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Systematic Review

Condition Monitoring of Electrical Transformers Using the Internet of Things: A Systematic Literature Review

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Featured Application: IoT-based transformer monitoring enhances predictive maintenance, reduces downtime, and optimizes power grid reliability and efficiency in smart grids.

Abstract: The adoption of Internet of Things (IoT) technology for transformer condition monitoring is increasingly replacing traditional methods. This systematic review aims to evaluate the existing research on IoT frameworks used in transformer condition monitoring, providing insights into their effectiveness and research trends. This review seeks to identify the leading IoT frameworks employed in transformer condition monitoring; analyze the key research objectives, methods, and outcomes; and assess the global research distribution and technological tools used in this field. A systematic literature review was conducted by searching published databases using keywords related to "Internet of Things", "transformers", "condition monitoring", and "fault diagnosis". The search spanned publications released between 2014 and 2024, yielding 262 articles. Of these, 120 met the predefined review criteria and were included for further analysis. This review found that Arduino boards are the most used microcontrollers for monitoring and analyzing transformer operational parameters, with Arduino IDE 1.8 being the predominant software for programming. The primary research focus in the reviewed literature is the identification of transformer faults. The geographical distribution of research contributions shows that India leads with 65% of the studies, followed by China (11%) and Pakistan (5%). The findings indicate a strong global interest in developing IoT-based transformer condition monitoring systems, particularly in India. This review highlights the potential of IoT technologies to enhance transformer monitoring and diagnostics. The insights gained from this review can guide future research and the development of more advanced IoT frameworks for transformer condition monitoring.

Keywords: condition monitoring; electrical transformer; systematic literature review; Internet of Things

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1. Introduction

The primary goal of the Internet of Things (IoT) is to link physical objects with digital world together so that they can exchange data and communicate. The IoT involves embedding sensors and actuators in physical objects (including nature, people, and animals) [1]. These sensors monitor changes (e.g., temperature, motion) and communicate via wired or wireless networks with computing systems [2]. The phrase "Internet of Things" originated in 1999 from Kevin Ashton, a British computer scientist. Ashton suggested embedding radio-frequency identification (RFID) computer chips to track products within a supply chain. The Internet of Things has made big breakthroughs in industries like pharmaceuticals and smart homes. Previously, only computers, smartphones, and tablets had access to the Internet; now, the IoT allows devices to be connected to the Internet to exchange data. The number of devices connected to the Internet is rapidly increasing. In [3] it is stated that at the end of 2023, there were approximately 16.1 billion connected IoT devices,

which is expected to rise to 39.9 billion by 2033. Condition monitoring of transformers is crucial to ensure their reliability and prevent unexpected failures [3]. Current practices require that a team of technicians be dispatched on-site to manually assess the condition of transformers; this process is subject to human error and hampers continuous condition monitoring. To achieve their return on capital investment, every owner of a transformer wants to see that such crucial equipment runs as efficiently and productively as possible. Historically, transformer owners have maintained this equipment using predictive and corrective maintenance techniques. Although it requires utility in labor, downtime, and non-routine maintenance requirements, corrective maintenance ensures that transformer parts can be used without reservation. By carrying out preventive maintenance, which involves determining the lifespan of specific parts and carrying out maintenance before actual breakdown occurs, several utility owners have been able to utilize transformers for long periods of time. Although the high costs of labor, planned downtime, and underuse of the component during its operational lifespan persist, this strategy prevents unanticipated and catastrophic failures. Utility owners are now leaning toward developing a predictive maintenance model that improves the maintenance cycle and follows a corrective and preventative maintenance approach, thanks to the development of the Internet of Things (IoT). Just-in-time component replacement is a strategy used in predictive maintenance. By reducing unplanned maintenance and labor expenses, this technique extends a component's lifespan, in addition to replacing components that are closer to failure. It was not until 2014 that early research on the application of IoT technology, specifically in transformers, began to surface [4,5]. The evaluation of IoT applications' timeliness, prediction, and visibility in comparison to traditional monitoring systems was a specific focus of this review. A total of 262 academic publications that were published between 2014 and 2024 were evaluated based on predefined criteria. PRISMA for systematic review was employed to evaluate the 262 publications. PRISMA refers to Preferred Reporting Items for Systematic Reviews and Meta-Analyses [6]. PRISMA mainly gives recommendations for the presentation of systematic reviews that evaluate the effectiveness of interventions [7]. Some critical aspects of the PRISMA 2020 checklist were adopted and used in this review paper to conduct an effective systematic literature review. After the screening process, a total of 120 publications were considered for this review. A detailed examination of the primary research elements of IoT technology in transformer condition monitoring, including the type of transformer or physical item, the examined transformer aspect, the microcontroller, the communication channel, and the cloud, was conducted. Eight research questions described below are presented in this systematic literature review (SLR):

- What are the primary research objectives and goals addressed in the collected literature on Internet of Things technology for electrical transformer condition monitoring?
- Which research methods and approaches have been predominantly utilized in the literature to study IoT applications in transformer monitoring?
- From which countries or regions do most of the articles on IoT technology for transformers originate?
- What specific software and tools have been frequently mentioned and employed in the articles related to IoT technology in transformer condition monitoring?
- How has the research landscape on IoT technology for electrical transformer monitoring evolved, and what trends emerge from the collected literature?
- What emerging opportunities and technological advancements are highlighted in the collected literature that may shape the future of transformer monitoring using IoT?
- Which transformer types does the collected literature investigate?
- What are the common challenges and limitations documented in the collected literature regarding the implementation of Internet of Things technology in transformer condition assessment?

1.1. Rationale

The current literature reviews provided knowledge about both the technical and operational components of transformer condition monitoring through the IoT. However, there is a dearth of in-depth analysis of how this new technology will be deployed, what the obstacles of adoption and sustainability are, and what the uniformity over time will be. Furthermore, depending on various features of the IoT and geographies, the benefits of IoT-based transformer condition monitoring may change, complicating the situation. IoT-based transformer condition monitoring has grown swiftly and is altering the technology world, offering benefits such as interoperability, dynamic capabilities, scalability, and affordability, which transformer operators and utility owners value. However, the use of the IoT is growing in other areas such as smart homes, agriculture, and pharmaceuticals. Nevertheless, there is a lack of broad comprehension of the adoption of an IoT smart monitoring system for electrical transformers and its overall effectiveness. This systematic review seeks to generate a body of information regarding the present results of using IoT technology for transformer condition monitoring. This assessment aims to identify the developments, possibilities, and issues connected with the use of IoT technology to collect real-time data needed to track the condition of transformers. Various studies published on the subject were reviewed. This evaluation will provide helpful information to transformer operators, stakeholders, and academics.

1.2. Objectives

The Internet of Things (IoT) has transformed everyday life, and breakthroughs have been made to revolutionize transformer condition monitoring. The IoT provides various advantages, including affordability, scalability, interoperability, dynamic capabilities, and improved business processes. However, the deployment and long-term viability of this new technology in power system environments remain crucial areas of research. The purpose of this systematic review is to investigate what various researchers have accomplished in terms of real-time transformer condition monitoring utilizing IoT technology. This study will undertake a thorough evaluation of the key research elements of IoT technology in transformer condition monitoring, such as the type of transformer or physical item, the analyzed transformer aspect, the microcontrollers, the communication channel, IoT clouds, and sensors. By examining these research factors, this study seeks to provide a comprehensive understanding of how the introduction of the Internet of Things will change transformer condition monitoring. Thus, the objectives of this research are as follows:

- Determine how the integration of various sensors is achieved to ensure effective transformer condition monitoring using IoT systems.
- Understand how different types of microcontrollers and peripherical components are used to develop an IoT prototype for transformer condition monitoring.
- Evaluate the acceptance of IoT-based transformer condition monitoring.
- Evaluate the Internet of Things' role in improving transformer condition monitoring compared to previous methodologies.
- Investigate the long-term implications and viability of transformer condition monitoring using IoT technology.
- Determine the common challenges and limitations documented in the collected literature regarding the implementation of Internet of Things technology in transformer condition assessment.

1.3. Research Contribution and Novelty

The task at hand includes evaluating novel aspects. Based on the writers' current understanding, there is currently no previous research in the published literature that presents a PRISMA systematic review of Internet of Things-based transformer condition monitoring, solely concentrating on the interfacing of multiple sensors to form a community of sensors to ensure effective transformer condition monitoring in a real, practical environment setting. This study follows a PRISMA 2020 checklist to present a complete examination of

an IoT-based transformer condition monitoring system. This study further presents the most preferred transformer types, investigated aspects, IoT clouds, microcontrollers, and IoT implementation challenges such as standardization, data security, and the computing power of IoT cloud services and microcontrollers.

With regard to the rapidly developing field of Internet of Things technology for electrical transformer condition monitoring, this SLR significantly advances the field. It serves as a thorough and perceptive examination of the most recent advancements and patterns in this developing field. This SLR carefully examines the field of research, including important details about the main goals of the study, the publications that are most recommended, the study's place of origin, and the types of transformers that are being examined. It also revealed microcontrollers, communication channels, software for programming the microcontrollers, tools, and IoT cloud platforms that researchers chose, providing insight into their preferences. Notably, this SLR explores the type of transformers being investigated and the investigated aspects. Power and distribution transformers are highlighted, and the types of transformers that have been the subject of research are categorized and discussed. This SLR also provides a temporal perspective, illuminating the dynamic progress of this field's study. It points out typical problems and restrictions with the use of the Internet of Things and highlights new developments and prospects that could influence the direction of transformer monitoring with the IoT in the future. This SLR essentially acts as a lighthouse, shedding light on the present situation and future direction of a revolutionary technology that is poised to completely alter the field of electrical transformer condition monitoring. This literature review is important because it demonstrates the potential to change how the power systems industry approaches transformer condition monitoring and maintenance through the implementation of IoT monitoring systems. This literature review provides a workable substitute for more conventional, costly techniques by reviewing an affordable IoT-based transformer condition monitoring system. A wider range of power utilities, even those in resource-constrained regions, can now access advanced monitoring technology thanks to the use of inexpensive components like Arduino boards, Raspberry Pi, ESP32, ESP8266, etc.

The early identification of any faults is made possible by real-time monitoring of critical transformer parameters like voltage, current, temperature, and oil level. This prolongs the life of transformers and makes timely maintenance possible, thereby averting catastrophic failures. Moreover, IoT integration makes it easier to gather data continuously and remotely monitor systems, which eliminates the need for manual inspections and on-site visits. This increases operational efficiency, saves a significant amount of money, and optimizes resource allocation for power utilities. The suggested system's modular architecture guarantees its scalability and adaptability to different kinds of transformers and power systems, making it simple to expand and customize in accordance with operational and monitoring requirements. Furthermore, this study offers a useful illustration of the Internet of Things use in power systems, making it an important teaching resource for scholars and students. The components and software utilized are open source, which promotes additional innovation and advancement in the industry. The IoT monitoring system advances the development of smart grid technologies by incorporating IoT-based monitoring into transformer maintenance procedures, thereby facilitating the shift to more resilient, intelligent, and efficient power grids.

1.4. Study Implications

The findings of this systematic literature review (SLR) on Internet of Things technology for electrical transformer condition monitoring have important ramifications for scholars and practitioners in the field. This SLR emphasizes the importance of giving priority to research areas including fault identification, health index development, and lifecycle management since these are essential to guaranteeing the dependability and efficiency of transformers. Furthermore, the preference for conference publishing over journal articles implies that researchers ought to think carefully about the publication medium they choose,

striking a balance between thorough peer review and quick distribution. India's leadership in this area emphasizes the possibility of international cooperation and promotes a thorough comprehension of applications for the Internet of Things. Moreover, the multiplicity of modeling techniques, AI algorithms, and software tools highlights how crucial it is to customize these decisions to research goals. This work has been organized as follows: Section 2 covers the conceptual and methodological aspects of IoT technologies in transformer condition monitoring. Section 3 introduces the research methodology based on the PRISMA 2020 guidelines, Section 4 presents the results and discussions of the review, and the following section concludes this work.

