International Journal of Advanced Research in Science, Engineering and Technology

ISSN: 2350-0328

Vol. 12, Issue 10, October 2025

Analysis of existing studies carried out on the early diagnosis of oil-immersed transformers

Togaymurodov S.Z.

Doctoral student of «Electrical power engineering» Department. NSUMT

ABSTRACT: This paper presents an analytical overview of existing studies on the early diagnostics of oil-immersed transformers and highlights the growing role of the Digital Twin method in transformer condition assessment. Conventional diagnostic approaches—such as visual inspection, insulation resistance testing, Dissolved Gas Analysis (DGA), infrared thermography, vibration, and acoustic emission—are compared in terms of reliability, cost, and diagnostic capability. Results indicate that while traditional methods achieve reliability levels between 50–93%, the Digital Twin approach demonstrates superior performance, reaching up to 95–99% accuracy. The study emphasizes that Digital Twin technology enables real-time monitoring of key parameters, including oil temperature, dissolved gases, vibration, and load regimes, by integrating sensor data and computational models. However, practical implementation in Uzbekistan reveals significant economic constraints, as the diagnostic setup for a 100 kVA transformer costs approximately 150–200 million UZS, exceeding the equipment's base price. Consequently, the method is considered most feasible for high-capacity transformers (≥1 MVA), where its predictive and reliability advantages justify the investment. The analysis confirms that the Digital Twin method represents the most advanced and accurate solution for transformer diagnostics, despite its high implementation cost[1,2].

KEYWORDS: Oil-immersed transformer; Early diagnostics; Digital Twin; Dissolved Gas Analysis (DGA); Infrared thermography; Vibration monitoring; Microcontroller; ESP32; Real-time monitoring; Predictive maintenance; Transformer reliability; Remaining Useful Life (RUL); Condition assessment; Sensor integration; Smart grid diagnostics.

I.INTRODUCTION

At present, transformers are among the most essential electrostatic devices in the field of energy, and various types have been developed. Among them, the most widely used and highly demanded in power supply systems are oil-immersed transformers. These transformers are generally installed in regions with low atmospheric humidity and minimal risks of fire or explosion, serving as the primary electrical equipment for voltage transformation. The stable operation of high-power oil-filled transformers at nominal ratings is of crucial importance, since any deviation—whether an increase or decrease—from nominal parameters in power transmission directly affects the reliability and efficiency of transformer performance. Therefore, continuous monitoring and diagnostic evaluation of oil-immersed transformers have become one of the most critical tasks[3].

Numerous studies have been conducted to develop diagnostic techniques for oil-filled transformers, and this line of research continues to advance. The use of wireless devices for monitoring primary power equipment, including transformers, allows for real-time data acquisition and supervision of essential parameters. This ensures not only uninterrupted and reliable power supply but also provides safe operational maintenance of the equipment. The main objective of these monitoring methods is to control and manage the transformer through modular systems. Today, the remote monitoring of primary power devices using temperature sensors, microcontrollers, and wireless communication technologies is regarded as a highly reliable and efficient approach.

International Journal of Advanced Research in Science, Engineering and Technology

