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A Review on Technologies Used in Transformer Health Monitoring Systems

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Abstract: Transformer health monitoring is a critical aspect of power system reliability, and numerous researchers have explored various technologies to enhance real-time monitoring and predictive maintenance. Reliable operation of distribution transformers is essential to achieve efficient power distribution. The conventional maintenance practices are reactive, which results in the faults being detected late, an increase in downtime, and higher operational expenditure. As communication technologies have improved, transformer health monitoring systems have been developed, which can offer real-time data collection and predictive maintenance, enhancing efficiency and reliability. This paper discusses different technologies employed for transformer condition monitoring, such as Bluetooth, GSM, Zigbee, LoRa, and other wireless communication technologies. Each technology has specific strengths regarding data transmission distance, power consumption, and network capacity. When these communication systems are combined with IoT sensors, the most important transformer parameters like temperature, voltage, current, and oil condition can be monitored continuously. The data is processed for fault prediction, allowing early warnings and preventive maintenance. The comparative study of these technologies identifies their applicability in various deployment scenarios based on coverage area, data rate, and cost-effectiveness. The paper also addresses how IoT and machine learning contribute to improving fault detection and maintenance optimization. Finally, the fusion of these technologies in transformer health monitoring systems can powerfully enhance operational efficiency, decrease failures, and prolong transformer lifespan.
Keywords: IoT , Zigbee , Bluetooth , GSM , THMS

I. INTRODUCTION

A transformer has a set of copper windings (i.e., primary and secondary) and magnetic core. Primary and secondary windings are kept isolated from each other and core. Mutual induction principle is applied to transfer power from one side to another. In operation various forces like expansion and contraction in the thermal cycles, core vibrations due to presence of the continuous electric flux, core heating due to the eddy currents, shape impact forces of over current and over flux that accurate when faults are caused, and thermal heating that is generally caused by overloading[6]. Transformer faults are generally classified as internal and through or external faults. Internal faults are the faults, which happen inside the transformer and can severely damage its insulation, which leads to its breakdown[2]. While external faults are the faults that occur beyond the transformer zone and cleared by the components downstream. Approximately 70 to 80 percent of transformer breakdowns are initiated by internal faults. Transformers are an integral part in electrical power grids, stepping up or stepping down voltage for power transmission and distribution efficiency. Since transformers handle high voltage and hostile environmental conditions, their on-time monitoring is needed to avert failures that result in power disruption, cost inefficiencies, and safety risks. Transformer Health Monitoring Systems (THMS) are implemented to monitor the health of transformers in real time, thereby aiding in the identification of probable faults at an early stage. A Transformer Health Monitoring System is a sophisticated technology that continuously monitors the most important parameters of a transformer, including temperature, oil condition, voltage, current, and insulation resistance. It employs sensors, data acquisition systems, and Artificial Intelligence (AI) to examine transformer performance and identify any anomalies. Conventional methods of transformer maintenance are based on regular inspections, which can be unable to identify problems that occur between maintenance periods. A real-time monitoring system provides round-the-clock surveillance, enabling operators to identify slight problems before they become catastrophic failures. Transformer health monitoring enhances efficiency by offering early fault detection, scheduling maintenance, minimizing downtime, and prolonging the transformer operating life. It also reduces the risk of expensive failures, guaranteeing a reliable and stable power supply. Contemporary THMS utilize Artificial Intelligence (AI) and the Internet of Things (IoT) to improve predictive maintenance. AI-based analytics can identify patterns in transformer performance data, while IoT-based remote monitoring enables operators to monitor several transformers from a single location.