2. Literature Review

2.1. Transformer Maintenance: A Review

In the power industry, the field of maintenance expertise has started to change in recent years. It is customary to immediately shut down the transformer when a fault is found in the production area to prevent negative impacts; nevertheless, doing so typically requires significant time and financial loss and is best carried out at opportune times [8]. Utility owners have therefore developed a new maintenance action plan to prevent malfunctions and minimize financial losses. Maintenance can be divided into two types of action plans: proactive and reactive. While post-fault diagnostic conditions and economic losses are present in a reactive action plan, the major goals of a proactive maintenance action plan are to save costs and keep the system operating at its peak capacity. As a result, prognostic (i.e., predict and prevent) techniques have replaced diagnostics (i.e., fail and fix) procedures in the maintenance action plan [9–11]. Utility owners can use sensors and digital platforms to gain insights about the state of their transformers as part of the Fourth Industrial Revolution. By converting these data and comparing them with other anomalous circumstances, we can forecast both the remaining operational lifespan of the transformer in use, as well as future anomalous events. Utility owners can schedule maintenance by providing this information to the relevant departments, allowing them to resolve transformer failures that are unavoidable and prevent system breakdowns from occurring. This is a thorough examination of current and relevant research works. A wireless transformer monitoring parameter was proposed by the authors in [12–20]. This system's primary goal is to monitor and regulate the transformer using an RF module. Monitoring and controlling are made possible by temperature sensors, microcontrollers, and wireless communication technology, or RF transmission. Voltage, current, and temperature are the three transformer parameters that are being observed. The tracked data are then sent to a remote location after that. Data are transmitted between the client and the RF via the controller. In [21–30] GSM technique is proposed. For systems with protection functions, this approach is effective. These technologies were developed earlier and are based on communication. In the event of network disruptions, the recommended GSM strategy can increase the system's dependability. Communication is accelerated using the GSM technique, which is independent of the distance parameter [31]. The Internet of Things could be used in conjunction with a distribution transformer monitor and control system, according to authors in [32]. The graphical signatures of the oil temperature, winding temperature, ambient temperature, current, voltage, and oil level were examined using ThingSpeak. Seven embedded sensors, a microprocessor, and ThingSpeak, which is utilized for processing, displaying, and storing, made this possible. To monitor the five power transformer parameters' current, voltage, oil level, winding temperature, and ambient temperature, the authors in [33] looked at a tool for creating graphical signatures. This was made possible in [34], by permitting early fault detection readings. Operators were alerted by Pushing Box when any parameter exceeded pre-established limits. Using the IoT, the study in [35] created the best possible protection for a power transformer. Two embedded sensors were used with the ESP32 microcontroller. Specifically, temperature and flow sensors were employed. The system proposed by [36] sends SMS messages to a central database for further processing via a GSM modem. A GSM modem, several sensors,

and a chip microcontroller are combined by the system to create an online monitoring system. [37] demonstrated how a rapidly expanding field of machine-to-machine (M2M) communication is referred to as the "Internet of Things" (IoT) and holds great potential for facilitating data transfer between autonomous devices. Along with recording critical dispersion transformer operational indicators like load current, voltage, transformer oil, and ambient temperature and humidity, this task also entails developing, installing, and testing a system for continuous transformer monitoring and fault detection. Data transmission and retrieval were accomplished using Bluetooth and Wi-Fi. Nevertheless, the IoT cloud platform and data processing tools were not mentioned in [38]. The authors in [39–51] used an ESP8266 microcontroller embedded with four sensors—voltage, current, oil level, and oil temperature—to monitor the voltage, current, oil temperature, and oil level of a power transformer. An IoT monitoring system was created in [52] to obtain a distribution transformer's real-time status. The microcontroller utilized was an Arduino UNO, which had three sensors, built-in voltage, current, and smoke. To avoid malfunctions and unplanned shutdowns, the work in [53] remotely measured a power transformer's load current, voltage, and temperature. A subset of parameters, such as only temperature and humidity or only current and voltage, are monitored in several publications. Systems that combine a wide range of sensors (temperature, oil level, humidity, voltage, current, etc.) to give a full picture of transformer health are scarce. Although many studies describe how to develop and execute IoT-based transformer monitoring systems, very few conduct real-world validation of their prototypes. Researchers should explore and further investigate the validation of the IoT system in real-world power system monitoring of big transformers in the field.

2.2. Knowledge Gaps

The reviewed studies in the literature only track a limited number of characteristics (for example, temperature and humidity or current and voltage). There are few publications that combine a wide range of sensors to monitor the various parameters of a transformer to ensure complete condition monitoring of the transformer. New studies should try to close this research gap by combining various sensors into one cohesive system transformer condition monitoring system. The lack of standardization within IoT-connected devices sometimes causes problems when connecting devices and platforms in IoT systems. New researchers should focus on this gap and explore new innovative ideas to overcome standardization issues within this field. Although this aspect is a work in progress, it is critical that researchers highlight progress made in standardizing IoT protocols and how this affects the implementation of such systems in transformer condition monitoring. Improvements in connectivity technology and service providers might lead to service interruptions, increasing complexity because of gateway changes. To address and identify huge numbers of variable IoT devices, a distinctive address identity and ample space are required. Scalability is an obstacle because of the large number of IoT devices interconnected to just one application. Handling device dispersion and effectiveness demands flexible operations. Integrating protocols and standards is pricey and difficult, making expansion and expense minimization a significant problem. Internet of Things devices lack power-harvesting capabilities. The Internet of Things devices require extended battery lifespans to incorporate additional embedded devices, which results in challenges regarding battery replacement. Gathering energy from renewable sources, like a Battery Energy Storage System, might be a solution. Compatibility in diverse IoT infrastructures presents difficulties due to the diverse technological advances, platforms, communication protocols, and privacy and security measures involved. To ensure compatibility, programmers and producers must offer solutions that are independent. Protocols assist with handling problems, arrangement, effectiveness, and the security of networked gadgets. Reliability is crucial for compatibility, as both software and hardware must remain available and compatible to ensure ongoing services even during outages. Furthermore, communication protocols must be compact enough to fit in IoT devices with limited space [8].

2.3. The Internet of Things: A Review

Not all technologies or apps use the same IoT architecture. Every technology has its own structure and best practices [54]. Nonetheless, IEEE suggested a smart grid architecture standard and a draft of an IoT architectural framework for smart cities in 2018 and 2019 [55–60]. Because of its heterogeneity and breadth in terms of scalability when it comes to addressing and providing, the Internet of Things can be complicated. Devices, networks, and apps must all work together smoothly in an IoT design to transmit data in accordance with user-accepted services and generate intelligent outcomes while taking security into account. A minimal number of technological layers, protocols, and standards make up IoT architecture. IoT characteristics are tabulated in Table 1.

Table 1. Notable IoT characteristics.

Characteristic	Description	Area
Dynamic	Devices are connected dynamically and/or disconnected from a service due to varying uptime and downtime.	Communication, Security, Application
Scalability	The number of devices that are connected to one another varies based on the application, which can involve a small or big number of devices.	Architecture, Technology
Heterogeneity	Because of variations in technological platforms and network environments, devices are diverse.	Communication, Security, Technology
Interoperability	Communication across devices with disparate architectures and technologies makes networks accessible and compatible, facilitating the use of apps and services.	Architecture, Communication, Technology

Transformer condition monitoring can be carried out with the IoT to evaluate the health and functionality of transformers, as illustrated in Figure 1. The IoT can be used for the following kinds of condition monitoring:

- Using a variety of state parameters, the IoT can assess a transformer's general state and provide valuable information about its functionality.
- Data gathered from the IoT can be used to discover and diagnose transformer faults, such as winding failures or the deterioration of insulation.
- Real-time condition assessment, i.e., the IoT, can continually and instantly monitor the state of transformers, which makes it possible to identify possible problems early and schedule maintenance accordingly. Researchers have conducted studies on Internet of Things (IoT)-based condition monitoring systems of transformers and concluded that they can precisely identify and locate issues within a transformer. An IoT online monitoring system will be able to handle these issues more rapidly as a result, protecting transformers from damage and catastrophic failures. The IoT system utilizes IoT sensors such as temperature, voltage, current, and oil level to monitor different parameters of the transformer. IoT technology uses microcontrollers to control embedded sensors and peripheral devices with the goal of sending these data to the IoT cloud for visualization and analysis using the Internet. The IoT system can also be able to send messages when predefined settings are exceeded. Furthermore, the system can be integrated into switchgear and protection relays to isolate the faulty transformer when required. There are differences across IoT technologies in terms of cloud platform integration [61], hardware [62], and middleware [42]. Sensors form part of the hardware part of IoT-based transformer condition monitoring architecture. Sensors play a vital role in sensing the parameters of the transformer. Complete IoT-based transformer condition monitoring systems are made up of sensors embedded on boards with a microcontroller, microprocessor, and network interface as illustrated in Figure 1. The Raspberry Pi and Arduino boards are the most widely used IoT hardware boards. The transformer's long service life is assured when a transformer is operated under rated

conditions (as specified on the nameplate). [63] stated that a transformer is designed to operate between 20 and 25 years. However, its dependability becomes impacted by overloading, heating, low or high voltages and currents, or both. In these cases, it will experience abrupt failure, and many users will lose power. Overloading, insulation failure, and insufficient transformer cooling are the primary causes of distribution transformer failure. Most of the papers reviewed in this paper proposed IoT systems to address issues associated with overloading, oil temperature, load current, voltage, and oil level. The extensive dispersion of transformers in today's electric networks makes it difficult to manually evaluate each one's condition; hence, researchers are delving more into the IoT-based transformer condition monitoring approach for timely fault detection and condition monitoring of transformers.

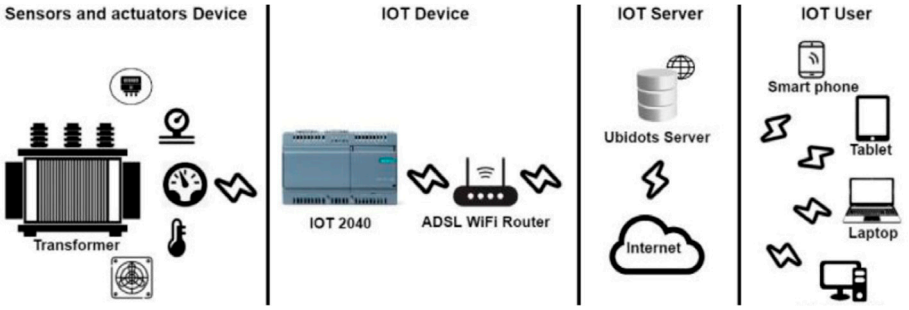


Figure 1. A typical diagram of the Internet of Things [5].

The papers collected for this review indicated that there are layers of technologies, protocols, and standards required for IoT-based transformer condition monitoring architecture to establish successful IoT communication. These layers are crucial in assisting the IoT-based transformer condition monitoring devices to communicate with each other and enable scalability, heterogeneity, and interoperability [63]. The level of layers differs as required by that application. [64] stated that there are various layers, namely, three layers, four layers, five layers and OSI layers in IoT systems, with OSI being a seven-layer system. The papers considered for this review adopted a three-layer approach where there was a top layer, middle layer, and bottom layer. The top layer is mainly employed for the user functions requirement, the middle layer is utilized for the network functions requirement, and the bottom layer is designated for the hardware functions requirement [65]. The top layer is also known as the service data layer for data storage and visualization; in simple terms, this is a cloud IoT platform where the transformer's monitored data are being monitored and stored. The middle layer falls under network and communication and includes the network layer [65], transport layer [66], and middleware layer [67] or Internet layer [68]. This layer oversees connections to other smart devices and network nodes, such as IoT clouds, gateways, servers, and routers. It offers a variety of services to both the lower and upper layers. This layer manages the transmission of sensor data via networks such as Wi-Fi, Bluetooth, ZigBee, GSM, radio frequency identification (RFID), LAN, WAN, GPRS LTE, etc. It also controls data packet routing and processing. The most used method of communication for IoT-based transformer condition monitoring was Wi-Fi due to many projects' experiments conducted in controlled areas and distance being a major constraint. The bottom layer is referred to as the sensing layer [69]. This layer connects the physical sensing devices to the digital world, allowing for machine-to-machine communication. The sensors on this layer detect and collect data, including physical properties of the transformer such as the load current, voltage, transformer temperature, and oil level. The sensors can measure the humidity, pressure, temperature, voltage, current and level. The value of the measured parameters is converted into signals and machine languages that can be transmitted and received. The papers mostly used IoT technology to measure load current, voltage, temperature, and oil level. Other papers utilized these data to estimate the health index and conduct fault diagnosis in the transformer.

3. Materials and Methods

This review paper adopted procedures for systematic reviews proposed by [70] for reviewing the related studies. The process commonly comprises four stages; these are (1) planning, (2) selection, (3) extraction, and (4) execution, as shown in Figure 2. The planning stage is a vital stage, as it incorporates the criteria for inclusion and exclusion, as well as scholarly searches and keyword searches. The selection stage comprises the search process and screening. The extraction phase deals with the assessment of quality. The final phase, which is the execution phase, deals with data synthesis. This section describes the methodology for conducting a proposed systematic review on transformer condition monitoring using IoT technology. This systematic review evaluated published papers between 2014 and 2024.

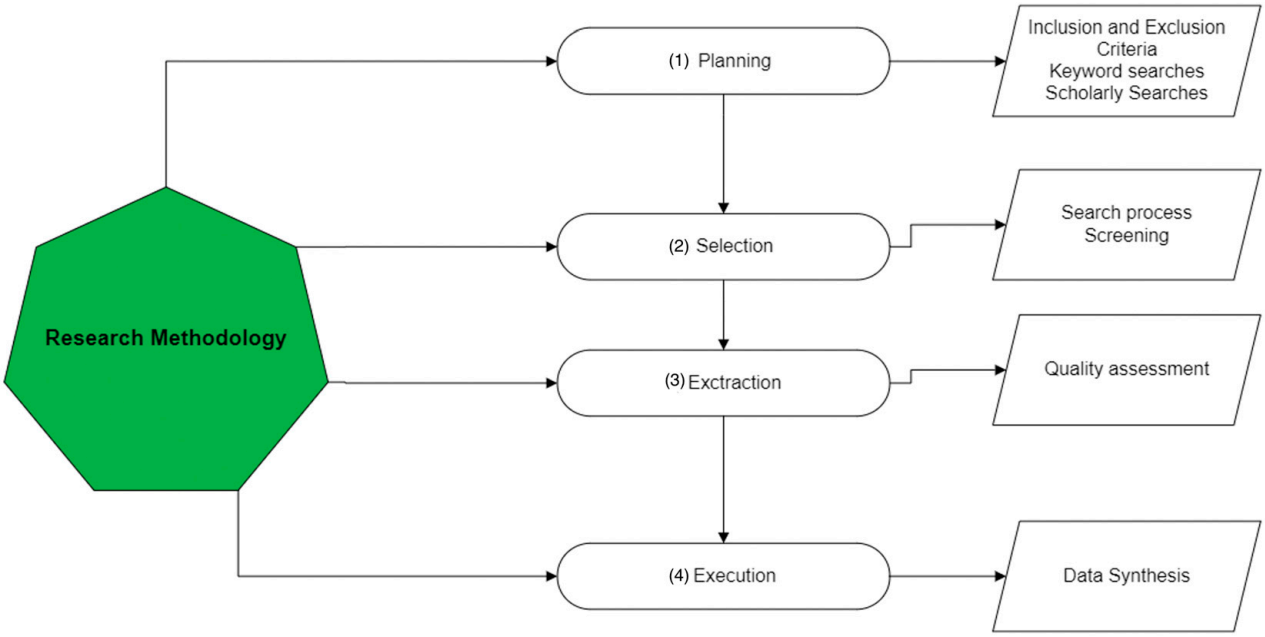


Figure 2. Systematic review flow diagram.

