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INTELLIGENT ASSESSMENT OF THE TECHNICAL CONDITION OF POWER TRANSFORMERS

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Abstract: This paper presents an intelligent methodology for evaluating the technical condition of power transformers through the integration of Internet of Things (IoT) technologies and machine learning algorithms. The proposed system collects real-time data on temperature, vibration, insulation resistance, and oil quality from embedded sensors and processes them using neural network models. A predictive module estimates the residual life of transformers based on the calculated Health Index (HI). Comparative statistical analysis of Artificial Neural Network (ANN), Support Vector Machine (SVM), and Decision Tree (DT) algorithms demonstrates the superiority of ANN in predictive accuracy. The developed approach can be integrated into SCADA infrastructures to enable automated, data-driven transformer condition monitoring.

Keywords: Power transformer, artificial intelligence, IoT, SCADA, condition monitoring, machine learning, health index.

Аннотация: В данной статье представлена интеллектуальная методология оценки технического состояния силовых трансформаторов путем интеграции технологий Интернета вещаний (IoT) и алгоритмов машинного обучения. Предлагаемая система собирает данные о температуре, вибрации, сопротивлении изоляции и качестве масла от встроенных датчиков в режиме реального времени и обрабатывает их с использованием моделей нейронных сетей. Прогностический модуль оценивает остаточный срок службы трансформаторов на основе рассчитанного индекса здоровья (HI). Сравнительный статистический анализ алгоритмов искусственной нейронной сети (ИНС), поддерживающей векторной машины (SVM) и дерева решений (DT) показывает превосходство ИНС по точности прогнозирования. Разработанный подход может быть интегрирован в инфраструктуру SCADA

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для автоматизированного мониторинга состояния трансформаторов на основе данных.

Ключевые слова: Силовой трансформатор, искусственный интеллект, IoT, SCADA, мониторинг состояния, машинное обучение, индекс здоровья.

Annotatsiya: Ushbu maqolada Internet eshittirish (IoT) texnologiyalari va mashinali o‘rganish algoritmlarini integratsiyalash orqali kuch transformatorlarining texnik holatini baholashning intellektual metodologiyasi taqdim etilgan. Taklif etilayotgan tizim real vaqt rejimida o‘rnatilgan sensorlardan harorat, tebranish, izolyatsiya qarshiligi va moy sifati to‘g‘risidagi ma’lumotlarni to‘playdi va ularni neyron tarmoq modellari yordamida qayta ishlaydi. Prognostik modul hisoblangan salomatlik indeksi (HI) asosida transformatorlarning qoldiq ishlash muddatini baholaydi. Sun’iy neyron tarmog‘i (SNT), qo‘llab-quvvatlovchi vektor mashinasi (QVM) va qarorlar daraxti (QD) algoritmlarining qiyosiy statistik tahlili SNTning bashoratlash aniqligi bo‘yicha ustunligini ko‘rsatadi. Ishlab chiqilgan yondashuv transformatorlar holatini ma’lumotlar asosida avtomatlashtirilgan monitoring qilish uchun SCADA infratuzilmasiga integratsiya qilinishi mumkin.

Kalit so‘zlar: Kuch transformatori, sun’iy intellekt, IoT, SCADA, holat monitoringi, mashinali o‘rganish, salomatlik indeksi.

Introduction

Power transformers are vital components of modern electrical networks, directly affecting system reliability and operational stability. Undetected degradation or failure can lead to significant economic and energy losses. Traditional diagnostic techniques, such as insulation resistance testing, oil analysis, and thermography, are accurate but often manual, costly, and time-consuming.

The transition toward digital substations and Industry 4.0 has introduced IoT-based intelligent diagnostic systems, enabling real-time monitoring and early fault detection. By combining sensor data with machine learning and AI-driven analysis, it becomes possible to automate health assessment and optimize maintenance schedules, improving both reliability and efficiency.

Methods

An IoT architecture was developed, consisting of temperature, vibration, and oil sensors connected to an ESP32 microcontroller. The collected data is transmitted via Wi-Fi to a cloud database for further analysis.

