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Machine Learning-Based Real-Time Fault Prediction: Enhancing Distribution Transformer Health Monitoring System

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Abstract: Addressing the critical concern of real-time monitoring for transformers to mitigate potential operational problems due to damages, this paper highlights the substantial costs linked with maintenance and replacement, posing significant challenges. To address this, an IoT-based monitoring system is devised, ensuring continuous health assessment by tracking Voltage, Current, Temperature, and load capacity. The collected data is sent for analysis to a central server, offering insights into the broader electrical system's performance. IoT integration strengthens security, provides accurate environmental insights, and facilitates early fault detection, enabling prompt repairs and minimizing system failures. In contrast, traditional manual monitoring struggles to detect subtle changes, while IoT-driven remote monitoring requires a robust centralized data infrastructure and real-time transmission, preventing major faults and ensuring equipment protection. This approach reduces risks through centralized remote transformer data collection, complemented by machine learning techniques for proactive flaw prediction.

Keywords: *Transformer, Condition Monitoring Technique, Internet of Things (IoT), Machine learning, Fault detection*

1. Introduction

A substantial and crucial role in the electrical system network is played by the transformer. Transformers are everywhere; they can be seen almost anywhere. Having constant access to electricity is essential in the modern world since it supports everything from household necessities to business activities. Both homes and businesses depend on the steady supply of electricity. Operations could completely stop as a result of interruptions, which could cause serious financial losses.

By using IoT to monitor the health of electrical equipment, equipment may be proactively replaced before it fails, providing an uninterrupted power supply. A transformer's lifespan is closely correlated with its level of health [1][2]; greater longevity is associated with good health. Overburden and insufficient heating, which are frequent causes of transformer degeneration, highlight how important health care is. Prior until now, distribution networks did not fully integrate health monitoring systems, which resulted in post-failure fault detection and consequent blackouts. Due of enormous losses, this practise was subject to severe fines. Thus, the urgent need for a trustworthy health monitoring system to build preventive actions in advance and mitigate such problems and the consequences that go along with them arose.

The following are some of the problems that the existing health monitoring systems bring up:

(i) Standard transformer measurement techniques frequently concentrate on a single parameter. Even when some systems try to evaluate several parameters, the testing procedure takes time, which causes the system to operate slowly.
(ii) The consistency of detection systems is inconsistent, which lowers their accuracy. These systems display instability and unreliability due to slower fault detection [3][4][5][6][7].
(iii) The ability of monitoring systems to effectively track all user data relevant to transformers in order to control costs is lacking.

A monitoring system that can analyse distribution transformer real-time data is required given the aforementioned requirements. This system seeks to evaluate different operating parameters and rapidly transmit that information to a central monitoring facility. The Internet of Things (IoT) is useful in this situation. IoT makes it possible to continuously monitor distribution transformers' critical functioning features online, providing insightful data about their condition [8]. This information helps service providers maximise the use of transformers and increase their longevity. IoT helps to reduce penalties and provide cost-effective preventative solutions by seeing problems before they become more serious [9].

IoT is a better option than conventional systems since it guarantees greater stability and reliability.

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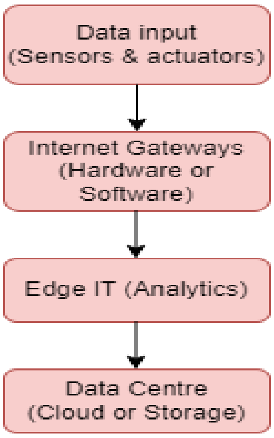


Fig 1. Basic IoT Technology Building Blocks

So, the integration of IoT and machine learning technologies has paved the way for a revolutionary approach to transformer health monitoring. This endeavour not only ensures the continuous and real-time assessment of transformer performance but also empowers us with the ability to predict and prevent potential failures. As the demand for reliable and efficient power distribution systems continues to grow, the development of an automated predicting and preventing real-time system for health monitoring transformers at the distribution end stands as a crucial step toward enhancing the overall stability and sustainability of our electrical networks.