3.1. Eligibility Criteria

All peer-reviewed published papers that were pertinent to IoT-based transformer condition monitoring were reviewed systematically prior to being selected for further evaluation. A review was only conducted on papers published in English between 2014 and 2024 concerning the use of IoT technology for transformer condition monitoring. Precise standards were devised to incorporate pertinent studies and omit those unrelated to the use of the IoT for transformer condition monitoring. As a result, only peer-reviewed publications that primarily focused on IoT-based technology for transformer condition monitoring were given consideration. Included in this were publications that discussed the outcomes of IoT system testing for proof of concepts, IoT-based transformer fault diagnostics, health indexes using the IoT, and energy management using the IoT. Also included were papers that were chosen from pertinent papers' references. All the papers were finally assembled. As shown in Table 2, the inclusion and exclusion criteria were compiled. These criteria ensured that the selection of the literature was consistent with the study's objectives and scope.

Table 2. Proposed inclusion and exclusion criteria.

Criteria	Inclusion	Exclusion
Topic	Must pertain to IoT technology in electrical transformer condition monitoring or fault diagnosis	Articles unrelated to IoT technology for transformers
Research Framework	Must include a research framework or methodology	Articles lacking a clear research framework
Language	Must be written in the English language	Articles published in languages other than English
Publication Period	Must be published between 2014 and 2024	Articles published outside the specified timeframe

3.2. Information Sources

The scholarly articles that were examined in this systematic review were first sought after in 2014. A comprehensive search of published scholarly publications was performed utilizing IEEE Xplore (IX), Google Scholar (GS), IEEE Xplore (IX), Science Direct (SD), Emerald Insight (EI), Springer Link (SL), Wiley Online Library, Taylor & Francis Online (TFO), and ELSEVIER repositories to gather the literature for this SLR.

3.3. Search Strategy

To find publications that presented aspects of IoT-based transformer condition monitoring experiments and transformer online monitoring, a search strategy was created specifically for this review [26,71–134]. Repetitive pilot searches were utilized to choose search phrases. Terms that failed to provide articles meeting the inclusion requirements were eliminated. The synonyms of the designated terms were identified to guarantee that the synonyms of the key terms were included. Thus, the synonyms for "transformer condition monitoring" include "Transformer fault detection" "Transformer health index", and "Transformer asset management". Defining terms for the term "Internet of Things" were "IoT review," and "IoT survey", relating to transformer condition monitoring. Table 3 illustrates keyword searches utilized to facilitate the selection of relevant papers.

Table 3. Proposed keyword search.

Keywords Search
Internet of Things (IoT)
"Transformer Monitoring" or "Electrical Transformer Condition" or "Transformer Maintenance" or "Transformer Management".
"Condition Assessment" or "Transformer Health" or "Transformer Diagnostics" or "Transformer Data Analysis".
"Predictive Maintenance" or "Transformer Performance" or "Transformer Reliability"

Since keywords are the basis for the attainable nature of relevant material, choosing the right keywords is crucial to the process of choosing academic works for this SLR. The online match found with the above-mentioned keywords provided attainability to 262 research publications. Figure 3 illustrates the results, with 62 articles from IEEE Xplore, 60 papers from Google Scholar, 21 papers from Science Direct, 15 papers from Emerald Insight, 11 papers from Springer Link, 46 papers from Wiley Online Library, 27 papers from Taylor and Francis Online, 13 papers from ELSEVIER, and 5 papers from other sources making up the obtained papers. These results comprise 142 additional study projects that were discarded. A total of 120 research articles were gathered because of this survey.

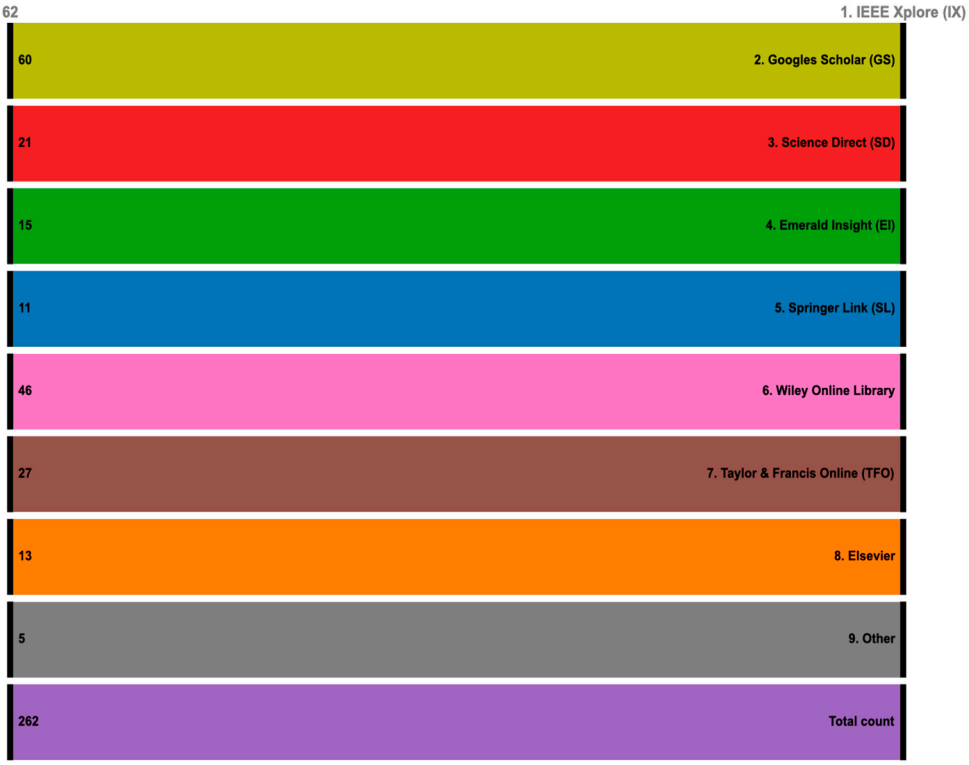


Figure 3. Search results of selected online repositories.

3.4. Study Selection

This current SLR examines a total of 120 research works regarding IoT-based technology in transformer condition monitoring that were conducted from 2014 to 2024 in order to determine answers to the 8 primary research questions specified below. To choose pertinent papers, the search procedure steps recommended in [26,71–134] were used in this review to choose relevant papers. To find pertinent publications, first thorough searches of the eight research databases or publishers (discussed above) and a systematic review database were conducted. Secondly, journals with papers related to investigations into transformer online monitoring and fault diagnosis using the IoT on transformers were chosen. Next, all pertinent papers that met the inclusion criteria had their reference lists examined. Every reference list was examined for any further citations related to this SLR that would have led to fresh publications. Those publications were gathered and examined. The filtering procedure started after the search reached a point of no further studies being retrieved. To guarantee relevancy, the primary selected papers were evaluated and checked. The following is a summary of the steps taken to facilitate a valid filtering process. Initially, the topic of each paper was assessed for relevancy, and then the contents were screened to ensure that they were related to the topics being reviewed. They were evaluated further based on the following criteria: whether the published paper was peer reviewed, the paper type, the journal rank, and whether the paper was written in English. Included were the most recent papers between 2014 and 2024, as well as those that covered the same subject.

3.5. Data Collection Process

This section describes the procedures for independent data extraction, the methods for gathering data from the included papers, the roles played by the authors during the reviewer process, and any other methods applied to validate and check the accuracy of the data. The data used in this study were gathered from reputable online repositories on IoT-based transformer condition monitoring publications. IoT-based transformer condition monitoring publications from various countries were the subjects of this systematic review. The technique for extracting data is comparable to that employed in [26,71–134].

A standardized data extraction checklist was created specifically for this review. This checklist was utilized to gather data from published papers of the included studies. The data extraction process was carried out by three separate writers and reviewers. Data were gathered by each reviewer independently from all relevant research. To verify data accuracy and consistency, a comparison of the received data was performed amongst the three reviewers/authors. Any contradictions discovered during this comparison process were handled by conversation, and the final decision was reached by a consensus. Where necessary, an additional reviewer was consulted to establish an agreement. Where information from the studies was ambiguous or lacking in completeness, we highlighted the missing data and recorded them appropriately. No automation techniques were used during the data collection procedure. When numerous reports referred to the same study, established decision methods were used to select the most relevant data. To ensure the integrity of the data included in the evaluation, any conflicts across recorded data were addressed using a systematic validation technique.

3.6. Data Items

This section explains all of the outcomes and variables for which information was collected, encompassing explanations and methods for selecting results that were pertinent. Furthermore, it outlines the strategy for dealing with insufficient or ambiguous data, as well as the hypotheses made throughout the data acquisition procedure.

3.6.1. Data Collection Method

This subsection identifies and describes the results for the information that was collected, such as the transformer type being monitored, investigated aspects, IoT cloud platform acceptance, and operational enhancements. For every result area, all relevant results in line with these measurements were searched for, over a wide range of precise moments in time, methodologies, and assessments. Where many results were available in the same area, a systematic review was used to rank the most credible and acceptable evidence based on specific requirements. This approach guaranteed that this study produced a methodologically sound and comprehensive appraisal of each result.

3.6.2. Variable Data Collection

Along with transformer types, investigated aspects, and the four IoT elements, this subsection identifies and gives all other variables for which data were sought. Variables such as the study design were thoroughly reported. Gaps due to lacking information were filled in with additional material from subsequent references. There were no assumptions regarding any missing or confusing information. Gaps such as papers not mentioning the cloud IoT or AI algorithms used for their publications were marked as "not specified" on the excel spreadsheet. The collected data were explicitly explained to ensure clarity and minimize the influence of partial or missing data on the overall study. Data were gathered using Table 4 criteria.

Table 4. Variable data collection.

Criteria	Description
Topic	Specify a concise and comprehensive topic for the publication.
Year	State the year the study was published.
Online Repository	Indicate where the research study was discovered (e.g., Science Direct, Springer Link, Google Scholar, Emerald Insight, etc.).
Research Type	Determine the type of research (e.g., journal, conference paper, article, or thesis).
Journal Name	Specify the name of the journal or publishing source.
Number of Citations	Specify the number of citations the paper has acquired.

Table 4. *Cont.*

Criteria	Description
Geographic location Economic Background	Specify the country or the area where the research was conducted. Consider whether the research originates from an industrialized developed country or underdeveloped country.
Monitored transformer parameters	Indicate monitored parameters of the transformer (e.g., voltage, current, temperature, oil level, etc.).
Iot Cloud Services	List adopted IoT cloud services (Adafruit IO, ThingSpeak, Arduino Cloud, Blynk App, etc.).
Technology Providers	Specify the cloud developers involved (e.g., Arduino, Adafruit industries, Microsoft Azure, MathWorks, AWS, etc.).
Transformer type	Indicate investigated transformer types (e.g., distribution transformer, power transformer, dry-type transformer, etc.).
Investigated Aspects	List investigated aspects (e.g., heath indices, fault identification, energy management, vibration monitoring, lifecycle management, etc.).
Microcontrollers	Provide microcontrollers used for data processing and command execution (e.g., ESP32, Arduino nano, Arduino uno, Raspberry Pi, ESP8622, etc.).
Communication Channel	Specify communication protocols adopted and utilized (e.g., Wi-Fi, BLE, GSM, ZigBee, Sigfox, etc.).
AI Algorithm	Identify the artificial intelligent (AI) algorithm model used (e.g., Ensemble Machine Learning (EML), Neural Network, Linear Regression, etc.).
Research Design	Specify the research design (e.g., survey, systematic literature review, article, etc.).
Data Collection Methods	Explain the way data were gathered (e.g., surveys, keyword searches, reputable online repositories, etc.).
Data Analysis Techniques	Determine how the data were examined (e.g., regression analysis, statistics analysis, etc.).
IoT Challenges	Specify IoT challenges (e.g., stable Internet connection, privacy and security, etc.).
Long-Term Impacts	Determine the implications for the future, such as IoT system sustainability or competitive edge.
Contribution to the field	Specify how IoT monitoring will impact and contribute towards revolutionizing transformer condition monitoring.

3.7. Study Risk of Bias Assessment

This section describes the methodologies used to determine and evaluate the risk of bias in the selected research publications, containing information on the tools used to effectively deal with large amounts of data and discover possible prejudices that may have been overlooked during the conventional evaluation procedure. A number of reviewers evaluated each paper independently, ensuring that individual biases were reduced and that a detailed analysis was achieved through conversations and agreements. This comprehensive technique ensured a rigorous, dependable, and uniform analysis of the risk of bias across all papers chosen for this SLR. This process ensured that there were no systematic errors that could deviate from the truth and lead to overscoring or underscoring.