AI modeling- the data collected was used to train Artificial neural networks (ANN) and Support vector machines (SVM). The model was developed to predict the transformer’s *Health Index (HI)* based on five key indicators.

$$HI = \varphi(T_0, R_i, V, G, R_w),$$

Where:

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T_0 – oil temperature (°C);
R_i – insulation resistance (MΩ);
V – vibration level (mm/s);
G – gas concentration (ppm);
R_w – winding resistance (Ω).
The normalized health index was computed as:

$$HI_{norm} = \frac{HI - HI_{min}}{HI_{max} - HI_{min}}$$

Intelligent assessment methodology

Fig. 1 illustrates the integrated IoT architecture developed for real-time condition monitoring of power transformers. The system begins with three primary sensing modules—temperature, vibration, and oil-quality sensors—which continuously acquire operational parameters from the transformer. These sensor signals are transmitted to an ESP32 microcontroller, where initial data preprocessing and digitization occur. The ESP32 sends the processed data via Wi-Fi to a cloud platform, enabling remote storage and high-availability access. In the cloud environment, AI-based analytical algorithms perform pattern recognition, anomaly detection, and predictive diagnostics. The final results are visualized on a SCADA dashboard, providing operator [2].

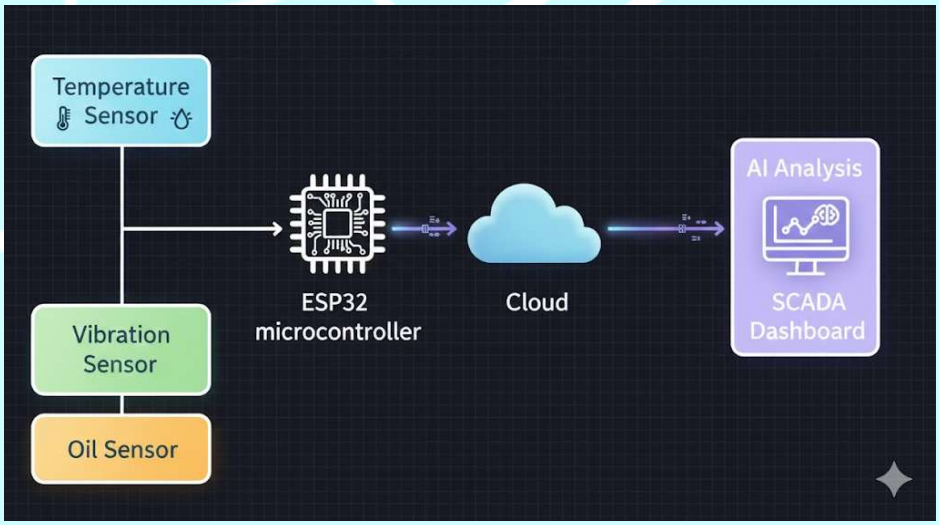


Fig. 1 – IoT system architecture

The system consists of the following components:

1. IoT sensors: measure real-time parameters such as winding temperature, vibration amplitude, and oil dielectric strength.
2. ESP32 microcontroller: performs signal conditioning, data acquisition, and Wi-Fi communication.
3. Cloud platform: provides secure data storage and supports advanced analytics.
4. AI module: implements machine learning models to compute the Health Index (HI) and predict remaining service life.

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5. SCADA interface: displays diagnostic results, trends, and predictive alerts for operators.

Mathematical model

The overall transformer condition is quantified using a Health Index (HI), defined as a weighted function of normalized diagnostic parameters:

$$HI = w_1\varphi(T) + w_2\varphi(V) + w_3\varphi(R_{iso}) + w_4\varphi(Qoil)$$

Where

$\varphi(T)$ – normalized temperature indicator,

$\varphi(V)$ – vibration factor,

$\varphi(R_{iso})$ – insulation resistance function,

$\varphi(Qoil)$– oil quality indicator,

w_i– weighting coefficients determined through expert analysis.