The proposed study holds significant importance in preventing losses and ensuring power distribution system reliability through fault prediction. Automated real-time monitoring observes critical transformer parameters like current, voltage, temperature, and level, allowing early detection of faults and timely maintenance. Integration of machine learning enhances predictive capabilities, minimizing downtime and risks. IoT-based remote monitoring facilitates real-time data access and analysis for quicker responses to issues. Graphical representation aids data interpretation, reducing human errors. Timely maintenance and fault prevention improve energy efficiency and reduce costs. Overall, this study contributes to a reliable, efficient, and cost-effective power distribution system.

2. Literature Review

Electricity is a fundamental component of our daily life, and transformers are essential conduits for transferring it from stations. Systems for distributing electricity rely heavily on transformers. Transformer management and control have inherent risks. Transformers frequently encounter overload due to increased electrical consumption due to the high demand for power. The efficiency of the transformers is negatively impacted by this overload, which causes issues with the electrical distribution system. To guarantee continuous operation and efficiency, transformer overload concerns must be avoided.

Numerous businesses use pricey Supervisory Control and Data Acquisition (SCADA) systems to implement online monitoring solutions for transformers. Many transformers continue to be monitored manually, which involves staff member's physically inspecting and keeping data. IoT technology is used in a related study by Biju Rajan B et al. [10] to track the condition of distribution transformers. A Wi-Fi module is used to transmit collected data, and the HTTP protocol is used to enable worldwide access to it.

The system in the work by Rohit R. Pawar et al. [11] consists of two units: the monitoring unit and the remote terminal unit (RTU). The RTU uses the PIC 18F4550 to analyse variables such as current, temperature, changes in oil level, vibration, and humidity. After analysing the monitoring data, the system sends warnings to mobile phones whenever an irregularity occurs. GPRS is used to send data to the monitoring node and can also be used to get warnings via a webpage. During emergencies, the RTU's proximity activates a buzzer and LCD notifications. The suggested method establishes communication via a GSM/GPRS module to notify during critical circumstances in distribution transformers in recognition that constant observation by an engineer may not be practical.

2010 saw the introduction of a design by V. Thiyagarajan and T. G. Palanivel [12] that attempted to protect against current surges brought on by overloading. The current of a distribution transformer at a substation was being monitored by their system, which was based around a microcontroller [13]. The implementation of automatic control circuits for a Programmable Logic Controller (PLC) system to monitor transformer conditions including temperatures, load current, and voltage was covered by Satya Kumar Behera in 2014. Both internal and external transformer defects can be found with this PLC-based monitoring system. It can also monitor and control the temperature, current flow, and voltage inside a distribution transformer. The PLC system is carefully planned to guarantee ongoing monitoring of transformer operating parameters [14].

A design including a temperature sensor, a PIC microcontroller, an LCD display, a GSM board, and an Xbee module for communicating with the electricity board was unveiled by Vishwanath R in 2015. This technology is skilled in finding different three-phase transmission line faults. It enables real-time monitoring of temperature, voltage, and current through the use of a GSM modem. The construction of a system that successfully monitors transmission line problems by utilising the capabilities of the GSM network is the main goal of the paper [15][9].

Table 1. Limitations of existing approaches

Ref.	Techniques	Parameter	Description	Limitations
[16]	IoT	Oil level Oil temperature Current Voltage	Health condition monitoring	Requires sensors for oil level monitoring
[17]	ANN	Oil temperature Ambient temperature Current	Oil-Immersed Distribution Transformer Condition Monitoring	Inadequate precision
[18]	Thermal imager	Thermal imager	Real time distribution transformer monitoring	Expensive
[19]	Wireless	Voltage pulses	Without sensors	Useful only for dielectric health
[20]	Machine Learning	Oil temperature Vibration Transformer loading	Assess service transformer health	Limited parameters

Table 1 concise overview of the shortcomings and constraints associated with current methods and strategies in the field. This table highlights key limitations to provide a clear understanding of areas where improvements are needed.