In this systematic review of transformer condition monitoring through the IoT, each selected study underwent a comprehensive risk of bias assessment to verify the validity and reliability of the SLR's findings. To examine both qualitative and quantitative data from research relevant to the topic under investigation, unique bias assessment frameworks were developed using the Mixed Methods Appraisal Tool (MMAT). This evaluation addressed five methodological quality criterion issues from the MMAT. Table 5 displays the mixed method category and five pertinent methodological quality criteria questions for assessing the risk of bias and ensuring that selected papers were scored appropriately. Three authors independently assessed each manuscript, documenting explanations and supporting evidence for their risk-of-bias assessments. Each question contains three alternative classifications, which the reviewers used to evaluate each study. The variable "yes" means

the article fulfills the stated methodological standards, "no" means the research does not satisfy the set methodological criteria, and "can't tell" means the reviewer says neither yes nor no. Any differences in their evaluations were resolved through collaborative exchanges, and disagreements were resolved through consensus decision amongst the three authors where necessary [121–134].

Table 5. Mixed Methods Appraisal Tool criteria.

Category of Study Design	Methodological Quality Criteria
Mixed Methods	Is there an appropriate justification for utilizing a mixed methods strategy to answer the research question? Are the study's components adequately combined to address the study's question? Are the results of the combination of qualitative and quantitative components appropriately determined? Are the differences and discrepancies between quantitative and qualitative outcomes effectively addressed? Do the study's components meet the quality criteria of each methodological approach concerned?

Table 6 tabulates all the steps consolidated with MMAT to ensure that the risk of bias process is effective and efficient. This rigorous method meant that the risk of bias was comprehensively examined on the IoT-based transformer condition monitoring performance, as well as application issues, identifying major breakthroughs and addressing any current deficiencies.

Table 6. Risk bias process.

Criteria	Description	Details
Risk of bias assessment tool	Develop MMAT risk of bias tool for qualitative and quantitative data.	MMAT technique, tailored for IoT-based transformer monitoring studies
Methodological quality criteria for bias	Refer to the five methodological quality criteria questions listed in Table 5	Refer to Table 5
Methodological quality criteria questions	Answer methodological quality criteria questions.	Yes, No, Can't tell
Agreement protocol	Address divergences through interactions.	Consensus decision through scoring
Results	Guarantee an exhaustive, accurate assessment of risk among every research study.	Defining the influence of the Internet of Things in transformer condition monitoring

3.8. Data Synthesis

The synthesis techniques for this comprehensive literature review of IoT-based transformer condition monitoring were established to enable a solid, clear, and repeatable aggregate of outcomes from the chosen papers. The method of choosing which papers were deemed appropriate for consideration in each synthesis was undertaken in a structured and a diligent manner, assuring conformity with the review's targets, which concentrate on the significance of IoT technology in revolutionizing condition monitoring of transformers. Excel spreadsheets were developed and utilized to consolidate the data collected from the research problems' answers. The Excel spreadsheet played a vital role in facilitating and ensuring that a valid data extraction process took place. During the synthesis stage, the most popular keywords were used, and the terms that described the study subject were standardized. These data were extracted from the 120 papers that met the minimum of 75% in the quality assessment checklist. The Excel spreadsheet incorporated the following data: (a) year of publication (b) research type (e.g., conference paper, journal, article, review), (c) online repository, (d) country, (e) transformer type or physical object, (f) investigated transformer aspect, (g), microprocessor (h) communication channel, and (i) IoT Cloud. From all 120 of the publications that made up this review, the data listed in Table 2 were

used to extract the relevant information. Using this approach, a clear picture was developed of the most favored microcontrollers for IoT-based transformer condition monitoring, communication channels, IoT clouds, transformer types, and investigated aspects.

The process of data synthesis eligibility entailed meticulously choosing papers that were relevant to transformer condition monitoring, used IoT technology, and aligned with the predefined objectives of the author. A regulated assessment with established requirements guaranteed that only relevant papers were included in the analysis, reducing biases and improving the evaluators' thoroughness. Information across numerous research papers was eventually harmonized to enable logical comparisons. The missing data were corrected using strategies such as multiple computation, resulting in a comprehensive and trustworthy database for evaluation. Table 7 provides information on the process of data extraction from relevant studies. The results were methodically sorted into tables, which were critical for recognizing patterns and presenting the findings clearly and openly.

Table 7. Data extraction.

Information	Description
Study Objective	The study's distinct objective
Study Details	Topic, author, country, year
Online repository	IEEE Xplore, Google Scholer, Science Direct, etc.
Publication Type	Book, conference, journal
Data evaluation	Qualitative/quantitative/mixed methods analysis
Methodology	Experiment, prediction evaluation, fault diagnosis, health index
Tools	Which tools were used in the research for transformer condition monitoring using the IoT
Experiment environment	Environmental setting under which the IoT-based transformer condition monitoring experiment was conducted
Contribution	What valuable contributions of the proposed research in transformer condition monitoring were

3.9. Reporting Bias Assessment

1. To reduce subjective bias, three impartial reviewers oversaw the entire evaluation procedure. Any disputes between reviewers were handled through conversation or by consulting an additional reviewer to obtain a consensus on the interpretation of results. This study relied heavily on manual analysis and visualization. There were no automated tools explicitly designed to measure reported bias; rather, data were assessed and visualized manually using Microsoft Excel. This method entailed constructing charts and plots to uncover trends and potential biases in the reporting, allowing for a thorough evaluation of the data without relying on computerized automated tools. To assure that everything was correct and complete, an exhaustive manual search of multiple web repositories was performed. This strategy allowed for the matching of data from various studies and sources, correcting any differences or questions about stated findings without requiring personal interaction with the writers.

Quality Assessment

This part discusses the procedures used to determine the degree of trust or assurance in the data collected for each result, assuring the dependability and validity of the outcomes. The acquired literature was then reviewed using criteria derived from a set of six quality assessment (QA) examinations, as shown in Table 8. After filtration (n = 120), the quality of the research works that were selected for further study was assessed using a quality assessment (QA) checklist consisting of six categories. QA is just as important as the inclusion and exclusion criteria covered in the section above.

Table 8. Quality assessment checklist questions.

Question #	Questions
1	Are the objectives of the research work well defined?
2	Is there a clear specification of the research work methodology?
3	Is the research model reported?
4	Are the data collection methods properly detailed?
5	Is the study context/discipline clearly specified?
6	Do the results add to the literature?

References [16,18,23,25,55,56] were on the borderline, scoring 75%, as shown in Table 9. A total of 66 publications obtained 92%, as depicted in Table 5. Papers [14,15,26,50,52,54,65,66,72–80,96,100,101,118] scored 100%, meeting and exceeding the set QA checklist.

Table 9. Studies' quality assessment scores.

Studies	Score
[1–13,26–28,30,34,37–39,41–49,51,53,57,60–64,70,71,81,83–90,94,95,97–99,102–104,106,112–117]	92%
[16,18,23,25,55,56]	75%
[17,19–22,24,29,31–33,35,36,58,59,67–69,82,91–93,105,107–111]	83%
[14,15,26,50,52,54,65,66,72–80,96,100,101,118]	100%

The questions scoreboard card is based on a three-point rating system, where "No" is worth zero points, "Partially" is worth 0.5 points, and "Yes" is worth one point. Every research paper is eligible to receive one of six possible points. Each QA question weighs a maximum of 1 point. A higher overall score for the research study indicated that QA checklist questions were satisfied. Table 10 under Section 4 tabulates QA results, showing how each study was scored per QA question.

Table 10. Gathered publications' quality assessment results.

Ref.	QA1	QA2	QA3	QA4	QA5	QA6	Total	%
[1]	1	1	0.5	1	1	1	5.5	92
[2]	1	1	0.5	1	1	1	5.5	92
[3]	1	1	0.5	1	1	1	5.5	92
[4]	1	1	0.5	1	1	1	5.5	92
[5]	1	1	0.5	1	1	1	5.5	92
[6]	1	1	0.5	1	1	1	5.5	92
[7]	1	1	0.5	1	1	1	5.5	92
[8]	1	1	0.5	1	1	1	5.5	92
[9]	1	1	0.5	1	1	1	5.5	92
[10]	1	1	0.5	1	1	1	5.5	92
[11]	1	1	0.5	1	1	1	5.5	92
[12]	1	1	0.5	1	1	1	5.5	92
[13]	1	1	0.5	1	1	1	5.5	92
[14]	1	1	1	1	1	1	6	100
[15]	1	1	1	1	1	1	6	100
[16]	1	1	0.5	0.5	0.5	1	4.5	75
[17]	1	1	0.5	0.5	1	1	5	83
[18]	1	1	0.5	1	0.5	0.5	4.5	75
[19]	1	1	0.5	1	1	0.5	5	83
[20]	1	1	0.5	1	1	0.5	5	83
[21]	1	1	0.5	1	0.5	1	5	83
[22]	1	1	0.5	1	1	0.5	5	83
[23]	1	1	0.5	0.5	1	0.5	4.5	75

Table 10. *Cont.*

Ref.	QA1	QA2	QA3	QA4	QA5	QA6	Total	%
[24]	1	1	0.5	1	0.5	1	5	83
[25]	1	1	0.5	0.5	1	0.5	4.5	75
[26]	1	1	0.5	1	1	1	5.5	92
[27]	1	1	0.5	1	1	1	5.5	92
[28]	1	1	0.5	1	1	1	5.5	92
[29]	1	1	0.5	0.5	1	1	5	83
[30]	1	1	0.5	1	1	1	5.5	92
[31]	1	1	0.5	0.5	1	1	5	83
[32]	1	1	0.5	0.5	1	1	5	83
[33]	1	1	0.5	0.5	1	1	5	83
[34]	1	1	1	0.5	1	1	5.5	92
[35]	1	1	0.5	0.5	1	1	5	83
[36]	1	1	0.5	0.5	1	1	5	83
[37]	1	1	1	0.5	1	1	5.5	92
[39]	1	1	1	0.5	1	1	5.5	92
[40]	1	1	1	0.5	1	1	5.5	92
[41]	1	1	1	0.5	1	1	5.5	92
[42]	1	1	1	0.5	1	1	5.5	92
[43]	1	1	1	0.5	1	1	5.5	92
[44]	1	1	1	0.5	1	1	5.5	92
[45]	1	1	1	0.5	1	1	5.5	92
[46]	1	1	1	0.5	1	1	5.5	92
[47]	1	1	1	0.5	1	1	5.5	92
[48]	1	1	1	0.5	1	1	5.5	92
[49]	1	1	1	0.5	1	1	5.5	92
[50]	1	1	1	1	1	1	6	100
[51]	1	1	1	0.5	1	1	5.5	92
[38]	1	1	1	0.5	1	1	5.5	92
[52]	1	1	1	1	1	1	6	100
[53]	1	1	0.5	1	1	1	5.5	92
[54]	1	1	1	1	1	1	6	100
[55]	1	1	1	0.5	0.5	0.5	4.5	75
[56]	1	1	0.5	0.5	1	0.5	4.5	75
[57]	1	1	1	0.5	1	1	5.5	92
[58]	1	1	0.5	0.5	1	1	5	83
[59]	1	1	0.5	0.5	1	1	5	83
[60]	1	1	1	0.5	1	1	5.5	92
[61]	1	1	1	0.5	1	1	5.5	92
[62]	1	1	1	0.5	1	1	5.5	92
[42]	1	1	1	0.5	1	1	5.5	92
[63]	1	1	1	0.5	1	1	5.5	92
[64]	1	1	1	0.5	1	1	5.5	92
[65]	1	1	1	1	1	1	6	100
[66]	1	1	1	1	1	1	6	100
[67]	1	1	0.5	0.5	1	1	5	83
[68]	1	1	0.5	0.5	1	1	5	83
[69]	1	1	0.5	0.5	1	0.5	4.5	83
[70]	1	1	0.5	1	1	1	5.5	92
[71]	1	1	1	1	1	0.5	5.5	92
[72]	1	1	1	1	1	1	6	100
[73]	1	1	1	1	1	1	6	100
[74]	1	1	1	1	1	1	6	100
[75]	1	1	1	1	1	1	6	100
[76]	1	1	1	1	1	1	6	100
[77]	1	1	1	1	1	1	6	100
[26]	1	1	1	1	1	1	6	100
[78]	1	1	1	1	1	1	6	100
[79]	1	1	1	1	1	1	6	100

Table 10. *Cont.*

Ref.	QA1	QA2	QA3	QA4	QA5	QA6	Total	%
[80]	1	1	1	1	1	1	6	100
[81]	1	1	1	0.5	1	1	5.5	92
[82]	1	1	0.5	0.5	1	1	5	83
[83]	1	1	0.5	1	1	1	5.5	92
[84]	1	1	0.5	1	1	1	5.5	92
[85]	1	1	0.5	1	1	1	5.5	92
[86]	1	1	0.5	1	1	1	5.5	92
[87]	1	1	0.5	1	1	1	5.5	92
[88]	1	1	0.5	1	1	1	5.5	92
[89]	1	1	0.5	1	1	1	5.5	92
[90]	1	1	0.5	1	1	1	5.5	92
[91]	1	1	0.5	0.5	1	1	5	83
[92]	1	1	0.5	0.5	1	1	5	83
[93]	1	1	0.5	0.5	1	1	5	83
[94]	1	1	0.5	1	1	1	5.5	92
[95]	1	1	0.5	1	1	1	5.5	92
[96]	1	1	1	1	1	1	6	100
[97]	1	1	0.5	1	1	1	5.5	92
[98]	1	1	0.5	1	1	1	5.5	92
[99]	1	1	0.5	1	1	1	5.5	92
[100]	1	1	1	1	1	1	6	100
[101]	1	1	1	1	1	1	6	100
[102]	1	1	1	0.5	1	1	5.5	92
[103]	1	1	1	0.5	1	1	5.5	92
[104]	1	1	1	0.5	1	1	5.5	92
[105]	1	1	0.5	0.5	1	1	5	83
[106]	1	1	1	0.5	1	1	5.5	92
[107]	1	1	0.5	0.5	1	1	5	83
[108]	1	1	0.5	0.5	1	1	5	83
[109]	1	1	0.5	0.5	1	1	5	83
[110]	1	1	0.5	0.5	1	1	5	83
[111]	1	1	0.5	0.5	1	1	5	83
[112]	1	1	1	0.5	1	1	5.5	92
[113]	1	1	1	0.5	1	1	5.5	92
[114]	1	1	1	0.5	1	1	5.5	92
[115]	1	1	1	0.5	1	1	5.5	92
[116]	1	1	0.5	1	1	1	5.5	92
[117]	1	1	1	0.5	1	1	5.5	92
[118]	1	1	1	1	1	1	6	100

4. Results and Discussion

This section explains the outcomes, particularly how they were interpreted, and draws certain implications from them.