Transformers suffer from different types of faults like insulation failure, overheating, short circuits, and oil dirt. Fault detection systems assist in detecting these types of faults early on, hence avoiding sudden failures of transformers due to power outages. Manual maintenance practices prove to be highly expensive and time-consuming, using fixed schedules over actual transformer states. Fault detection systems facilitate the practice of condition-based maintenance and minimize unnecessary expenditure on servicing in addition to rationalizing repair action. Overheating is the most frequent reason for transformer failure. Thermal sensors and infrared monitoring systems can sense increasing temperatures, allowing for corrective measures before the heat destroys insulation and other vital parts. Transformer oil is both a coolant and an insulator. Oil contamination or degradation may signal emerging faults. Sophisticated sensors are able to scan dissolved gases in the oil to identify problems like partial discharges, arcing, and overheating. Transformer failure may lead to power outages impacting industries, companies, and residential areas. Through early identification of faults, detection systems allow prompt intervention, limiting downtime and preserving power system stability. Transformer failure is potentially hazardous to result in conditions like explosions, fire, or electrical shock. Fault detection prevents accidents by allowing transformers to stay within safe conditions and minimize the likelihood of calamitous failure.

A. *Transformer Health Monitoring Systems and Typical Faults Identifiable at an Early Stage*

Transformers play a key role in electrical power systems, enabling the safe and efficient transfer of electricity. It is imperative that they are reliable and long-lasting, and this is where transformer health monitoring systems (THMS) become critical. They employ sophisticated sensors to track vital parameters, identify faults at an early stage, and avoid sudden breakdowns.

B. *Real-Time Condition Monitoring*

The transformer health monitoring systems give permanent real-time feedback on major performance parameters like temperature, oil quality, and electrical insulation. With this pre-emptive attitude, problems can be detected beforehand before they build up to big failures.

C. *Predictive Maintenance Approach*

In contrast to conventional periodic maintenance, which might miss concealed faults, health monitoring systems make predictive maintenance possible. Trends in the sensor data are examined by operators, and maintenance is scheduled on time to prevent the high cost of emergency maintenance.

D. *Preventing Transformer Failures*

Transformer failure leads to power outages, economic losses, and safety risks. Monitoring systems can detect faults early, and corrective action can be taken, preventing unforeseen breakdowns.

E. *Enhancing Operational Efficiency*

Transformer efficiency is based on effective load management and cooling performance. Monitoring systems enable transformers to be optimized for operation through the provision of information regarding load fluctuations, temperature changes, and other performance factors.

F. *Safety and Compliance*

Failure of transformers may result in unsafe conditions like fires, explosions, or electrical faults. A health monitoring system maintains safety standards compliance by detecting and preventing risks ahead of time.

G. *Typical Transformer Faults that Can Be Detected at an Early Stage*

1) *Overheating and Thermal Stress*

Overheating causes insulation to deteriorate and fail. Abnormal heat buildup is sensed by temperature probes and infrared sensors so that cooling actions can be taken in time.

2) *Insulation Degradation*

Winding and oil insulation deteriorates with the passage of time under electrical and thermal stress. Partial discharge sensors and dissolved gas analysis (DGA) sensors sense insulation weaknesses prior to causing short circuits.

3) Oil Contamination and Moisture Ingress

Transformer oil is also vital for cooling and insulation. Moisture content and dielectric strength of oil-measuring sensors are able to detect contamination and hence prevent breakdown of insulation and failure of transformers.

4) Winding Short Circuits and Electrical Faults

Short circuits between turns and winding deformation are likely to result in calamitous failures. Fault detection through current and voltage sensors, coupled with frequency response analysis, facilitates these faults at an early level.

5) Vibration and Mechanical Deformation

Loose joints, central movement, and mechanical stress induce abnormal vibrations, resulting in failures. Vibration sensors and acoustic emission monitoring identify such faults early, enabling corrective action.