3. Methodology

The proposed model introduces an approach for monitoring the health of transformers using Internet of Things (IoT) technology. This innovative system goes beyond mere monitoring by integrating a predictive capability through machine learning, which aids in the early detection of faults and subsequent alerts. The primary aim of this system is to mitigate substantial losses resulting from power system faults. By utilizing real-time data, it enables remote monitoring and precise fault localization, while also reducing the need for human intervention, thereby minimizing errors and bolstering overall accuracy.

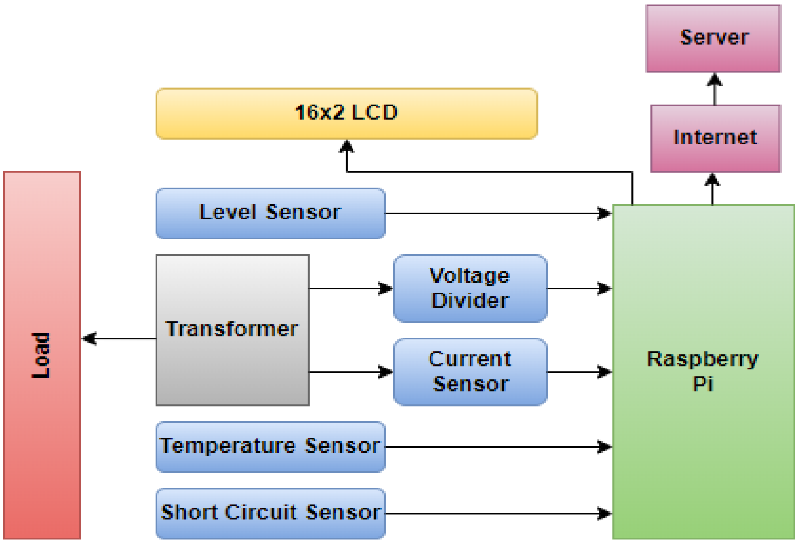


Fig 2. Automated predicting and preventing real time system for health monitoring transformer at distribution end

Figure 2 shows that the system's user interface is facilitated through an LCD screen, which conveniently presents crucial information such as the current (I) in milliamperes (mA), voltage (V), temperature (T), and the liquid level percentage (L). This comprehensive display ensures that users have immediate access to vital operational parameters.

To extend its usability and accessibility, the proposed system is seamlessly integrated with an Android application via WiFi connectivity. This integration enables users to visualize the real-time data remotely and in a user-friendly manner. The Android app serves as a conduit for data visualization, allowing users to monitor the transformer's performance and conditions even when not in close proximity to the physical system.

Graphical figures provide a clear visual depiction of data changes. Particularly, the fluctuations in the current, temperature, and liquid level parameters as seen on the IoT device are vividly captured in these pictures. This graphical representation improves user comprehension and gives a clear picture of the trends in the transformer's performance.

The system's capacity to effortlessly transfer real-time data via the network emphasises its operational effectiveness even more. A cloud server acts as a conduit between the IoT device and the Android app, enabling this real-time data exchange. The IoT gadget and cloud server communicate through WiFi, allowing for continuous and quick online presentation of the most recent operating data. This dynamic link guarantees that users receive the most recent information, promoting prompt decision-making and efficient control of transformer health.