4.1. Study Selection Results

A Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) flowchart that was suggested for the literature search and filtering phases of this systematic literature review (SLR) is shown in Figure 4. With the use of the keyword search terms tabulated in Table 3, the published papers were gathered from online repositories with good reputations. From these papers, data extraction was performed as discussed in Section 3.5. The inclusion and exclusion criteria were strictly applied and followed. After obtaining 262 publications, their topics and abstracts were examined. Figure 3 in Section 3 illustrates the results, with 62 articles from IEEE XPLORE, 60 papers from Google Scholar, 21 papers from Science Direct, 15 papers from Emerald Insight, 11 papers from Springer Link, 46 papers from Wiley Online Library, 27 papers from Taylor and Francis Online, 13 papers from ELSEVIER, and 5 papers from other sources making up the obtained papers.

As a result, 187 papers that passed the first screening stage after the screening were based on the titles and abstracts of the published papers. The remaining publications underwent a full-text review and met all the eligibility requirements included in this systematic review, while the remaining publications were eligible for full-text review. A total of 67 papers were eliminated after the full-text review was conducted, leaving 120 papers selected for this review. The 67 papers were disqualified because the studies lacked detailed information on research methodology or because they only examined the same parameters of the transformer as other published papers. Rejected papers were categorized as below 75% based on the qualifying requirements, whilst accepted papers were categorized as 75% and above. Papers that achieved 92% and above from the qualifying assessment criteria were categorized as very high level, whereas papers that achieved 75% and above were categorized as high level. Papers that achieved below 75% were rejected, and the papers that satisfied all four exclusion criteria were categorized as low level, while those that fulfilled only three were categorized as extremely low level. The quantity of papers that satisfied the inclusion and exclusion criteria is shown in Figure 4.

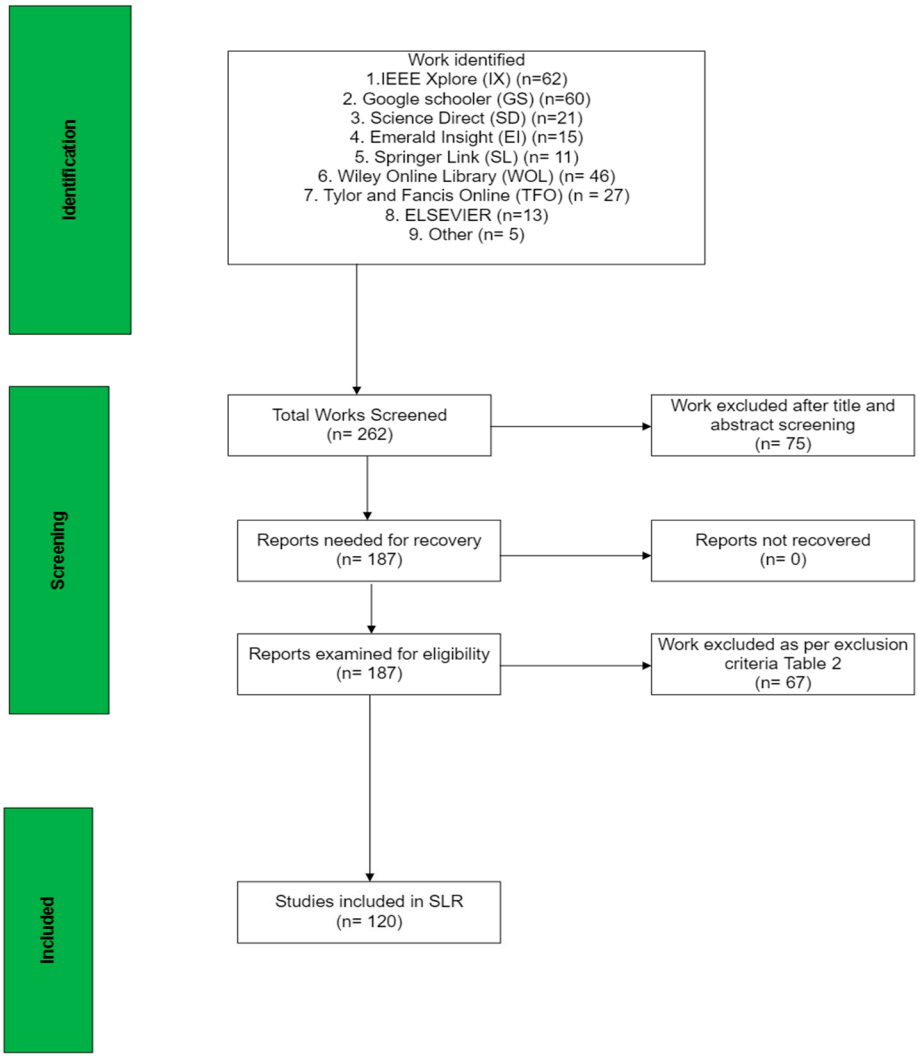


Figure 4. Proposed PRISMA flowchart.

The initial identification search commenced with a keyword search, as shown in Table 3, and the year of publication. The steps in the procedure were to use keyword searches for search queries, assess the standard of the published literature, identify the most important research, gather data gathering, record the review, and, finally, determine eligibility. Moreover, as it immediately defines the reference framework for this study,

the creation of the research topic is a crucial step in the SLR process. Keywords that were applied during this stage are the Internet of Things, transformer online condition monitoring, transformer fault diagnosis, IoT review, and IoT survey. The selected paper cluster types were conference papers, journal articles, and review articles. The selected years ranged from 2014 to 2024. The identification stage discovered a total of 262 articles. The eligibility part incorporated an extraction process. During the exclusion part, to adopt and implement a selection criterion that is valid, full-length papers from journals with a high reputation were considered. This stage produced 187 papers. The last part of the screening process involved quality assessment and classification based on IoT system architecture, microcontrollers, adopted communication protocol, IoT cloud platform, security, and challenges. Finally, the inclusion/exclusion criteria were applied, and quality assessments were conducted. The last part of the screening produced 120 papers. The three steps of the survey methodology used for this investigation are shown in Figure 4.

4.2. Study Characteristics

The compilation of published papers in Figure 5 shows how the field of study on IoT technology for electrical transformer monitoring has evolved significantly over time. The data, which span the years 2014 to 2024, show that both the amount of research being conducted on this issue and the interest in it are increasing. The fact that only three studies were published in 2014 suggests that before 2018 little research has been conducted on the use of IoT technology for transformer monitoring. The research landscape did not acquire traction until fifteen and twelve new publications were published in 2019 and 2020, respectively. The observed increase indicates that more people are becoming aware of the potential advantages of IoT technology for transformer monitoring. The most significant movement happened in 2021 and 2022, where there noticeably were 24 and 35 new studies published, respectively. This increase can be ascribed to the increased availability of implementation tools and data, as well as the growing public awareness of IoT applications. Researchers and practitioners seem to be quite interested in the idea of using the IoT to improve transformer status monitoring. Research question two shows that conference papers make up the bulk of the landscape with 55% of publications, while journal articles only account for 45% of publications.



Figure 5. Trends over the years on IoT-based transformer condition monitoring.

4.3. Risk of Bias in the Studies

The 120 papers included underwent a thorough process to ensure effective evaluation without bias. The findings of the studies that were part of this SLR and the QA that went along with them are illustrated in Table 9 and Figure 6, which indicates that all 120 research projects met the QA requirements, indicating that they were accepted and qualified for additional examination. Figure 6 illustrates that 4.65% of studies evaluated using the QA checklist obtained 75 percent. Of the studies, 23.15% obtained an 83 percent QA score, 50.38% of the evaluated studies obtained a 92 percent QA score, and 21.70% of the evaluated studies obtained a 100 percent QA score.

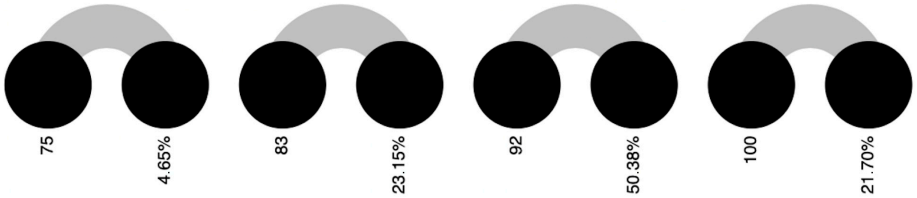


Figure 6. Publications' quality assessment scores.

4.4. Result of Individual Bias

Figures 7 and 8 show considerable variation in the reporting of software and the tools researchers chose for the research on transformer condition monitoring using the IoT. Notably, 20% of the research papers did not specify IoT cloud platforms, and 12.5% did not specify their preferred microcontrollers. This is troublesome since it restricts the capacity to evaluate the proof of concept and functionality of their proposed IoT systems for transformer condition monitoring. The absence of disclosure might raise the possibility of presentation bias, rendering it harder to assess the validity of information offered by these research papers. Studies [3,5,18,19,21,25,43,44,90,105,108–110,115,116] did not specify their preferred microcontrollers. Studies [5,18,21,22,25,29,30,40,42,44,48,52,53,59,64,86,89,90,105, 106,108–110,116] did not specify their preferred IoT clouds for real-time data monitoring and visualization.

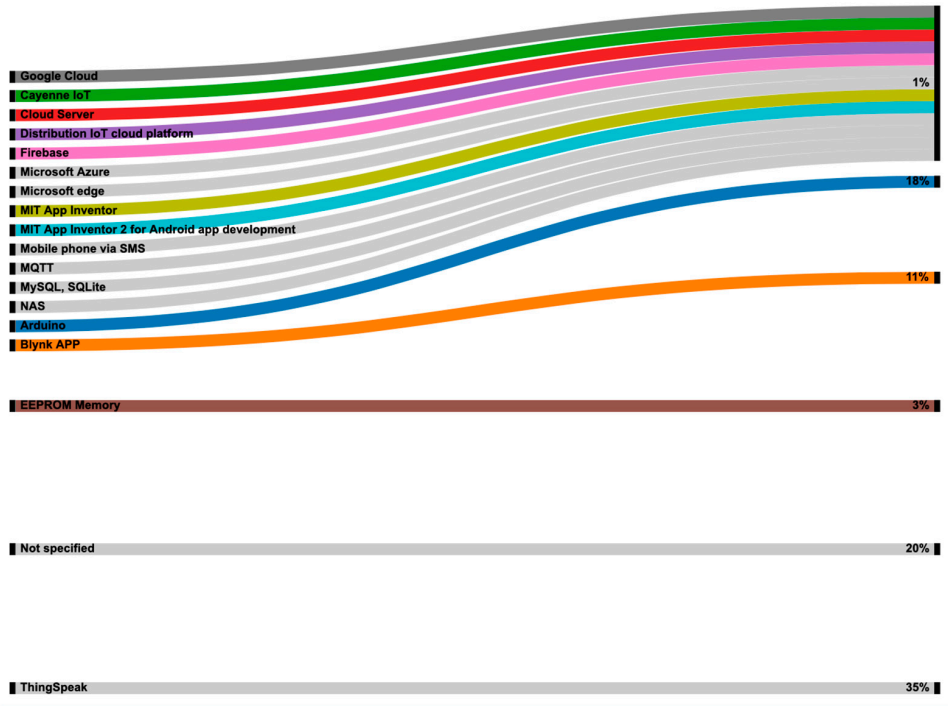


Figure 7. Research distribution by IoT cloud platforms.

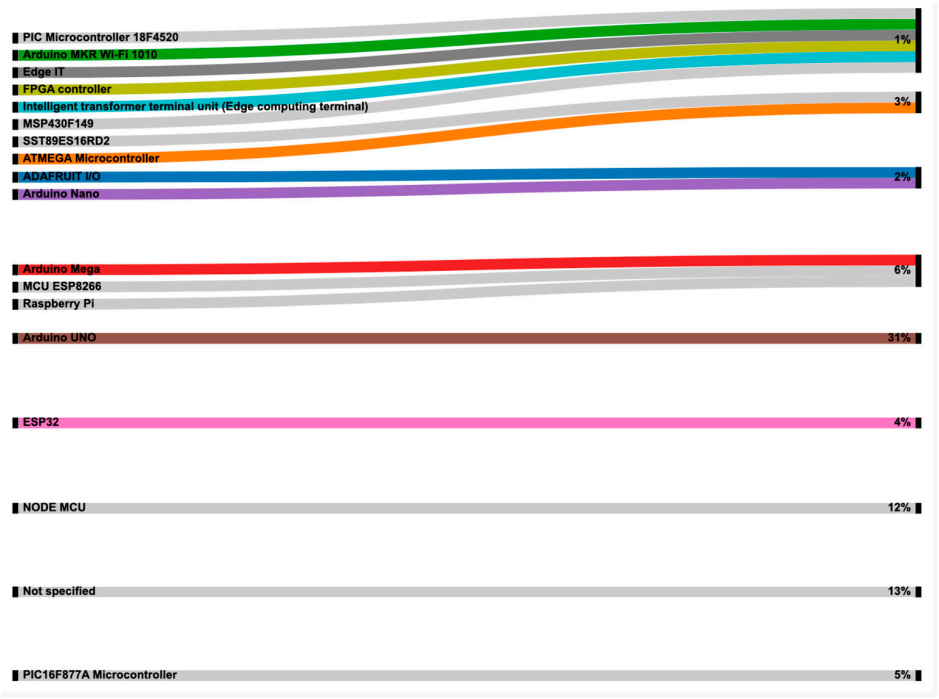


Figure 8. Research distribution by hardware development platform.

