IoT-Based Monitoring and Protection Applications in Power Substations: A Critical Review

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Abstract: This review paper presents a comprehensive analysis of recent research on IoT-based monitoring and protection systems in electrical power substations published between 2019 and 2025. The reviewed studies indicate that IoT technology have been extensively adopted to enhance real-time monitoring, condition assessment, data acquisition and remote supervision of substation equipments. A major portion of the existing literature focuses on monitoring-oriented applications such as transformer health monitoring, smart metering and substation surveillance where IoT mainly serves as a data collection and communication platform. In contrast, fewer studies address protection-related functions, including fault detection, overcurrent, earth fault, differential protections and coordination concept. In many of these studies, the protection logic is either simplified or still heavily dependent on conventional protective relays, with IoT used primarily to support communication or centralized decision-making instead of acting as a core protection element. This review classifies the selected studies into monitoring-based, protection-supported and intelligent or AI- based approaches, and compares them in terms of application scope, role of IoT, level of protection functionality and validation methods. Depending on this analytics, key limitations and research gaps are identified, highlighting the need for practical and standard-aware IoT-based protection schemes that can be effectively deployed in real substation environments.

Keywords: Internet of Things (IoT), Power substations, Monitoring systems, Protection systems, Overcurrent protection, Smart grids, Fault Detection.

I. INTRODUCTION

Electrical power substations consider the backbone of modern power systems, as they are responsible for energy transformation, protection and the control of power flow between transmission and distribution networks. In practice, even a small fault or undetected abnormal condition inside a substation can escalate into serious outages, equipment damage or long recovery times. For utilities and operators, maintaining reliable monitoring and protection mechanisms has therefore always been a practical necessity rather than a theoretical concern. In the past, power substation monitoring and protection were mainly based on manual inspections, and dedicated protection relays. These methods often come with high costs, limited flexibility, and heavy reliance on wired communication and human involvement. Besides, the limited real-time condition information, especially in large and complex networks and power systems such as the Aden's transmission lines and substations.

IoT-based technology improves the visibility and the situational awareness through the continuous monitoring and remote access to substation data. Recent research has therefore focused on areas such as transformer monitoring, environmental monitoring, smart metering, and simple fault alerts. However, IoT adoption in protection applications remains limited. Protection requires fast, reliable, and standards-compliant operation, which is difficult to achieve with typical IoT solutions. As a result, IoT is mostly used for monitoring and data sharing, while actual protection decisions are still made by conventional relays. This highlights the need to examine whether IoT can offer real benefits for protection beyond data collection.

This review intentionally highlights the imbalance between IoT-based monitoring maturity and protection limitations

II. IOT-BASED MONITORING SYSTEMS IN POWER SUBSTATIONS

A large body of research has focused on deploying IoT architectures to monitor electrical equipment, environmental conditions and operational parameters within the substations because they allow better visibility, real-time condition awareness, and easier remote supervision. This section reviews and analyzes existing IoT-based monitoring approaches, classifying them according to their primary application fields. The discussion highlights common system architectures, monitoring objectives and validation practices, as well as identifying key limitations that restrict the transition of these solutions from advanced monitoring tools to protection-capable systems.

2.1 Transformer Condition Monitoring:

Power transformers offer one of the most critical and expensive assets in electrical substations so their failure can lead to severe operational and economic consequences. As a result, a substantial portion of the literature on IoT-based substation monitoring has focused on transformer condition assessment and health monitoring. Recent researches widely adopt IoT technology to enable continuous monitoring of key transformer parameters, including voltage, current, temperature, oil condition and loading profiles with the objective of early fault detection and predictive maintenance. Several studies suggest IoT-based architectures for transformer monitoring which integrate multiple sensors with microcontroller units and cloud platforms. For example, the system presented in [1] implements real-time monitoring of voltage and current for a 100 kVA distribution transformer with fault indications transmitted to a remote monitoring interface. The overall system architecture shown in Figure 1, demonstrates a typical IoT-based monitoring framework consisting of sensing, data processing, communication and visualization layers [1].