II. LITERATURE REVIEW

This section reviews key studies that have contributed to the development of transformer health monitoring systems using wireless communication technologies such as Bluetooth, GSM, Zigbee, and LoRa. Hongyan Mao [1] has employed GPRS for wireless communication and LPC2132 module as central processor for data communication, and GR47 module is utilized for data link. Setup of GPRS and network is performed previously as it causes an issue without setting up. Various transmission methods of data were also employed for the communication as every time different IP addresses were obtained by devices. J. Crossey, W. Ferguson [2] have demonstrated how Dissolved Gas Analysis (DSA) is a well-experienced and well-established technique of transformer diagnosis. Approximately 70% of the faults can be identified by it. The faults faced by DGA are partial discharge named the corona. Each fault forms various key gases with varying gas ratios that can be easily determined. SH. Mohamadi and A. Akbari [3] have introduced a model in which they have employed DTMAS software for the analysis. A transducer box is utilized to make the measurement signal compatible for transmission by GSM modem. DTMAS softwarecan also be employed when there are multiple transformers where different layers are employed in the process. An alarming layer of DTMAS compares the values with the rated one andgenerate an alarm accordingly. Avinash Nelson, Gajanan, Makarand, and D.R. Tutakne [4] have demonstrated an effective technique for improved life oftransformers. Since the life of the transformer is reduced owing to overloading and they approached the transformer's health index monitoring by computing with some algorithm for the prediction of health status. Humming sound is also employed for prediction based on frequency spectrum Pawar and Deosarkar [5] have given a paper in which they have implemented a mobile embedded system. In which GSMGPRS technology has been utilized for monitoring of the distribution transformer. The control unit was split into two sections in which the first section is the Remote Controlling Unit (RTU) in which data is gathered from sensors and the second section is at the monitoring node in which software is present for monitoring parameters of the transformer and the information is shown on engineers screen.. Sajidur Rahman and Nipu Kumar Das [6] have employed a wireless module system which employs SMS (short message service) to assign mobile telephones to receive information about any abnormality at the transformer location. Because this method is wireless, it is very cost-effective. The utilization of PIC16F877A microcontroller makes the system act as a real-time embedded system that meets the industrial requirements.. A new technique is experimented by Tarun Kanti Roy and Tusher Kanti Roy [7] where they have utilized Messaging Queuing Telemetry Transport (MQTT) rather than HTTP because it is suitable for the response of client-server communication. MQTT consumes less bandwidth compared to HTTP and also less power. This can be obtained while login to the gateway even using mobile devices and this feature is not supported by GSM.. Diagnosis of vibration spectrum has been depicted in the paper by Md. S Naderi and Oveis Abedinia [8] in which vibration spectrum frequency gets disturbed upon introducing faults within it. They have also generated the graph through which they have arrived at the conclusion that an increment in Short Circuit Current (SCC) increases the gap between the healthy and faulty characteristic curve indicates that SCC influences the vibration spectrum. Hassan Jamal, Ayesha Anjum, and Mohsin khan Janjua [9] have laid out the overloading solution in Distribution Transformer in their article. They have also deleted the full loss of the transformer and shedding load when faults occur. They have utilized the feature of backtalk where the operating person can make control requests for protection redundant. DC fan is also applied for cooling. A program is formed for maintaining the range of mean value of current to match with a threshold value. The mechanism involves transistors interfaced with the ports of Node MCU (Microcontroller). Priyanka R. Chaithshree N [10] has employed a Raspberry Pi microcontroller with a different approach. First, sensors and raspberry pi modem initialization are carried out. Then the desired data are measured from the sensor and then raspberry pi begins matching the received values with the saved values and even if any of the parameters rejects the saved values then the action of sending alerts initiates through the Twilio cloud server and this procedure goes on until decision making output logic becomes negative.

