively low in absolute terms. Although this represents a good example of scientific transparency, it also indicates that multi-label classification remains an incompletely solved problem. Lukovenko [9] demonstrated that adding oil temperature changed the prediction error from 1.5–4.4% to 0–7.2%, providing additional evidence of the influence of a second parameter; however, this result is specific to a stationary object.

The existence of this research gap is not accidental: thermal/insulation parameters are measured periodically at low frequencies, whereas vibration/harmonic signals constitute a continuous high-frequency data stream. Synchronizing these two categories therefore requires a dedicated architecture. In addition, installing heterogeneous sensors onboard requires additional hardware and organizational coordination, which may constitute a practical barrier to experimental research.

Comparative Analysis

As shown in Table 2 and Fig. 2, the proposed model offers several advantages over existing studies:

- Complexity: integrates four heterogeneous parameter groups within a single model; none of the existing studies incorporates more than this;
- Object specificity: designed specifically for an onboard traction transformer of an electric locomotive (IEC 60310), rather than directly transferring methods developed for stationary transformers;
- Theoretical foundation: operates at a higher (feature + decision) level according to the Dasarathy taxonomy;
- Two-layer prediction: the neural network classifies the current condition, while a probabilistic (Weibull) model predicts the remaining useful life;
- Transparency: the results are compared with conventional methods and the 93.62% performance reported by Li et al. [5] using a clearly defined methodology.

4. Conclusion

This paper analyzed the scientific literature on ANN-based assessment of the technical condition of electric locomotive traction transformers using a three-stage methodology: chronological, theoretical-taxonomic, and critical analysis. Nine studies directly related to the topic



were identified, their methodological limitations were highlighted, and, based on the Dasarthy taxonomy, it was demonstrated that none of the existing approaches implements genuine heterogeneous multi-domain fusion. Both the empirical and the technical-methodological reasons for the identified research gap were discussed. These findings provide a solid scientific and theoretical foundation for designing, mathematically substantiating, and experimentally validating a multi-parameter hybrid model architecture.

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Information about the author

Khamidov Otabek	Toshkent davlat transport universiteti “Lokomotivlar va lokomotiv xo‘jaligi” kafedrası professori E-mail: otabek.rustamovich@yandex.ru Tel.:+99890 811 21 00 https://orcid.org/0000-0003-0821-5754
Shakhboz Samatov	Toshkent davlat transport universiteti “Lokomotivlar va lokomotiv xo‘jaligi” kafedrası katta o‘qituvchisi E-mail: shaxbozbek4089525@gmail.com Tel.:+99894 408 95 25 https://orcid.org/0000-0002-4014-3845
Bakhodir Gayratov	Toshkent davlat transport universiteti “Lokomotivlar va lokomotiv xo‘jaligi” kafedrası tayanch doktoranti E-mail: bgayratoff@gmail.com Tel.:+99894 134 54 27 https://orcid.org/0009-0005-3957-337X
Abbos Djuraev	Toshkent davlat transport universiteti “Lokomotivlar va lokomotiv xo‘jaligi” kafedrası tayanch doktoranti Tel.:+99888 854 40 00



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