Similar architectures are offered in [2] and [3], where transformer temperature, current and phase conditions are monitored continuously using IoT-enabled sensing units. Transformer condition monitoring is further extended in several studies through enhanced sensing and real-time data collection frameworks; For example, the system offered in [4] focuses on continuous monitoring of transformer operating parameters and remote fault indication using IoT-enabled communication. The proposed approach enhances operational visibility and supports preventive maintenance by providing real time monitoring data, while protection-related functions and decision-making mechanisms are addressed separately in later sections of this review. Other researches emphasize transformer condition monitoring as a part of a broader substation monitoring framework.

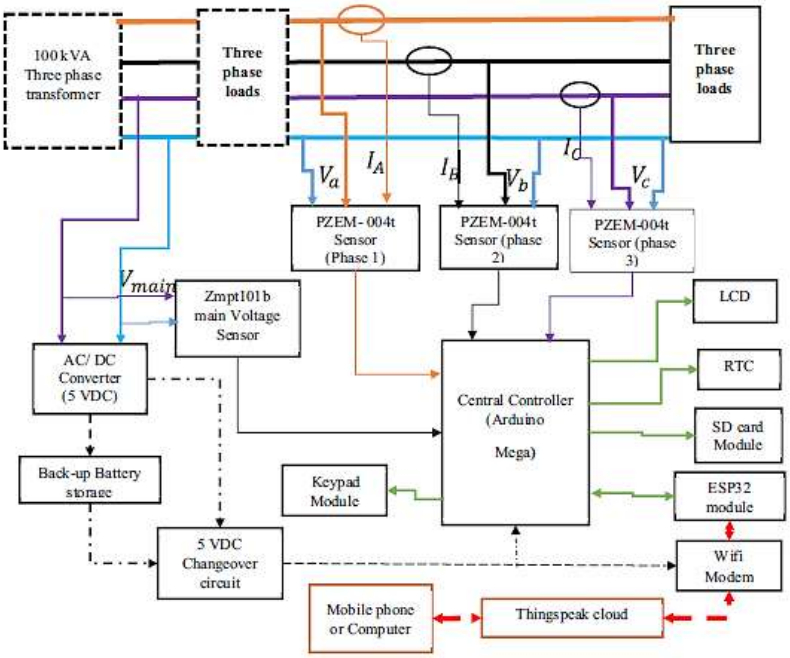

Fig.1: Block diagram of distribution transformer remote monitoring and faults detection system [1].

The works in [5], [6] and [7] integrate transformer monitoring within IoT-based substation management systems where transformer parameters are collected beside other substation data and visualized through cloud dashboards. In these systems, IoT mainly supports real-time data collection and remote supervision, while fault response and protection functions are still handled by protective relays. Recent researches have also explored advanced condition monitoring approaches by incorporating data analysis and machine learning techniques. The framework proposed in [8] enables edge computing and learning-based models to detect measurement errors and abnormal conditions in instrument transformers and metering devices. Although this approach improves diagnostic accuracy and responsiveness, it focuses mainly on measurement reliability and condition assessment rather than on fast protection functions. Similarly, the review presented in [3] highlights the increasing use of IoT and data-driven methods for transformer health index estimation and fault diagnosis, while noting the limited integration of these techniques with practical protection schemes. The reviewed studies show that IoT-based transformer monitoring systems are now technically mature, especially in sensing, communication, and data visualization. Nevertheless, most approaches focus on monitoring only, using IoT to improve condition awareness rather than to support standardized protection logic. This suggests a recurring gap in the literature, where better monitoring does not directly enable reliable protection or coordination with existing substation protection schemes.