A. GSM, Bluetooth and ZigBee as Technologies for THMS Communication Interface

Patel & Sharma (2018) proposed a GSM-based transformer monitoring system that enables real-time data transmission to a remote monitoring station. The study highlighted how GSM networks effectively transmit voltage, current, and temperature data, allowing for early fault detection and reduced downtime. Kumar et al. (2019) designed a Zigbee-based wireless sensor network for transformer monitoring, emphasizing its low power consumption and short-range communication capabilities. Their findings suggested that Zigbee networks are ideal for local transformer monitoring within substations. Singh & Verma (2020) investigated the use of LoRa technology for long-range transformer health monitoring. Their study demonstrated that LoRa's low power and long-range capabilities make it suitable for monitoring transformers in remote locations where GSM coverage is limited. Rahman et al. (2017) developed a Bluetooth-based monitoring system that allows nearby technicians to access transformer health data through mobile applications. The research indicated that Bluetooth is suitable for on-site diagnostics but has limitations in remote monitoring applications. Zhang et al. (2021) explored IoT-enabled multi-sensor fusion techniques, integrating Zigbee and LoRa for comprehensive transformer monitoring. Their system achieved high accuracy in fault detection by combining real-time sensor data with predictive analytics. Ali et al. (2022) introduced an AI-driven transformer monitoring system using GSM and LoRa. Their study demonstrated that combining AI with real-time sensor data significantly improves fault prediction and reduces false alarms. Gupta & Rao (2016) proposed a GSM-based system with SMS alert functionality to notify maintenance teams of transformer abnormalities. Their research found that GSM remains a cost-effective and widely available communication technology for transformer health monitoring. Wang et al. (2019) compared the performance of Zigbee and LoRa for transformer monitoring applications. Their study concluded that Zigbee is more suitable for high-data-rate, short-range applications, while LoRa is better for low-data-rate, long-range scenarios. Prasad et al. (2020) developed a hybrid monitoring system combining Bluetooth and GSM to offer both local and remote monitoring capabilities. Their research highlighted the advantages of using multiple communication technologies to enhance system reliability. Chen et al. (2023) explored the integration of edge computing with LoRa-based transformer monitoring. Their study demonstrated that edge computing reduces data transmission latency and enhances real-time decision-making for predictive maintenance. This review highlights the strengths and limitations of various wireless communication technologies in transformer health monitoring. While GSM and Zigbee are well-suited for urban areas with reliable network coverage, LoRa emerges as a promising solution for remote transformer monitoring due to its long-range capabilities. The integration of AI and IoT further enhances fault prediction, paving the way for more efficient and proactive maintenance strategies.

B. Sensors Used in THMS

1) Temperature Sensors

Type: Resistance Temperature Detectors (RTDs), Thermocouples, Infrared (IR) Sensors
Function: Measures temperature of transformer windings, oil, and core to indicate overheating.
Importance: Averts thermal stress, breakdown of insulation, and transformer failure by initiating cooling processes.

2) Dissolved Gas Analysis (DGA) Sensors

Type: Gas Chromatography Sensors, Online DGA Sensors
Function: Detects gases dissolved in transformer oil, including hydrogen, methane, ethylene, and carbon monoxide, to identify internal faults.
Importance: Assists in detecting early-stage problems such as arcing, overheating, and insulation deterioration.

3) Moisture Sensors

Type: Capacitive and Optical Moisture Sensors
Function: Measures the moisture level in transformer oil and insulation.
Importance: Avoids insulation failure due to excessive moisture, which lowers dielectric strength.

4) Partial Discharge (PD) Sensors

Type: Ultrasonic Sensors, High-Frequency Current Transformers (HFCT), Acoustic Emission Sensors
Function: Detects tiny electrical discharges in insulation that signal early insulation failure.
Importance: Prevents insulation breakdown, which can result in disastrous failures.

5) Vibration Sensors

Type: Accelerometers, Piezoelectric Sensors
Function: Picks up unusual vibrations due to loose terminations, core shift, or mechanical stress.
Importance: Maintains mechanical stability and prevents structural damage to the transformer.

6) Voltage and Current Sensors

Type: Potential Transformers (PTs), Current Transformers (CTs), Rogowski Coils
Function: Measures voltage and current levels to identify overloads, short circuits, and phase imbalance.
Importance: Guarantees transformers run within secure electrical parameters, avoiding overloading and breakdowns.

7) Oil Level Sensors

Type: Float Type, Ultrasonic, Optical Sensors
Function: Detects the oil level in transformers to avoid oil spillage and ensure cooling effectiveness.
Importance: Guarantees adequate insulation and cooling, avoiding overheating and transformer failure.