4.5. Result of Syntheses

This review formulated eight research questions that were established to assess and synthesize collected data. The formulated research questions gave insight into the aspects mostly investigated by the researchers, with fault diagnosis, energy management, health index, lifecycle management, and energy management emerging as key components of the examination by most researchers. The research questions also examined the publication sources and discovered that conferences were preferred over journals, most likely due to the importance of immediately sharing research findings in this rapidly developing sector. The regional distribution of research was also assessed, revealing that interest in transformer condition monitoring via IoT technology is broad, with India leading the way, followed by China and Pakistan. This study also looked at IoT clouds, microcontrollers, communication channels, and software tools used in this area of research. The Arduino IDE was the most popular software because it allows for easily programming Arduino boards and third-party microcontrollers. Wi-Fi was one of the most common communication protocols, while the most preferred IoT clouds and microcontrollers were Things Speak and Arduino Uno, respectively. Data synthesis findings and results are further discussed in detail under Research Questions.

4.6. Reporting Biases

Figure 9 shows that quantitative analyses dominated investigation into transformer condition monitoring using IoT technology. The quantitative approach dominated mainly because these studies focused on experiments to test the hypothesis. Data outcomes can be demonstrated in numbers, graphs, and tables with fewer words needed to explain them. Quantitative research papers accounted for 117 of the 120 papers reviewed. This approach demonstrates the importance of quantifiable data in evaluating crucial performance measures of IoT-based transformer condition monitoring. These key performance measures include performance validation, affordability, sustainability, efficiency and profit growth. These measures are all crucial in assessing the adopting of transformer condition monitoring through the IoT. Weighing the benefits and drawbacks of implementing IoT-based transformer condition monitoring, transformer operators, utility owners, and those making decisions may depend on unbiased, accurate insights generated by quantitative methodolo-

gies that utilize statistical examination of data that are numerical. Three studies [13,14,87] used a mixed methods research methodology due to them being surveys and reviews where statistical data were analyzed and expressed in depth, using words for explanation. Mixed methods studies verify quantifiable results with contextual observations to offer a full understanding of how Internet of Things technology will revolutionize the condition monitoring of transformers.

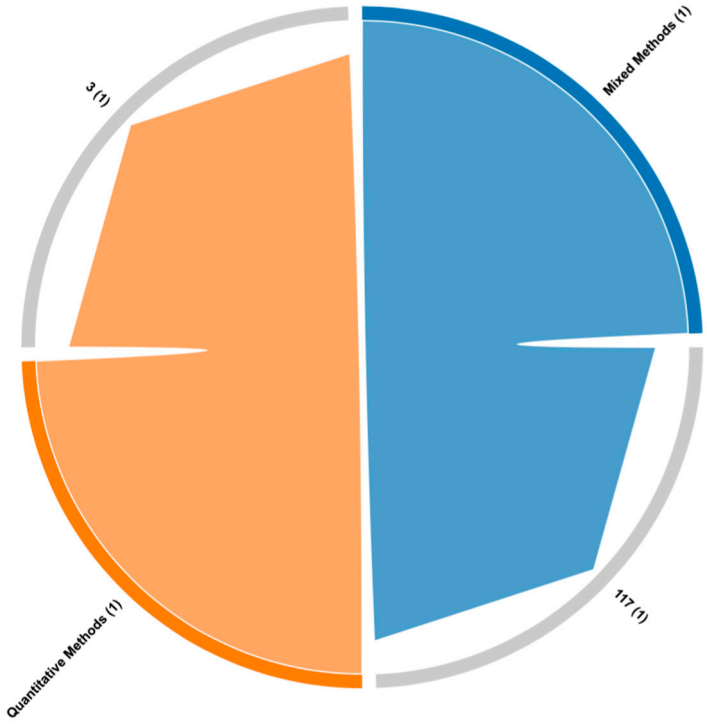


Figure 9. Type of research studies.

4.7. Certainty Evidence

The overwhelming desire for IoT-based transformer condition monitoring amongst researchers, academics, and utility owners arises from the IoT's low power consumption, scalability, dynamic, flexibility, and affordability. IoT-based services provide operators and utility owners with real-time data of a transformer's conditions, which is crucial to make data-driven decisions before catastrophic failures. There are various developers of IoT cloud platforms that are open source and offer free trials for a limited number of services and features. The components for IoT prototype development are affordable, thus minimizing the requirement for large initial financial commitments. Being adaptable is critical for IoT technology with evolving requirements around parameters to be monitored in order to ensure effective transformer condition monitoring. Furthermore, the use of IoT cloud platforms reduces the hassle of servicing and upgrades, allowing transformer operators and utility owners to concentrate on operations and on maintaining the continuity of supply to consumers whilst profiting from modern technology. The certainty of evidence is discussed in detail under research questions.

4.8. Transformer Condition Monitoring

In the discipline of electrical engineering, transformer condition monitoring is the procedure of gathering and analyzing information regarding numerous transformer aspects to identify their condition and anticipate their potential for failure. This is accomplished by monitoring the trends and alterations in the critical parameters of transformers from their normal conditions [17]. Transformers are important assets in both electrical transmission and distribution networks. Their breakdowns can result in blackouts, endangering

people's lives and posing a risk to the environment. Furthermore, transformers are expensive equipment in a power system network. Effective condition monitoring facilitates the identification of transformers that are approaching failure and can enable data-driven, proactive maintenance strategies [23]. These transformers can be replaced under controlled circumstances to avoid catastrophic failures. The traditional condition monitoring techniques are manually performed, which presents a risk of inaccuracies due to human errors. This section presents critical parameters of transformers that can be monitored using IoT technology.

4.8.1. Voltage and Current

Voltage and current are critical parameters of any electrical transformer; monitoring and analyzing the trends and behavior of these parameters can reveal a great deal of information about the transformer during operation. The relationship between these two parameters is inversely proportional to each other for both primary and secondary circuits [28]. Whenever the primary voltage steps up the current, the primary side of the transformer should step down, and the same relationship applies to secondary voltage and current as well [33]. Voltage and current parameters are critical and can be utilized to monitor the loading of transformers, thus minimizing overloading and power theft. These parameters can also be utilized to calculate power and efficiency and to perform diagnostic tests such as the transformer voltage ratio test, no-load losses, and load losses, etc. Monitoring these parameters using the IoT with transformers in service can determine developing issues with interturn insulation failure. There are various IoT sensors available in the market that can be utilized to gather real-time data of these two critical parameters of the transformer, with the ACS712 IoT current sensor and the ZMCT103C current module being widely used sensors in IoT-based condition monitoring systems. The Zmpt101B voltage sensor is the most preferred sensor for transformer condition monitoring due to this sensor being rated at a maximum of 250Vac. Various voltage sensors are rated at a maximum of 25 V, hence the preference for the Zmpt101B voltage sensor by most researchers.

4.8.2. Temperature Oil and Winding

Temperatures for both oil and windings are fundamental aspects of transformer monitoring. Temperature influences all other accessories that make up the transformer. Excessively high temperatures might represent a fault, which might ultimately damage multiple parts of the transformer if left unaddressed. Temperatures should be monitored in several areas, namely ambient, windings, top oil, bottom oil, tap changer, etc. Ref. [56] mentioned that winding insulation is extremely sensitive to both moisture and temperature. Monitoring the winding hot spot is critical since it has an immediate effect on the transformer's deteriorating rate. Refs. [17,22] stated that for approximately every 6-degree rise in winding temperature beyond the specified maximum range of 110 degrees, the transformer decaying rate nearly doubles. The reviewed studies revealed the importance of gathering real-time temperature data of transformers to ensure the reliable and efficient operation of these devices in the power system. There are various IoT temperature sensors available in the market, with the DHT11 sensor and LM335Z sensor predominately used for dry-type transformers, small single-phase transformers, and instrument transformers. A waterproof DS18B20 temperature sensor is also available and is predominantly used for IoT studies involving oil-impregnated transformers.

4.8.3. Transformer Oil Level

Transformer oil is used mainly for insulating and cooling in transformers. Transformer oil should possess a high quality of dielectric strength, thermal conductivity, and chemical resilience. It must maintain these attributes while operating at higher temperatures for a lengthy period. Depreciation in transformer oil may result in overheating of the transformer, resulting in electrical faults and catastrophic failures. Monitoring the oil level is an essential part of transformer condition monitoring to monitor the level of transformer oil inside the

transformer [4]. Sustaining a sufficient transformer oil level is critical in order to prevent instances of the transformer oil level dropping below what is required or being excessively low. This level drop may result in insufficient insulation durability [2]. Electrical discharges take place, leading to insulation failure and transformer explosion. The oil level drop may also result in unsatisfactory localized heat transfer for the transformer, leading to localized overheating and complete insulation failure as time passes [1]. Numerous reviewed studies conducted research on this aspect using IoT-compatible sensors to gather real-time data of the transformer oil. The HC-SR04 ultrasonic distance sensor and JSN-SR04T/AJ-SR04M Waterproof Ultrasonic Module are widely used by most researchers.

4.8.4. Partial Discharges

Partial discharge (PD) is a leading cause of transformer deterioration and failure. PD happens when electrical stress surpasses the transformer's insulation resilience, resulting in tiny sparks or arcs that damage the insulation and impair the transformer's reliability [33]. Partial discharges are commonly defined as minor electrical sparks that are generated in the windings of the transformer [20]. This phenomenon takes place when there are small air gaps in or within the insulation. When the sparking happens, the transformer windings begin to degrade. The wider the void in insulation, the larger the probable discharge, which could potentially contribute to equipment breakdown. Partial discharge analysis and monitoring is a strong predictor of possible transformer failure. If kept undiagnosed, it may ultimately result to a total breakdown of the electrical insulation, which serves as one of the leading causes of transformer unplanned outages. Partial discharge analysis and monitoring is a strong predictor of possible transformer failure. If kept undiagnosed, it may ultimately result in total breakdown of the electrical insulation, which serves as one of the leading causes of unplanned outages in transformers.

Utilizing online monitoring systems such as the IoT to gather real-time data and detect partial discharges can help prevent transformer failures. The following condition monitoring techniques for partial discharges was proposed by [20]. Dissolve gas analysis (DGA) is one technique that can be utilized to monitor the concentration of dissolved gasses in the transformer oil. A DGA can reveal significant levels of thermal gasses in transformer oil such as methane, ethane, and ethylene as an indication of transformer oil overheating. These gasses are produced because of transformer oil thermal degradation. DGA forms part of the predictive maintenance strategy that can be utilized to monitor incipient faults and take reasonable action before transformer failure occurs [20]. There are IoT sensors available in the market that can facilitate real-time data gathering of the concentration of these gasses. Gas sensors such as the HKD MQ7 gas sensor module monitors carbon monoxide (CO), and the MQ-4 Methane gas sensor, etc., are readily available in the markets. IR sensors such as the IR Infrared obstacle avoidance sensor module are available in the market to monitor hot spots due to partial discharges in the transformer. To ascertain responses to the eight main research questions formulated in Section 1, this current SLR examines a total of 120 research works about IoT technology in transformer condition monitoring that were conducted from 2014 to 2024.

RQ1: What are the primary research objectives and goals addressed in the collected literature on IoT technology for electrical transformer condition monitoring and fault diagnosis?

The results of the literature study conducted for this paper provide a comprehensive overview of research articles relevant to the application of Internet of Things technology in electrical transformer condition monitoring, as shown in Figure 10. Fault diagnosis is the most notable of the highlighted research fields in terms of primary focus. The application of advanced modeling and monitoring techniques for the diagnosis and identification of problems in transformers has been the subject of 45.8% publications in total. Moreover, 24.2% of the studies examined the development and use of health indices to assess the overall well-being of transformers using an IoT infrastructure. Transformer lifecycle management is another important component. To optimize transformer lifespan, 22.5% of researchers

used Internet of Things technology to study this topic. The analysis also highlights 1.7% of vibration monitoring research and 4.2% of studies that optimize transformer energy usage. There was no partial discharge identification or thermal performance analysis in any of the literature that was gathered. Together, these findings demonstrate the breadth of research conducted on the use of the Internet of Things to enhance the efficiency, dependability, and performance of electrical transformers. The relatively small amount of research articles in areas such as vibration analysis, energy consumption optimization, and partial discharge analysis in the context of IoT technology for electrical transformer condition monitoring points to a few noteworthy conclusions.