2.2 Environmental Monitoring in Power Substations:

A substantial amount of IoT-based research has focused on the continuous environmental monitoring within power substations which may indirectly affect equipment performance, safety and reliability. Typical monitored parameters include temperature, humidity, gas concentration, intrusion status, fire indicators and auxiliary power conditions. Several researches employ IoT-enabled sensor networks to monitor substation environmental conditions and send real-time data to cloud computing platforms. For instance, the system presented in [9] implements an IoT-based environmental monitoring framework that measures temperature, humidity, SF6 gas concentration, and oxygen content inside substation premises to support early detection of abnormal operating conditions. The study confirms that continuous environmental monitoring can improve preventive maintenance practices by alerting operators to conditions that may accelerate insulation aging or equipment degradation. Auxiliary monitoring functions have also been explored in recent literature as a part of IoT-based substation monitoring systems. For example, the system offered in [10] focuses on monitoring electrical and environmental parameters such as voltage, current, temperature and humidity using IoT-enabled sensing and communication technologies. As shown in Figure 2, the proposed architecture shows real-time data acquisition, transmission and visualization through cloud-based platforms, thereby enhancing operational visibility and remote supervision of substation conditions. However, the system stills focused on monitoring and data visualization without interaction with protection schemes or fault-clearing mechanisms [10].

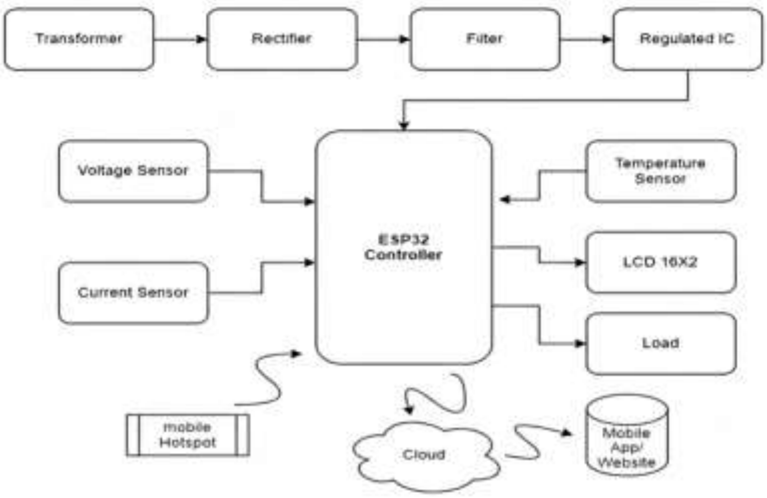

Fig.2: IOT-Powered Substation Surveillance System [10].

Across the reviewed studies, IoT architectures for environmental monitoring mainly follow a similar pattern: distributed sensing units collect data locally, communication modules send measurements to centralized or cloud-based platforms and visualization interfaces provide real-time status information and alarms. Validation is commonly performed through prototype implementations, laboratory testing or limited field demonstrations, as reported in [9], and [10]. However, these validations focus on data accuracy, communication reliability and monitoring responsiveness rather than on protection-grade performance metrics such as fault-clearing time or selectivity. In general, IoT-based environmental monitoring systems have been shown to be effective in improving visibility, safety and maintenance planning within substations. Nevertheless, their functional scope remains clearly monitoring-oriented, with IoT serving as an enabling layer for data acquisition and remote supervision. These approaches do not address protection coordination, real-time fault isolation, or standard-compliant protection logic, reinforcing the distinction between enhanced monitoring solutions and true protection systems, that distinction becomes critical in the subsequent analysis of IoT-supported protection schemes.

2.3 Smart Metering and Data Acquisition Systems:

Smart metering and data acquisition systems represent a large application field of IoT technologies within power substations and smart grids. These systems mainly focus on continuous measurement, data logging and remote visualization of electrical parameters in order to support operational monitoring, energy management and post-analysis. Several researches have proposed IoT-based smart metering architectures for substations and distribution networks. In [11], an IoT-based power monitoring and management system is developed to measure voltage, current, power and energy consumption in a distribution substation. As shown in Figure 3. the suggested architecture integrates distributed measurement units with IoT communication modules and a centralized monitoring platform, enabling continuous data acquisition and remote supervision of substation operation [11].