8) Humidity Sensors

Type: Capacitive and Resistive Humidity Sensors
Function: Detects the humidity within transformer enclosures to monitor moisture buildup.
Importance: Prevents deterioration of insulation and corrosion caused by excessive humidity.

9) Pressure Sensors

Type: Piezoelectric Pressure Sensors, Strain Gauge Sensors
Function: Measures internal transformer pressure to register abrupt pressure buildup as a result of faults such as arcing.
Importance: Avoids explosion hazards through operation of pressure relief systems as needed.

10) Load Sensors

Type: Strain Gauge Load Cells, Smart Load Monitors
Function: Records electrical load on the transformer.
Importance: Facilitates load balancing to avoid overload, which might cause overheating and failure.

C. Need for AI integration in Transformer Health Monitoring Systems and Predictive Maintenance

Transformers are critical building blocks in the power distribution networks, and they can cause high-cost downtime, electrical outages, and hazardous conditions if they fail. Most traditional monitoring technologies are reactive, and they suffer from limited effectiveness in identifying fault stages at their initial stages. But the adoption of Artificial Intelligence (AI) in transformer health monitoring systems is revolutionizing the maintenance approach with real-time diagnostic capabilities, predictive analysis, and fault detection using automation.

1) Improved Fault Detection and Diagnosis

Monitoring systems based on AI utilize machine learning (ML) and deep learning (DL) techniques to process data from multiple sensors. These monitoring systems can identify even slight deviations that may signify impending failures, enhancing early fault detection.

2) Real-Time Monitoring and Decision-Making

AI allows real-time data gathering and analysis, triggering immediate alerts for abnormal situations. This enables utility operators to take immediate corrective measures, avoiding transformer failures before they occur.

3) Pattern Identification and Predictive Analysis

AI programs can recognize patterns and trends in transformer operating performance data that would go unnoticed by human operators. AI can predict failures with high accuracy and recommend preventive action by analyzing historical and real-time data.

4) Elimination of False Alarms

Conventional monitoring systems tend to trigger false alarms caused by sensor noise or changes in operating conditions. AI-based systems are able to differentiate between regular variations and genuine faults, avoiding unnecessary maintenance activities.

5) Optimized Load Management

AI-based health monitoring enables utilities to optimize the load distribution on transformers through predicting stress points and possible failures. This maximizes efficient use of energy and avoids transformer overloading.

III. CONCLUSION

Transformer Health Monitoring Systems (THMS) are essential for maintaining the reliability, efficiency, and lifespan of transformers in today's power networks. THMS utilize sophisticated sensor technologies to monitor critical parameters like temperature, dissolved gases, water content, and electrical loading in real-time. By picking up on early warning signs of incipient failure, THMS facilitates predictive maintenance, mitigating the risk of sudden failures, expensive repairs, and power outages. The convergence of Artificial Intelligence (AI) and the Internet of Things (IoT) has further augmented the functionality of these systems to enable real-time data analysis and remote monitoring for enhanced operational effectiveness. Fault detection mechanisms in THMS are critical to detect problems such as overheating, insulation deterioration, and mechanical stress before they become major failures. Conventional maintenance practices, based on regular checks, tend to miss concealed faults that occur between servicing periods. With the implementation of smart monitoring technology, however, power utilities are able to move from reactive to predictive maintenance, aligning maintenance schedules for optimal efficiency and increasing the lifespan of transformers. Such a forward-looking approach not only improves safety but also reduces the cost of maintenance and minimizes the environmental footprint of transformer failures. In summary, the transformer health monitoring system review emphasizes the need for continuous monitoring, predictive analysis, and fault detection in contemporary power systems. The combination of advanced technologies guarantees transformers are run within secure parameters, enhancing energy efficiency and grid stability. With increasing demand for reliable electricity, investment in sophisticated health monitoring solutions will be crucial to guaranteeing the smooth operation of transformers and the viability of power infrastructure.

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