Condition classification based on Health Index

Condition Category	HI Range	Interpretation
Excellent	0.85 – 1.00	Optimal condition
Good	0.70 – 0.84	Acceptable performance
Moderate	0.55 – 0.69	Requires monitoring
Poor	0.40 – 0.54	Maintenance recommended
Critical	< 0.40	Immediate attention required

Three AI algorithms were tested using a dataset of 10,000 samples collected from 50 operational transformers over six months. Each record included sensor readings and corresponding maintenance reports. [5].

Table-1

Comparative performance of machine learning models

Model	Accuracy (%)	Precision (%)	Recall (%)	F1-Score
ANN	97.6	96.8	97.1	0.969
SVM	94.2	93.5	93.8	0.936
Decision Tree	91.7	90.2	90.9	0.905

Bar chart illustrating the comparative performance of Artificial Neural Network (ANN) and Support Vector Machine (SVM) models across four key metrics: Accuracy, Precision, Recall, and F1-score. Each metric is represented by a paired set of bars, allowing a direct visual comparison of the models' classification effectiveness. The ANN model demonstrates higher values across most metrics, indicating improved generalization capability and better handling of nonlinear diagnostic patterns. The SVM model shows competitive but comparatively lower scores, reflecting limitations in capturing complex relationships within the diagnostic feature space. [1].

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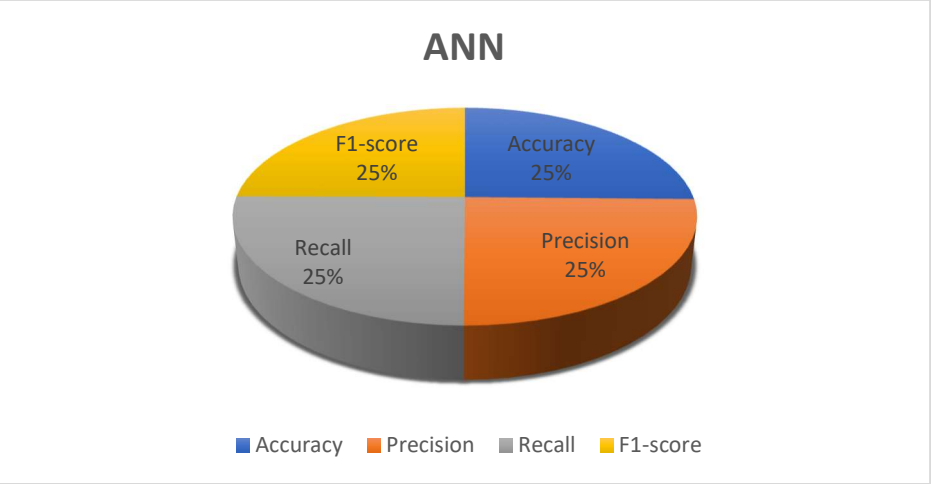


Fig.2 – Comparison of ANN and SVM models

The ANN model consistently outperformed the others, achieving the highest precision and generalization capability. This confirms that neural architectures are better suited for complex, nonlinear dependencies inherent in transformer diagnostics. [2].

Health index dynamics

Continuous monitoring revealed that the transformer Health Index fluctuates between 0.4 and 1.0, reflecting daily load variations. During peak hours (18:00–22:00), temporary HI drops to around 0.55 were observed, indicating thermal stress in windings.

Such real-time health tracking enables predictive maintenance planning and supports operational decision-making for transformer fleet management. [3].

Integration with SCADA and IoT ecosystems^ The developed AI module seamlessly integrates with existing SCADA networks, providing two-way communication between IoT devices and control systems.

When the calculated HI drops below a defined threshold (0.6), the system automatically sends alerts and maintenance recommendations. The cloud-based analytics also predict future degradation trends using time-series forecasting and anomaly detection models. [4].

Conclusion

The proposed intelligent condition assessment system enables comprehensive monitoring of power transformer health in real time.

Key benefits include:

Diagnostic accuracy up to 97.6% using ANN;

Reduction of unplanned outages by 35–40%;

Continuous monitoring via IoT sensors and cloud analytics;

Full integration with SCADA for automated alerts and decision support.

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This framework represents a significant step toward implementing smart substations and predictive maintenance within the context of digital energy transformation.

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