ISSN: 2350-0328

IJARSET IMPACT FACTOR 7.150

Vol. 12, Issue 10, October 2025

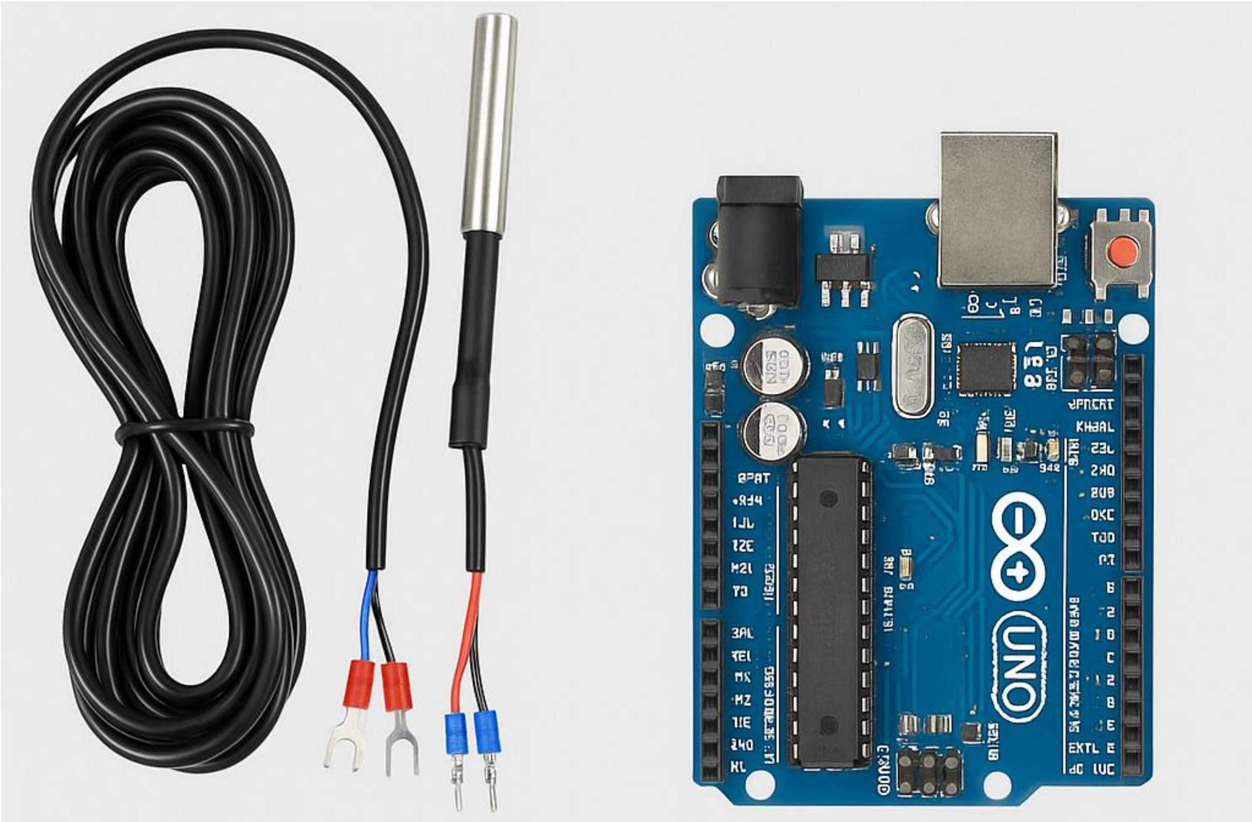

Figure 1. Temperature sensor and microcontroller used for the diagnostics of primary power equipment.

II. RESULTS AND DISCUSSIONS.

In most studies, only a limited set of parameters of primary power equipment—such as voltage, current, and temperature—are monitored. During real-time diagnostics, data are transmitted between the consumer and the power equipment via a controller, and in systems equipped with protection functions, this method proves to be highly effective. When interruptions occur in electrical networks, the GSM strategy enhances the communication speed of the system regardless of distance, thereby improving overall reliability [4,5].

Primary power equipment, particularly distribution transformers, can be integrated with monitoring and control systems to achieve more comprehensive supervision. The analysis of winding temperature, ambient temperature, current, voltage, and oil level in graphical form can also be effectively implemented through the use of microcontrollers. In short, the microcontroller serves as the key component in the early diagnostics of transformers, performing the crucial function of data integration and enabling the simultaneous monitoring of essential operational parameters.