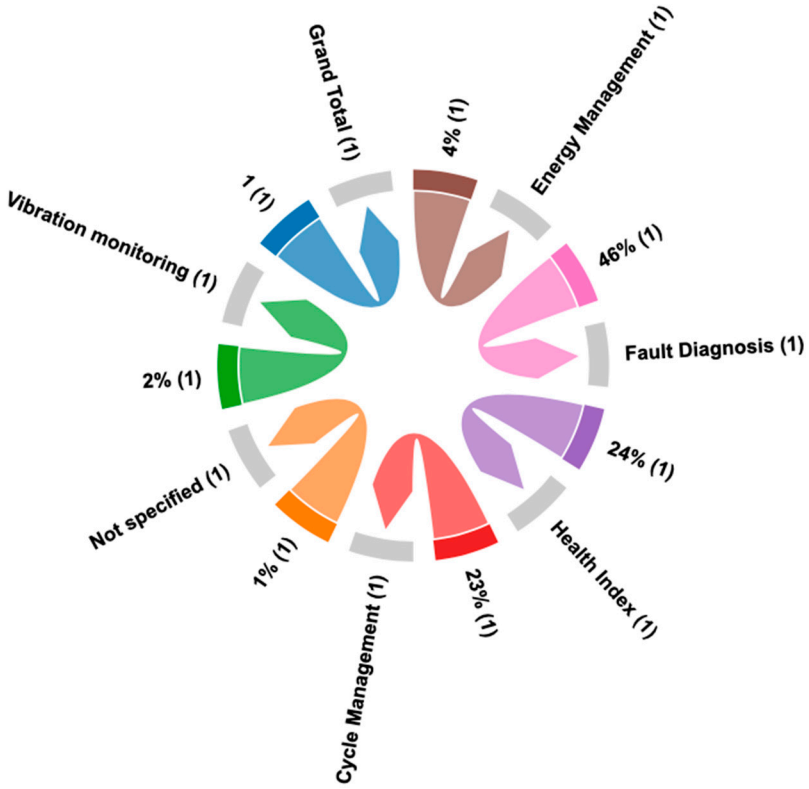


Figure 10. Research distribution by the transformer aspect investigated.

In the first place, it highlights a stark research gap in these areas, demonstrating that insufficient attention has been paid to them in the context of Internet of Things transformer applications. Secondly, it is possible that the complexity and unique challenges associated with these subjects have discouraged more research. Additionally, these fields may be considered niche or specialist, meaning that fewer scholars are working on them than on subjects like fault diagnosis or lifecycle management, which are subjects that are studied more extensively. Lastly, it is important to remember that research in these domains may still be in its early stages. However, if IoT technology for transformer monitoring develops further, we may anticipate seeing an increase in the amount of research produced in these areas. The dearth of research publications in these areas ought to be seen as a request for increased investigation and innovation inside the sector.

Figure 10 clearly demonstrates that the majority of the references conducted studies on fault diagnosis using IoT technology. Only [21,81] investigated the impact of vibrations in the transformer. When a fault condition arises within the transformer, the vibrations from the windings due to fault currents are a clear indication of the abnormal condition arising within the transformer. This area needs to be explored more. Figure 8 additionally illustrates that 55 publications conducted an investigation on transformer fault diagnosis using the Internet of Things. This aspect is crucial in ensuring longer service life of

transformers. A total of 29 publications conducted investigations on health indices to calculate transformer health indices and estimate the remaining life of transformers. A total of 27 reviewed papers focused on the lifecycle management of transformers. This is an asset management technique usually consisting of three steps; firstly, it involves risk evaluation for transformer assets. Secondly, it assesses the condition of each transformer, and, thirdly, involves alternative actions in the lifecycle, such as retiring, refurbishing, replacing, and discarding transformers [52]. Energy management aspects were the focus of five reviewed papers, utilizing IoT technology to monitor energy consumption and power theft. References [88,116] did not specify the aspects they investigated in their publications. References [21,81] were the only two papers looking into the vibration analysis of transformers using IoT technology.

RQ2: Which research publication sources have been predominantly utilized in the literature to study IoT applications in transformer monitoring?

The analysis of the published sources in Figure 11 shows how widely the literature on IoT technology for electrical transformer status monitoring is distributed. Conferences make up the bulk of the landscape with 55% publications, while journal articles only account for 45% publications. This distribution suggests that conference proceedings are the preferred means of disseminating research findings among the academic community researching this subject. Conference publications are very common for a variety of reasons. First of all, conferences are a well-liked substitute for disseminating cutting-edge studies in fields that are always evolving, such as IoT technology, since they usually provide a forum for scholars to promptly share their most recent findings and discoveries. Second, conferences might allow researchers to discuss their findings without the rigorous peer review process due to their laxer publication standards. The lower representation of journals may be explained by the rigorous peer-review procedures that they usually follow. Individual preferences, publishing schedules, and the target audience can all influence the decision between conferences and journals.

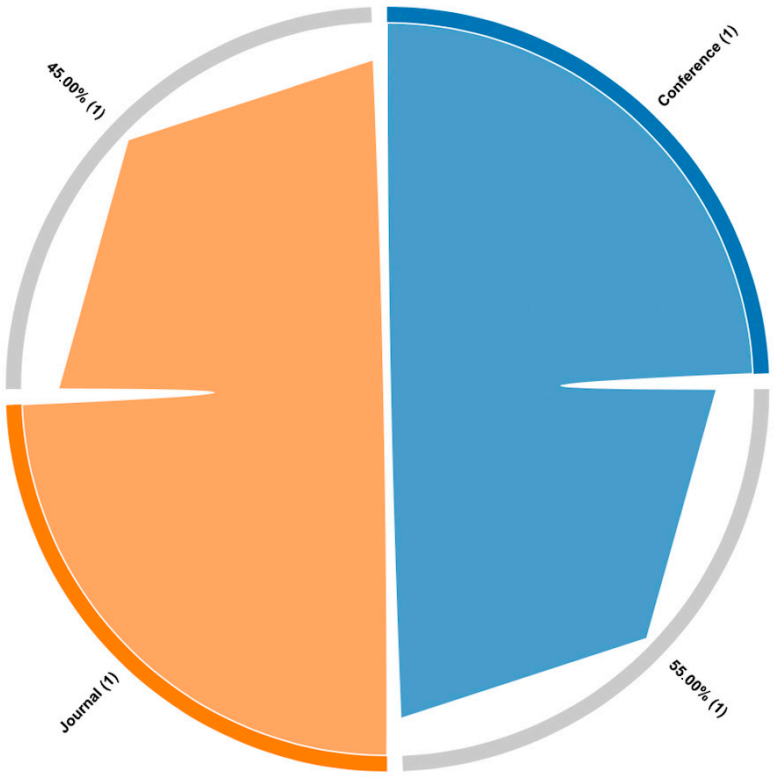


Figure 11. Research distribution by research type.

RQ 3: From which countries or regions do most of the articles on IoT technology for transformers originate?

The regional distribution of research contributions in the field of Internet of Things technology for electrical transformer status monitoring is depicted in Figure 12. Of these, India accounts for 55% publications of total contributions, suggesting a substantial concentration there. India has undertaken significant research efforts and has actively contributed to the growth of this technology, as evidenced by its dominance. Even though India leads by a large margin, other countries make substantial contributions as well, albeit on a smaller scale. China provides 8.3%, and Pakistan provides 3.3%, indicating a strong interest in this field. This worldwide distribution illustrates how ubiquitous the opportunities and problems associated with transformer condition monitoring are, as well as the possible advantages of IoT technology. A more thorough and strong understanding of this crucial sector can be achieved by cooperative efforts between nations with differing degrees of technological growth, which will ultimately help the power industry globally.

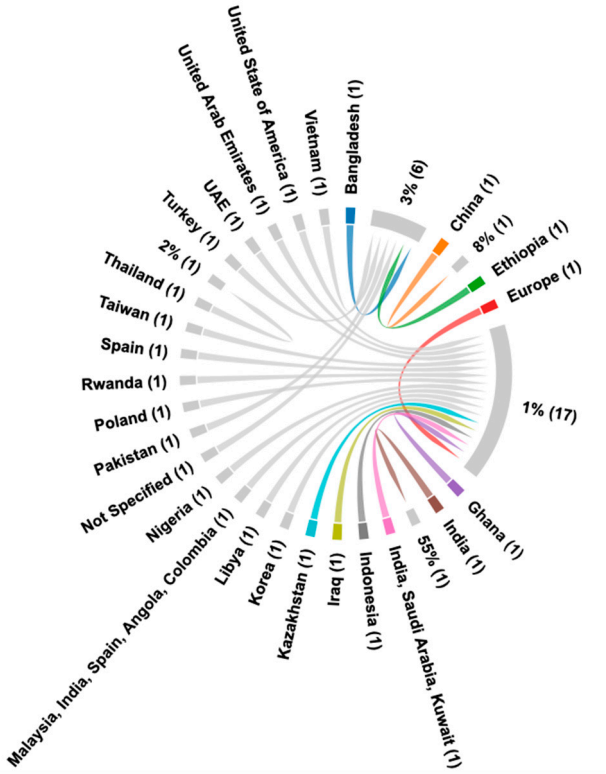


Figure 12. Research distribution by country.

RQ 4: What specific software and tools have been frequently mentioned and employed in the articles related to IoT technology in transformer condition monitoring?

The examination of the tools used in the research on IoT technology for electrical transformer status monitoring reveals a wide range of IoT platforms and software solutions. Among the solutions that are used most commonly is the Arduino IDE software. This program is well renowned for its capacity to set up third-party microcontrollers and Arduino boards. Researchers seem to prefer it because of its adaptability and ease of usage. Wi-Fi was the primary communication channel. Wi-Fi is preferred due to it being suitable for Local Area Networks and due to its ideal application benefits for the current infrastructure for close-quarters communication. The findings of the proposed study also indicate that the researchers' top choice for an IoT cloud was ThingSpeak, most likely because it is an open-source program that lets users aggregate, visualize, and analyze real-time data streams on the cloud. Finally, the Arduino Uno board was the microcontroller of choice for most researchers, mainly because the Arduino Uno boards are user-friendly

and easy to program, which makes them one of the most preferred choices for beginners. Arduino Uno boards are also affordable compared to other Arduino boards. The research distribution by communication channel is presented in Figure 13.

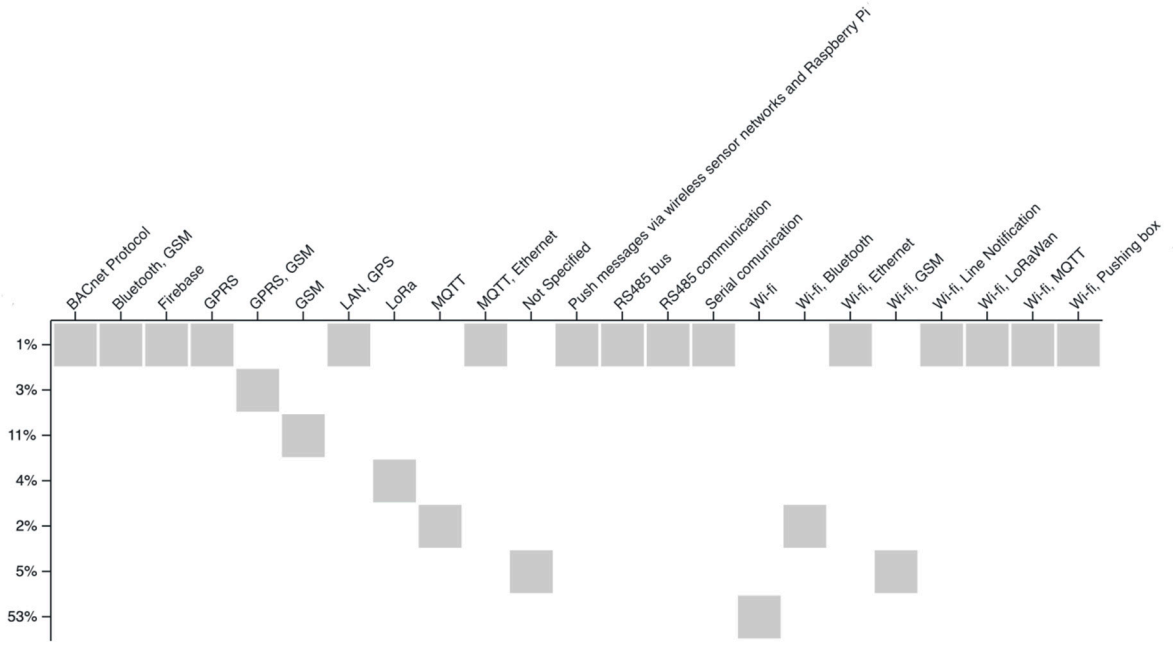


Figure 13. Research distribution by communication channel.

RQ 5: How has the research landscape on IoT technology for electrical transformer monitoring evolved over time, and what trends emerge from the collected literature?

The compilation of published studies in Figure 14 demonstrates the substantial evolution of the field of study on IoT technology for electrical transformer monitoring throughout the years. The information, which spans the years 2014 through 2024, indicates that both the number of studies being conducted on this subject and the interest in it are rising. The fact that only one study was released in 2014 indicates that, prior to 2018, there had not yet been much research conducted on the application of IoT technology for transformer monitoring. It took until the publication of 12.5% of new papers in 2019 and 10% of publications in 2020 for the research landscape to begin to gain traction. This noted rise suggests that more people are becoming aware of the potential benefits of IoT technology for transformer monitoring. The largest shift occurred in 2022 when there was a noteworthy increase of 25.8% of studies published. This spike can be attributed to the increasing availability of implementation tools and data, as well as the expanding awareness of IoT applications. There seems to be a lot of interest among researchers and practitioners in the idea of using the IoT to enhance transformer status monitoring.

The trend in growing interest and research activity in IoT technology for transformer monitoring is evident from these data. It suggests that researchers, industry professionals, and other interested parties are beginning to understand how the IoT might fundamentally change how electrical transformers are serviced, maintained, and optimized. As technology advances, this trend is probably going to continue, leading to more inventive uses and solutions in the years to come.