4. Implementation

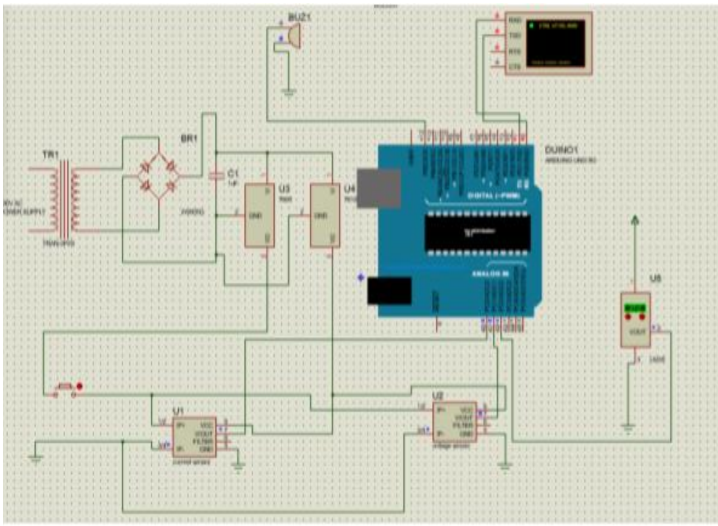


Fig 3. Circuit Diagram of the System

A thorough illustration of the interrelated parts of the monitoring system is provided by the circuit diagram (figure 3). The precise integration of crucial components, such as numerous sensors, a buck converter, a Raspberry Pi, and an LCD screen, is detailed in this thorough design. This complex system of interconnected parts works in unison to enable real-time monitoring and data visualisation of crucial transformer characteristics. The figure acts as a crucial blueprint, explaining the intricate relationships between each element and how they work together to ensure that information about current variations, voltage fluctuations, and temperature changes, and liquid level modifications is accurate and timely. The circuit diagram successfully captures the operation of the system through this visual depiction, highlighting its ability to improve transformer monitoring through precise data processing and display techniques.

Fig 4. Experimental setup

Overall, the suggested model not only builds a complex system for monitoring transformer health, but also makes use of machine learning and the Internet of Things to enable early failure detection and prediction. This helps to achieve the important goal of minimising losses brought on by power system defects, as well as expediting monitoring procedures, lowering errors, and eventually improving the accuracy and reliability of the overall system.

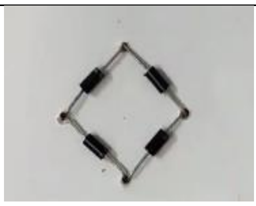
However, more than only data collecting plays a role in how effective this automated health monitoring system is. Strong data processing and analysis methods are essential if the acquired data is to be used to its full potential. Here is where machine learning and the Internet of Things converge. The system can deduce patterns and trends from the accumulated data by using sophisticated machine learning algorithms, which enables it to make predictions regarding the transformer's future health. By enabling maintenance teams to take preventative measures, this predictive capacity reduces risks and prevents system breakdowns.

5. Hardware Development

To harness this wealth of real-time information, an Internet of Things (IoT) device has been seamlessly integrated into the system. This IoT device serves as the central hub for data collection, efficiently gathering and transmitting the sensor-generated data from the transformer to a centralized data repository.

The hardware architecture elements of the proposed method are depicted in the Figure 2 including following components in table 3.

Table 2. Elements of the proposed method

Hardware's	Names	Specification	Configuration
	Transformer	Transfers energy between different voltage levels, enabling efficient power distribution and transmission	0-12 V, Metal Core, 1A, 230/12V
	Current Sensor	Measures and detects the flow of electric current within a circuit	230V/5A max, AC/DC
	Voltage Sensor	An instrument designed to measure and monitor the electrical potential difference between two points in a circuit	IN40007, Bridge Rectifier, 3A
	Temperature Sensor	A device used to detect and quantify the thermal energy of its surroundings	LM35, +10-mV/°C, −55°C to 150°C, 4 - 30 V
	Level Sensor	Gauges and reports the fluid or material level in a container or system	HC-SR04, Digital, 300cm, 5V
	Raspberry Pi	Raspberry Pi is a small, affordable computer board designed for various projects and educational purposes	Compute Module 4 I/O Board, 12 V, 160x90mm

	Load	The electrical device or component that consumes power from a power source	Incandescent Bulb, 12V/700mA, AC/DC, 8 watts
	LCD	LCD (Liquid Crystal Display) is a flat-panel technology used for visual displays that modulates light using liquid crystals	4 bit, 5V, 16x2, Blue Backlight, 32 Characters
	Buck Converter	A type of DC-to-DC converter that steps down voltage levels efficiently for various electronic applications.	LM2596, 3A max./38-4V

It needs phase voltage to three single-phase voltages with a 230V/12V rating.

6. Results and Discussion

The system's foundation lies in an IoT device that is linked to an array of sensors. These sensors gather diverse data pertaining to the transformer's operational parameters, and this data is subsequently subjected to analysis to identify any potential faults. The IoT system operates efficiently, promptly transmitting notifications in the event of any anomalies detected within the transformer's parameters. A noteworthy augmentation to this system is the incorporation of a machine learning model, which further enhances its capabilities. This machine learning model takes on the role of predicting transformer faults even before them manifest, adding an extra layer of preventive measures to the entire system.