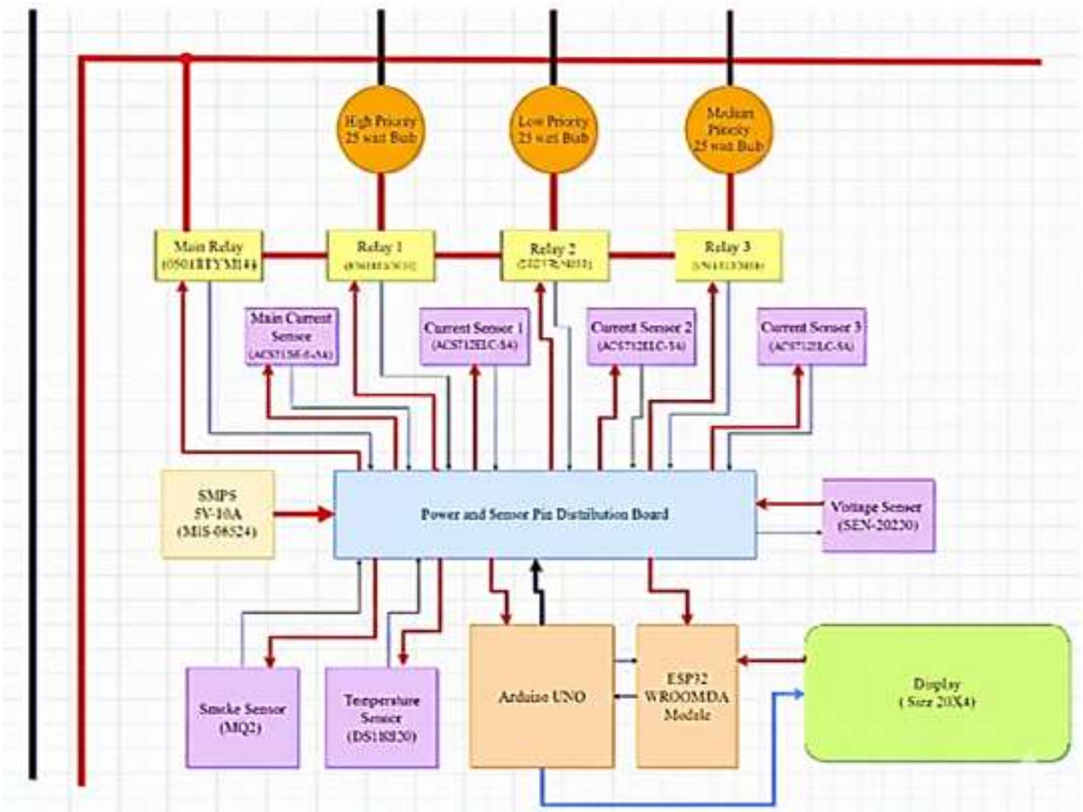

Fig.3: Single-line diagram of the proposed system [11].

The study explains the feasibility of IoT for smart metering and data visualization without addressing real-time control or protection logic. Similarly, the smart metering system offered in [12] integrates IoT-enabled measurement devices with MATLAB/Simulink-based analysis to study renewable energy generation and consumption patterns. The contribution of this work is limited to measurement, data analysis, and visualization, with no interaction with protection mechanisms. IoT-based data acquisition systems are further extended in some works through the integration of centralized communication and data aggregation platforms. The framework suggested in [13] focuses on collecting measurement data from substations and smart grids integrated with renewable energy resources and electric vehicles and transmitting them to centralized systems for monitoring and supervisory purposes. In this proposed approach, IoT acts as the data acquisition and communication layer (incorporate edge computing techniques) that enhances system observability and improve measurement reliability and diagnostic

capabilities, without considering the protection-related decision-making issues. For example, the approach offered in [8] applies edge-based processing to monitor measurement errors and abnormal conditions in instrument transformers (VTs & CTs) and energy meters. By processing data closer to the measurement source, the system improves traceability and reduces dependency on centralized processing. However, the primary objective of this work remains measurement accuracy and data validation instead of fault isolation or protection coordination. Across the reviewed literature, IoT-based smart metering and data acquisition systems exhibit common architectural characteristics. They depend on distributed measurement units to collect electrical parameters, communication networks to transmit data to cloud or edge platforms and software interfaces to visualize real-time and historical data. Validation is typically conducted through simulation studies, laboratory prototypes or limited pilot deployments as reported in [8], [11], [12], and [13]. These evaluations assess data accuracy, communication performance and system scalability but protection-grade requirements such as fast response time, selectivity and coordinated fault clearing are not taken into account.
In general, IoT-enabled smart metering and data acquisition solutions have significantly enhanced data availability and monitoring capabilities in substations and smart grids. Nevertheless, their functional scope remains strictly monitoring and data-oriented. The lack of protection logic, coordination mechanisms and compliance with protection standards clearly distinguishes these systems from true protection solutions which are discussed in the following sections of this review.