RQ 6: What emerging opportunities and technological advancements are highlighted in the collected literature that may shape the future of transformer monitoring using the IoT?

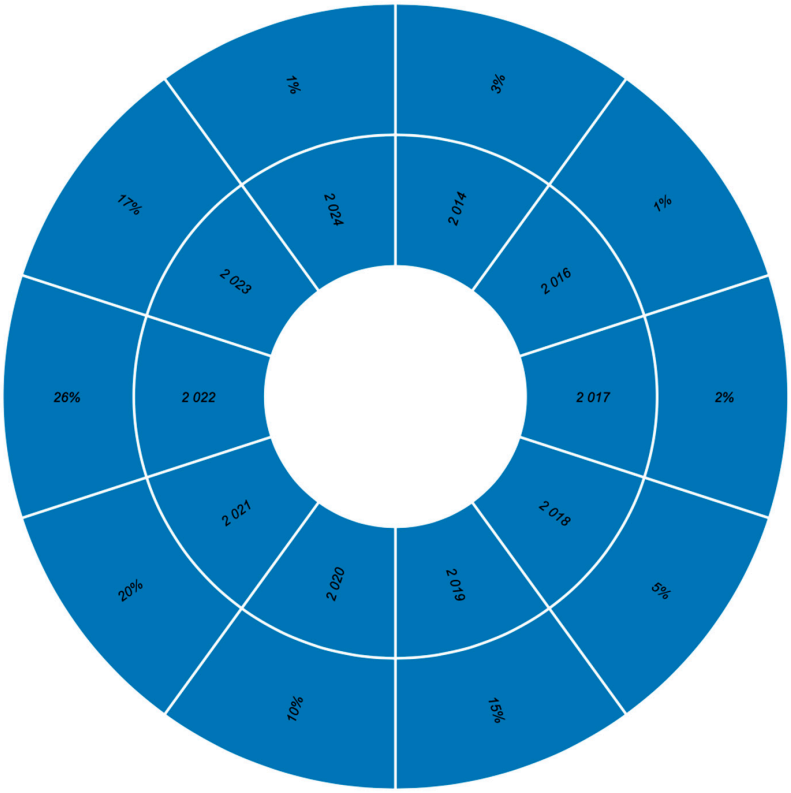


Figure 14. Research evolution over a decade.

The collected literature focuses on a number of recent innovations and technological advances that may have an impact on transformer monitoring via the IoT in the future. Among them are the following:

- Several studies discuss the use of advanced sensors and data collection tools to capture data in real time from transformers [65]. Improved monitoring and diagnostics may result from the more complete and accurate data collection provided by new sensor technologies, such as optical sensors.
- Studies show that machine learning, AI, and deep learning algorithms are being used more and more for defect identification and data analysis [22–37,39–42]. Improvements in fault prediction and classification made possible by these developments enhance transformer monitoring.
- A few works address the application of edge computing for data processing and analysis [34]. In situations where cloud connectivity may be limited, edge computing can reduce latency and enhance real-time monitoring capabilities.
- Cloud-based solutions are mentioned in some research. The scalability, storage, and data-processing capabilities of cloud computing can facilitate large-scale IoT deployments and data analytics.
- Internet of Things technology is crucial for managing the whole transformer lifetime, from design and manufacture to operation and maintenance, according to the literature [36]. By using a comprehensive approach, transformer performance can be optimized, and their lifespan can be increased.
- Maintaining the cybersecurity of IoT systems is essential given the growing connectivity and data sharing [28]. A few articles address the use of cybersecurity to safeguard infrastructure and data related to IoT technology.
- Several studies focus on improving energy efficiency through IoT technology [117]. Optimizing transformer operation and reducing energy losses are key objectives, contributing to sustainability efforts.

RQ 7: Which transformer types does the collected literature investigate?

The gathered literature explores a range of transformer types, representing a variety of uses and research interests in the topic of electrical transformer monitoring. Figure 15 illustrates that 49 percent of studies concern the "Power Transformer", the most often studied transformer type in the literature. This implies that power transformers, which are essential parts of electrical power systems, are the subject of a significant amount of research, with 40.8 percent of publications focusing on distribution transformers. The significance of guaranteeing dependable energy distribution is in line with the research interest in transformer monitoring, as these devices are essential to power distribution networks.

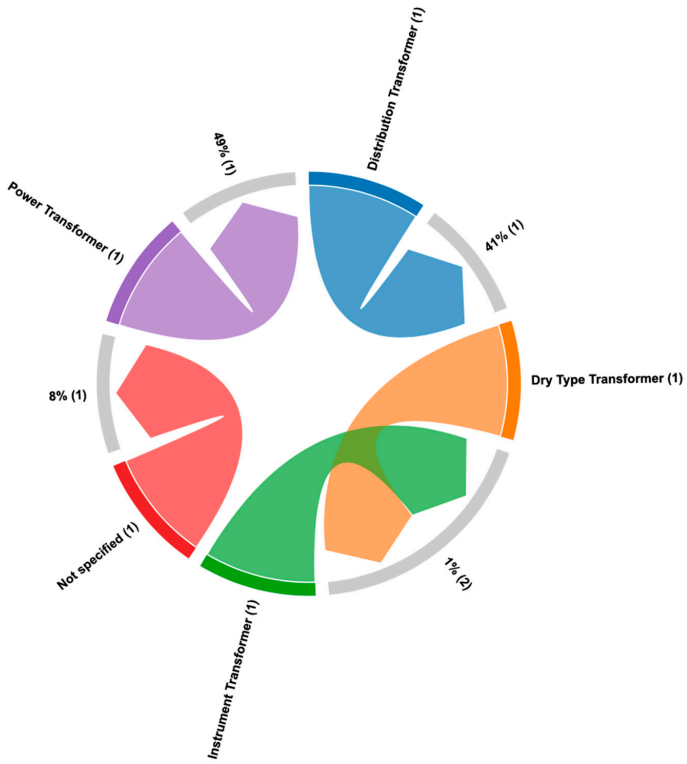


Figure 15. Research distribution by transformer type.

Table 11 tabulates different types of transformers that were mostly preferred by researchers to conduct condition monitoring, using an IoT-based system. Table 6 shows that power transformers and distribution transformers were the two transformer types being investigated by a high number of studies. The table also shows that there is a little focus on dry-type transformers and instrument transformers from the researchers. Studies [53,64,73,83,86,87,94,97,114,117] did not specify the transformer types being investigated in their papers. These references provided generic terms such as "electrical transformer" and "transformers".

Table 11. Investigated transformer types using the IoT.

Transformer Type	Paper ID
Distribution Transformer	[2,3,5,7,10,14,19,25,26,32,33,37–39,43,45,46,50,52,54,66,68,72,74–76,78,80–82,84,85,91,92,98,101–113,118]
Power Transformer	[1,4,6,8,9,11–13,15–18,20–31,34–36,40–42,44,47–49,51,55–63,65–67,69–71,79,88,89,93,95,96,99,100,115,116].
Dry-Type Transformer	[77]
Instrument Transformer	[90]
Not Specified	[53,64,73,83,86,87,94,97,114,117]

Transformers are essential electrical equipment in electrical power systems and other fields. The transformer is commonly utilized for different electrical applications to resolve electrical issues [42]. There are various ways to classify transformers. Transformers can be classified based on a number of phases. Transformers can either be classified into single-phase transformers or three-phase transformers. Transformers can also be classified according to their usage, namely step-up transformers and step-down transformers. Based on their application, they can be classified into distribution transformers, power transformers, isolation transformers, etc. Transformers can be classified based on winding configurations; there are two winding transformers and an autotransformer. Lastly, transformers can be classified based on core design. There are three types of transformers based on their core design, namely shell type, core type, and berry type, with shell and core types being commonly used [71]. The different types of transformers are briefly discussed below.

Power transformers are the most employed in high-voltage transmission systems. These transformers have voltage ratings of up to 400 kV. Most of the power transformers are rated 200 MVA and above [51,55]. They are utilized in generating power stations and transmission substations that require big transformers with higher ratings. The power transformer is constructed for optimum performance and is bigger compared to distribution transformers.

Distribution transformers are designed to lower voltage for delivery to customers or for business use. This transformer offers adequate voltage control and can run 24 h a day at 50 percent load efficiency. A distribution transformer, sometimes referred to as a demand transformer, converts a low- or medium-voltage supply to the voltage required for domestic appliances and machinery in factories [7].

The dry-type transformer is one that does not use insulating oil and instead uses insulating paper and natural cooling method for its windings. The windings and core are contained in a closed tank that is previously pressurized using air. They are safe to use without insulating oil [77]. Two types of dry-type transformers that are common are Cast Resin and Vacuum Pressure-Filled transformers.

Instrument transformers are intended to transmit either secondary voltage or current to instruments. The power system reticulation uses high voltages and currents, which can be detrimental to instruments, such as metering instruments, and protective relays [90]. Instrument transformers are then used to reduce high voltages and currents to safe levels in order for these devices to carry out their functions.

RQ 8: What are the common challenges and limitations documented in the collected literature regarding the implementation of Internet of Things technology in transformer condition assessment?

The most economical way to put timely condition monitoring into practice is to use open technologies, such as the Internet of Things, for power transformer real-time monitoring. With a sleep mode on the microcontroller, Internet of Things devices consume less power. This literature review discovered that transformer parameters may be monitored using Internet of Things sensors. While this literature review found that Internet of Things-based transformer status monitoring systems have shown encouraging results, there are still a number of areas that could use improvement. The concentration should be on enhancing sensor accuracy and the calibration procedure to further minimize measurement errors, especially for voltage and current measurements. It was discovered that the publications conducted research on IoT systems rated at 230VAC. This is a constraint, as this type of IoT system cannot be implemented for large transformers. The reviewed IoT monitoring system for transformers should utilize instrument transformers (i.e., current and potential transformers) for transformers rated above 230VAC on the secondary side. This intervention will minimize voltage and current variations sensed by the respective sensors and prevent damage to the components used. These instrument transformers will be connected to the monitored transformer. The IoT sensors can then be connected to the instrument transformers' secondary side, which will reduce the variation in voltage and current that each sensor detects. As discussed above, Wi-Fi communication protocol was

the most preferred protocol. However, Wi-Fi communication protocol is more suitable for Local Area Networks (LANs), which cover short distance ranges. Connection stability also becomes a challenge if there is a lack of proper infrastructure, which hinders seamless data transmission. Most of the publications focused on the monitoring of a single transformer using IoT. The scalability of the system to monitor several transformers in a substation, guaranteeing dependable communication and data aggregation from numerous transformers, should be investigated and studied further. The use of more advanced communication protocols, like GSM, LoRaWAN, Sigfox, etc., should be considered for seamless and long-range data exchange between physical transformers and IoT-based transformer condition monitoring in order to achieve optimal performance. These protocols improve the security, dependability, and long-distance transfer of data. Extended testing and validation carried out in various operational scenarios will yield more thorough insights into the functionality and areas that require the development of the system. Innovative IoT gadgets have become vital in the modern digital world. Security and data privacy precautions need to be effective and reliable in order to prevent significant breaches. Storage gaps and security fractures leave the vast amount of data being transferred through the IoT vulnerable to unauthorized access. Therefore, it is critical to ensure that standards exist to safeguard and handle them. If a manufacturer chooses an incorrect IoT platform and fails to comprehend their data obligations, data may be shared, traded in, or dispersed without authorization. IoT standardization would enable established means of data transmission, preventing critical data from falling into unauthorized people's hands. IoT standardization can promote a smooth integration process by providing norms for communication and data sharing across IoT-connected devices [80]. IoT standardization reduces the likelihood of connection and compatibility concerns, allowing gadgets to connect quickly and effortlessly while maintaining uniform performance, security, and dependability [80].

5. Conclusions

A thorough summary of the state of the research on Internet of Things (IoT) technology in the context of electrical transformer condition monitoring has been given by this systematic literature review (SLR). This study examined 120 research publications published between 2014 and 2024 using a strict process that included establishing inclusion and exclusion criteria, locating academic works from numerous reliable repositories, and performing quality assessments. Firstly, this review addressed important research concerns and clarified a number of important facets of this emerging topic. It began by outlining the main aims and objectives of this research, encompassing a wide range of topics, with fault diagnosis, lifecycle management, and health indices emerging as major aspects of the investigation. Secondly, it looked at the publication sources and found that conferences were preferred above journals, most likely due to the urgency of quickly disseminating research results in this quickly developing field. Thirdly, it looked into the regional distribution of research, showing that interest in transformer condition monitoring using IoT technology is widespread, with India leading the way, followed by China and Pakistan. This study also examined the IoT clouds, microcontrollers, communication channels, and software tools used in this field of research. The most popular software was Arduino IDE because it makes programming Arduino boards and third-party microcontrollers simple. One of the most popular communication protocols was Wi-Fi, while the IoT clouds and microcontrollers that were most preferred were Things Speak and Arduino Uno, respectively. Additional research is required to fulfill worldwide requirements, especially regarding privacy, security, technology, and connectivity. ZigBee communication protocol was found to be suitable for local IoT connections, while Sigfox or Lora communication protocols are more suitable for worldwide communication. IoT technology implementation must be able to integrate various communication protocols while balancing resource requirements and features. Scalability, standardization, dynamicity, and compatibility are some of the difficulties that may impede IoT growth. IoT standardization can help to smooth the integration process by establishing guidelines for communication and data sharing across IoT-connected devices.

IoT standardization eliminates connectivity and compatibility issues, allowing devices to connect fast and easily while ensuring consistent performance, security, and dependability.

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