International Journal of Advanced Research in Science, Engineering and Technology

ISSN: 2350-0328

IJARSET IMPACT FACTOR 7.150

Vol. 12, Issue 10, October 2025

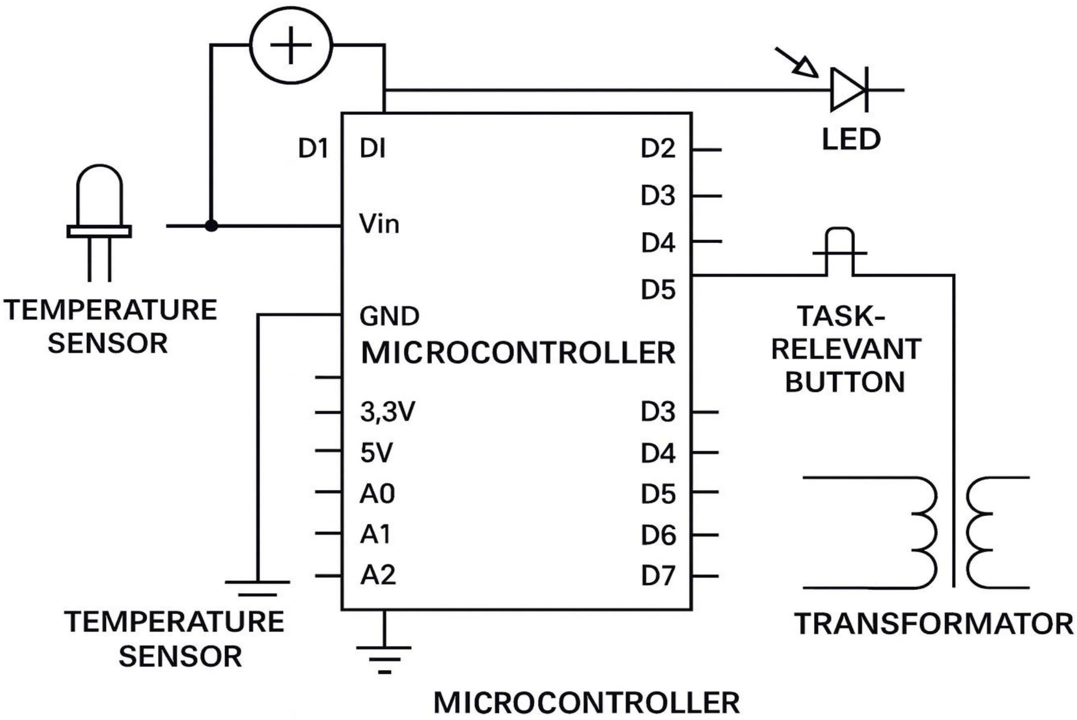

Figure 2. Working schematic of the microcontroller used for real-time diagnostics of the transformer.

In the early diagnostics of transformers, one of the most commonly used microcontrollers is the ESP32, which is equipped with two primary sensors — a temperature sensor and a current sensor. Through this configuration, it becomes possible to continuously monitor the temperature and current parameters of the transformer in real time[6,7].

At present, the diagnostics of oil-immersed transformers are carried out based on several approaches and parameters. These include visual inspection, Dissolved Gas Analysis (DGA) based on gas ratio percentages, insulation resistance testing (Megger diagnostics), infrared thermography, vibration and acoustic emission analysis, and the Digital Twin model, among others. Each of these diagnostic techniques focuses on a specific parameter of the transformer, analyzing its values either under operating conditions or when the transformer is disconnected from the network. Although such studies provide valuable insights into the transformer's technical condition, they do not yield precise information about its remaining useful lifetime (RUL).

The most effective and advanced diagnostic approach, as summarized in Table 1, is the Digital Twin method, which enables dynamic simulation and predictive assessment of the transformer's future performance based on real-time monitoring data and historical parameter trends.