2.4 Substation-Level Monitoring and Integrated IoT Platforms

beside component-level monitoring and isolated measurement systems, several studies have proposed integrated IoT platforms to provide a holistic view of substation operation. These platforms focus on collecting electrical measurements from multiple substation elements into unified monitoring and supervisory frameworks, with the primary objective of enhancing system-level visibility and remote supervision. The framework shown in [6] underscores real-time monitoring and supervisory control of distribution substations using IoT technology, where electrical parameters and equipment conditions are collected from multiple substation points and sent to a centralized platform for visualization and operational awareness.

Beyond traditional substations, integrated IoT-based monitoring approaches have been extended to smart grid environments in [7] and [14], hybrid and renewable energy systems [15]. In ref [15], an IoT-based framework had been proposed for real-time monitoring, control and automation of hybrid green energy systems. The primary contribution of this approach lies in monitoring and system automation rather than in protection-related applications. The mean structure of the these IoT-based substation-level monitoring platforms depend on a centralized or cloud-based data aggregation, a distributed measurement, and software dashboards.

III. IOT-SUPPORTED PROTECTION SCHEMES

Unlike monitoring applications, protection systems must satisfy strict requirements related to response time, reliability, selectivity and coordination as well as compliance with established protection standards. These requirements significantly constrain the role which communication-based and data-driven technologies such as IoT can play in protection-oriented applications. In recent literature, several studies have explored the use of IoT to support protection-related functions in substations and power systems. These approaches range from basic threshold-based fault indication and remote tripping to more advanced concepts involving centralized decision-making, communication-assisted

https://doi.org/10.5281/zenodo.18478064

protection and intelligent fault analysis. However, in most cases, IoT does not replace conventional protection relays but rather operates as a supporting layer, providing data exchange, remote supervision, or auxiliary decision support. This section reviews and analyzes existing IoT-supported protection schemes reported in the literature, with particular attention to how IoT is incorporated into the protection process. The reviewed works are classified based on the nature of the protection function, the role of IoT within the protection architecture and the level of compliance with conventional protection principles. Through a critical examination of these approaches, this section highlights the practical limitations of current IoT-supported protection schemes and clarifies the distinction between monitoring-enhanced protection awareness and protection-grade implementations.

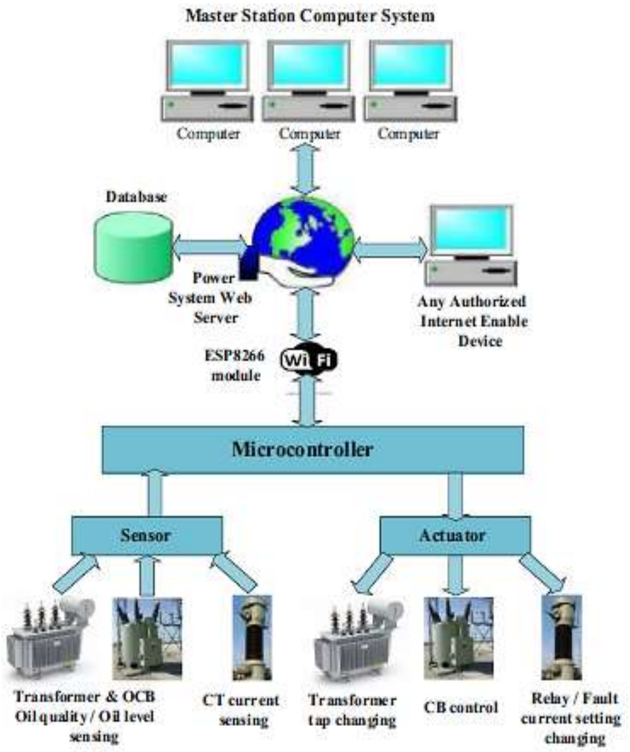

Fig. 4: Block Diagram of the proposed model [5].