Fig 5. Current Sensor Output

Figure 5 real-time current monitoring using a buck converter, with dynamic data displayed on an LCD screen connected to a Raspberry Pi for analysis.

Fig 6. Temperature Sensor Output

The figure 6 portrays intentional temperature variation at the transformer, with corresponding temperature values displayed on an LCD screen, showcasing the sensor's responsiveness and accuracy.

Fig 7. Level Sensor Output

Figure 7 depicts a level sensor accurately reflecting changes in liquid level by incrementally increasing the fluid, highlighting its precision and functionality.

In this study, a comprehensive observations are conducted utilizing a range of sensors to monitor various transformer parameters.

1. Current Sensor Output: To track current variations, a buck converter is employed, enabling real-time monitoring. The dynamic current data is then showcased on an LCD screen, which is interfaced with a Raspberry Pi for seamless visualization.
2. Voltage Sensor Output: Continuous voltage monitoring is executed to promptly detect fluctuations in voltage levels. This real-time tracking of voltage variations contributes to the early identification of potential issues.
3. Temperature Sensor Output: The investigation involves intentional temperature elevation at the transformer. Subsequent temperature variations are accurately captured and displayed on the LCD screen, allowing for effective analysis.
4. Level Sensor Output: By incrementally increasing the liquid level, the level sensor's functionality is thoroughly assessed. The sensor demonstrates its precision by promptly and accurately reflecting changes in the liquid level.

Through these observations, establishing a comprehensive understanding of the sensors' capabilities and their responsiveness to dynamic changes in transformer conditions. The data collected serves as a foundation for enhancing real-time monitoring mechanisms, ensuring the robustness and reliability of the entire monitoring system.

Benefits and limitations of the proposed module:

The transformer is equipped with an advanced array of sensors, strategically placed to measure critical parameters like current flow, voltage levels, oil composition, winding temperatures, oil levels, and short circuits. These sensors ensure thorough monitoring, offering a comprehensive view of the transformer's operational state.

The gathered data undergoes multifaceted analysis, using advanced algorithms and machine learning techniques to detect even subtle anomalies. By scrutinizing data patterns, potential issues are identified accurately and early, enabling timely intervention.

To validate the model's efficacy, it undergoes rigorous testing using the collected sensor data. The model is subjected to various operating conditions, including routine and challenging scenarios, while faults and disturbances are deliberately induced to evaluate its responsiveness and fault detection capabilities.

Through this meticulous testing, the model's performance is validated, affirming its robustness and reliability in safeguarding operational integrity. The synergy between cutting-edge sensor tech, IoT connectivity, and advanced analytics redefines transformer maintenance and reliability paradigms. This transformative solution ensures efficient and reliable transformer operation.

The IoT system is exceptionally responsive, instantly transmitting messages in the event of any fault observed in the transformer system related to the mentioned parameters. However, it's important to note that the system can be affected by external barriers such as high winds and adverse weather conditions, which might impact its reliability. Moreover, damages resulting from these conditions could potentially disrupt the system's functionality.

7. Conclusion

Amid the digital revolution, a dependable power supply is essential for machinery operation, driving the need to automate the power sector for reduced failures and costs. Advanced technologies prove effective in monitoring transformer health. IoT manages diverse data, aiding local and remote visualization. Raspberry Pi enhances local monitoring, lessening reliance on conventional computers. AI-based machine learning augments predictive capabilities for future failures. So, the integrated transformer health monitoring system merges sensor and IoT prowess for robust fault detection and parameter tracking. Precise measurements and validated components assure accuracy. IoT boosts efficiency, enabling swift fault communication and real-time parameter sharing. This fusion reshapes fault detection and adapts to power scenarios, elevating transformer performance and network stability. Study insights foresee issues, extending transformer life. Despite IoT enhancing monitoring, prepare for potential malfunctions like fire or short circuits during implementation, within this IoT-based solution's scope.

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