Method Name	Main Parameter	Average Cost (USD)	Reliability (%)	Remarks
Visual Inspection	Oil color, oil leakage, external damage	Very low (100–500)	50–60	Detects only external defects; internal faults remain unnoticed.
Insulation Resistance Test (Megger)	Resistance, dielectric strength	Low (500–1,000)	65–70	Offline test; useful only during periodic checks.
Dissolved Gas Analysis (DGA)	Gases dissolved in oil (H_2, CH_4, C_2H_2, CO, CO_2, etc.)	Medium (3,000–10,000)	80–90	Primary method for early diagnostics;

				identifies fault type by gas ratios.
Infrared (IR) Thermography	Temperature, hot spots	Medium (≈5,000–8,000)	75–85	Shows overheating in contacts and insulation but cannot detect internal gases.
Vibration and Acoustic Emission	Mechanical vibrations, partial discharge signals	Medium (≈5,000–12,000)	80–88	Detects winding deformation and partial discharges; effective only as a supplementary method.
Online Sensor Monitoring	Temperature, current, voltage, oil level, load	High (15,000–25,000)	85–93	Provides real-time data but cannot perform independent prediction.
Digital Twin	Temperature, gas (DGA), load, voltage, vibration, acoustic signals, moisture	Very high (15,000–20,000)	95–99	Most advanced method; combines real-time monitoring with predictive modeling; estimates remaining life and ensures economic efficiency.

Table 1. Main diagnostic methods used for oil-immersed transformers.

As seen from *Table 1*, one of the most widely used methods for the early diagnostics of oil-immersed transformers is the Digital Twin approach, which relies on computer-based simulation modeling. The term *Digital Twin* refers to a “digital replica” or “virtual counterpart” of the transformer, which is why this diagnostic method bears that name. In essence, it represents the real operational behavior of the transformer—its load conditions, operating temperature, protection status, and other physical and electrical parameters—through mathematical and physical modeling within a computer environment [8,9].

The Digital Twin model continuously updates real-time data obtained from sensors, thereby reflecting the actual processes occurring inside the transformer. This integration of real and virtual systems enables accurate visualization, analysis, and prediction of the transformer’s operational condition and degradation processes, forming the foundation for intelligent diagnostics and lifetime assessment.

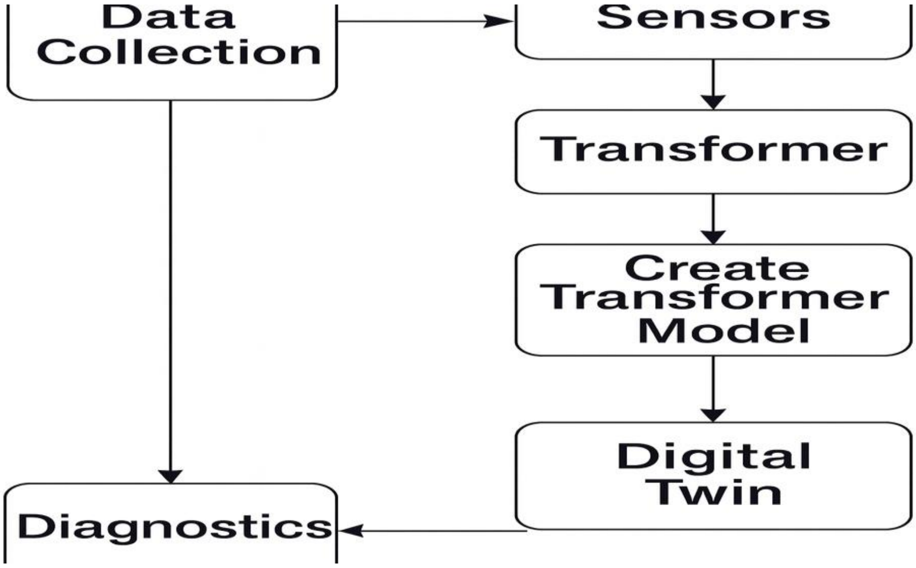

Figure 2. Sequence of oil-immersed transformer diagnostics using the Digital Twin method.

III. CONCLUSION

In the context of the Digital Twin method for oil-immersed transformer diagnostics, the key monitoring parameters include dissolved gases, oil temperature at the top and bottom parts of the transformer, load regimes, and the loading conditions under which the transformer is operating. This method enables direct real-time monitoring of how these parameters evolve. Although it is applicable from small-capacity oil-filled transformers up to high capacity ones, most research and empirical studies focus on large transformers because of the significant cost involved.