3.1 IoT-Based Fault Detection and Simplified Protection Functions

Several researches have studied the use of IoT technologies for fault detection and basic protection functions in power substations. In such implementations IoT-based sensors and communication modules are used to continuously monitor electrical parameters and detect abnormal conditions using threshold-based criteria. When a fault or abnormal condition is detected, alarms are generated and simple control or tripping actions may be executed. Although such systems are often described as protection solutions, their functionality remains fundamentally different from standardized relay-based protection schemes. An example of this category is offered in [5], where an IoT-based monitoring and control system is developed for substation equipments. The suggested system integrates sensors for measuring transformer and oil circuit breaker parameters, including current, oil level and oil quality. As illustrated in Figure 4, the measured data are processed by a microcontroller and transmitted to a web server using an IoT communication module. Fault detection is achieved by comparing measured values with threshold values and abnormal conditions trigger alarm messages and basic control actions.

This approach enables both the early fault awareness and the remote response, though its protection logic is limited to threshold-based decision-making [5].

In ref [4], proposed a transformer protection system that incorporates IoT-based monitoring with overcurrent and differential protection. This approach depends on the current and temperature measurements to identify any abnormal operating conditions. Figure 5. Illustrates the proposed architecture as it integrates sensing units, IoT communication, and centralized processing to support fault detection and protection-related actions. Although the study addresses overcurrent and differential protection mechanisms, the protection logic is primarily based on predefined thresholds and simplified decision rules. Therefore, essential protection features such as time-current characteristics, selectivity, coordination with upstream and downstream relays, and standard compliance are not fully addressed.

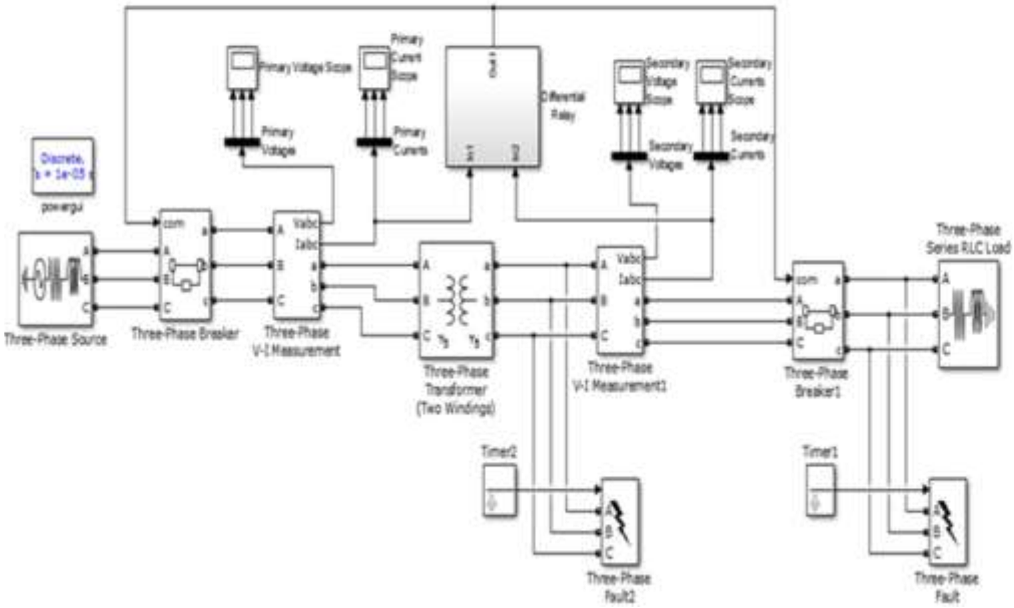

Fig.5: Arduino-Based IOT-Enabled Differential Protection for the Power Transformer [5].

While these approaches enhance fault awareness and responsiveness compared to manual supervision, their protection functionality remains limited when evaluated against traditional relay protection functions. Furthermore, simplified IoT-based protection schemes, some studies have investigated the integration of Industrial IoT concepts into relay-based protection devices. For example, the microprocessor-based protection device presented in [16] adopts an open architecture with IIoT support to enhance communication and system integration. While the core protection functions remain relay-based, IoT technologies are used to improve interoperability and data exchange rather than to modify protection logic.

Across this category of studies IoT technology plays a central role in data acquisition, communication and remote supervision but it doesn't replace the main numerical protection relays. Fault detection is typically depended on static thresholds or basic logical conditions, and validation is often limited to laboratory prototypes or simulation-based demonstrations. Performance metrics critical to protection systems such as fault-clearing time, selectivity, reliability and coordination with existing protection schemes are generally not evaluated. In general, IoT-based fault detection and basic protection functions represent an initial step toward integrating IoT into protection-related applications. These approaches successfully enhance fault awareness and remote operability. however, they fall short of delivering protection-grade solutions. Their limitations highlight the gap between monitoring-supported fault indication and standardized protection implementation, enhancing the need for more rigorous and coordinated protection architectures.

3.2 IoT-Assisted Communication-Based Protection

In communication-assisted protection schemes IoT technologies are mainly used to support data exchange and coordination between protection relays rather than performing protection decisions independently. In these schemes, traditional relays remain responsible for fault detection and tripping commands, while IoT-based communication networks enable the data exchange, fault status and control signals.

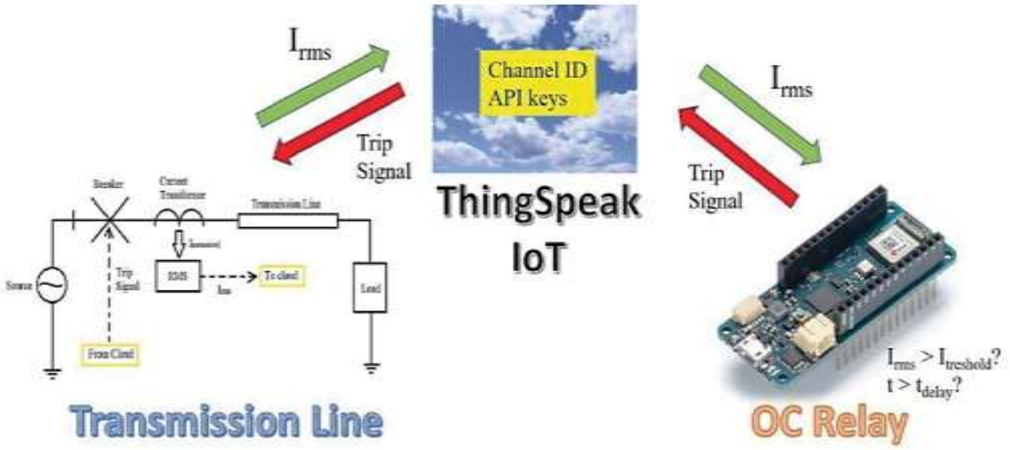

Fig.6: Proposed wireless IoT based OC relay [16].

Representative examples of this category are reported in [17] and [18], where IoT and wireless communication technologies are used to enable centralized or remote-assisted protection schemes. In [17], a LoRaWAN-based IoT protocol is proposed to support a centralized protection architecture for MT-HVDC networks in which protection-related data are sent to a central decision unit through IoT communication links. Similarly, the wireless IoT-based overcurrent relay presented in [18] demonstrates how IoT communication can be used to transmit current measurements and trip commands between protection devices wirelessly. The overall communication-assisted protection concept illustrated in Figure 6 highlights the role of IoT as a supporting communication layer rather than a standalone protection mechanism [19]. Communication-assisted IoT protection schemes face critical issues related to communication latency, and reliability which prevent their use as time-current protection scheme.