For example: to diagnose a 100 kVA oil-immersed transformer using the Digital Twin method under current conditions in Uzbekistan, one would require sensors (for temperature, dissolved gases in oil, vibration, etc.), a microcontroller, computer/server for model creation and operation, internet and communications equipment, plus installation, integration and maintenance services. The total cost of such setup is approximately 150–200 million UZS (Uzbekistani So'm). This cost is several times higher than the transformer's own purchase cost, making the diagnostic investment economically difficult to justify in many cases. Therefore it is recommended to apply the Digital Twin method primarily to large-capacity transformers, for example starting from 1 MVA and above—because economically, the diagnostic cost must be well below the asset cost to justify the investment [10].

In terms of reliability, modern diagnostic methods deliver accuracy rates in the range of 90-98 %, and in some cases approach 99 %; their prediction errors during in-service prognostics are also relatively low. The Digital Twin method surpasses many other diagnostics in both effectiveness and reliability. However, despite its superior precision, its primary limitation is that it mostly provides insight into the *current condition* of the transformer, rather than detailed information about specific resources or remaining lifespan. In short: while the Digital Twin method offers the highest diagnostic accuracy, in Uzbekistan's conditions its economic cost is high and it is *not* necessarily optimized for savings in structural or resource usage[11].

REFERENCES

1.Togaymurodov S.Z, Ataullayev N.O, Rasulova B.I " MOYLI TRANSFORMATORLARNI QOLGAN XIZMAT QILISH MUDDATINI BIRLAMCHI PARAMETRLARIDAN KELIB CHIQQAN HOLDA TASHXISLASH" Konchilik Xabarnomasi jurnali, Navoiy 2025 DOI:10.54073/GV.2025.3.102.021, 98-103 pages

2.S.Z Togaymurodov "TRANSFORMATORLARNING ISHLASH JARAYONLARIDA TEMPERATURANING O'ZGARISHI VA UNING TA'SIR NATIJASIDA MAGNIT O'ZAKNING FERROMAGNIT XUSUSIYATINI YO'QOTISH SABABLARI" Journal of Advances in ENERGY Engineering Technology Vol.6(18) Navoi, 2025, 37-41 betlar

3.Ataullayev A.O, Togaymurodov S.Z "Transformatorlarda magnit o'tkazgichlarining tashqi elektr maydonini kuchaytirishi sabablari" Fargona davlat texnika universiteti ilmiy texnik jurnali–2025/29/4 Farg'ona, 103-107 pages

4.de Azevedo, A. C., Delaiba, A. C., de Oliveira, J. C., Carvalho, B. C., & de S. Bronzeado, H. (2007). Transformer mechanical stress caused by external short-circuit: a time-domain approach. Proceedings of the 2007 IEEE International Power System Technology (POWERCON). ipstconf.org+1

5. Zahra, S. T. (2025). Power transformer health index and life span assessment. Electric Power Systems Research. ScienceDirect

6. Majzoobi, A., Mahoor, M., & Khodaei, A. (2017). Machine Learning Applications in Estimating Transformer Loss of Life. arXiv preprint. arXiv

7. Soleimani, M., & Kezunovic, M. (2020). Economic Evaluation of Transformer Loss of Life Mitigation by Energy Storage and PV Generation. arXiv preprint. arXiv

8. Moradzadeh, A., Pourhossein, K., Mohammadi-Ivatloo, B., Khalili, T., & Bidram, A. (2020). Radial Deformation Emplacement in Power Transformers Using Long Short-Term Memory Networks. arXiv preprint. arXiv

9. Köhler, M., et al. (2017). Load Assumption for Fatigue Design of Structures and Components. Springer. PDF библиотека

10. Dowling, N. E. (2012). Mechanical Behavior of Materials: Engineering Methods for Deformation, Fracture, and Fatigue (4th ed.). Pearson. dl.ojocv.gov.et

11. Budynas, R. G., & Sadegh, A. M. (2020). Roark's Formulas for Stress and Strain (9th ed.). McGraw-Hill. Википедия