3.3 Intelligent and Data-Driven IoT-Supported Protection Approaches:

Recent studies have offered the integration of IoT with intelligent and data-driven techniques to enhance protection functions in power substations. In such approaches, IoT infrastructures are primarily used to collect and transmit large volumes of operational data, while advanced analytics, machine learning, or artificial intelligence techniques are applied to support fault analysis, classification, and decision assistance. Several works demonstrate the potential of intelligent algorithms to improve protection awareness. For example, the study reported in [19] applied intelligent algorithms for fault location and isolation in power grid automation, where measurement data collected through communication networks are processed to identify faulted sections.

In general, intelligent and data-driven IoT-supported protection approaches demonstrate promising capabilities for fault analysis and decision support. Nevertheless, most existing solutions function as supportive or advisory systems rather than fully autonomous protection schemes. The lack of standardized protection logic, coordination mechanisms and protection-grade performance validation remain a key limitation, indicating that further research is required before such approaches can be reliably deployed in practical substation protection environments.

Table 1: Key limitations of IoT-based monitoring platforms in power substations

Ref.	Application	IoT Function	Key Limitation
[3]	Transformer monitoring	Data acquisition & visualization	No protection logic
[4]	Environmental monitoring	Sensor-based monitoring	Monitoring only
[10]	Instrument transformer monitoring	Edge-based diagnostics	Diagnostic only
[13]	Substation surveillance	Remote supervision	No protection capability
[19]	Cloud-based substation monitoring	Cloud analytics	Monitoring-focused

Table 1 presents a comparison between some of the IoT-based monitoring solutions reported in the literature, including transformer condition monitoring, environmental supervision, substation surveillance, and cloud-based monitoring platforms, shows that IoT is primarily used for data acquisition, remote supervision, edge diagnostics, and visualization. They remain strictly monitoring-oriented and lack integration with standardized protection logic. The consistent absence of protection functionality across these studies highlights the dominant role of monitoring in current IoT-based substation research [19],[20].

Table 2: Overview of IoT-supported protection-oriented approaches in power substations.

Ref.	Application	Protection Role	Key Limitation
[1]	Substation monitoring & control	Threshold-based protection	Non-standard logic
[7]	Transformer protection	OC & differential (simplified)	No coordination
[16]	Wireless OC relay	Communication-assisted tripping	Reliability concerns
[17]	IoT-supported protection device	Protection support	IoT not core logic

While most IoT applications in substations remain monitoring-focused, a smaller body of work has explored IoT-supported approaches for basic protection-related functions. Table 2 presents IoT-supported approaches that move beyond pure monitoring toward basic fault detection and protection-related functions such as overcurrent, differential, or threshold-based protection concepts. Certain core protection requirements (including selectivity, and coordination with established protection standards) are omitted. As a result, most of these systems function as supportive mechanisms rather than fully autonomous, protection-grade systems [21].

Table 3: Communication-assisted and intelligent IoT-based protection support approaches.

Ref.	Application	IoT Contribution	Key Limitation
[6]	Relay protection device	System integration	Limited real-fault testing
[11]	Intelligent fault analysis	Data analytics	Advisory only
[15]	Centralized HVDC protection	IoT communication	Latency dependency

Table 3 focuses on communication-assisted and intelligent IoT-based approaches that utilize IoT infrastructures for data exchange, centralized decision-making, and advanced analytics. These methods demonstrate potential benefits in flexibility, fault analysis, and decision support. However, their effectiveness is constrained by communication latency, reliability concerns, cybersecurity issues, and limited validation under real fault conditions. Consequently, such approaches are generally more suitable for supervisory, backup, or advisory roles rather than primary protection functions in power substations.

IV. DISCUSSION AND RESEARCH GAPS

A review of recent studies shows a noticeable gap between the rapid progress of IoT-based monitoring in power substations and the relatively slow development of IoT-supported protection schemes. Monitoring solutions have reached a practical level of maturity and are already being used in many real installations. In contrast, protection-oriented applications are still limited, mainly due to technical difficulties, dependence on communication infrastructure, and the absence of widely accepted standards. This section discusses the main reasons behind this imbalance and outlines the challenges that currently restrict the use of IoT in protection functions.

4.1 Dominance of Monitoring-Oriented IoT Applications

Several studies report that most IoT deployments in substations are designed for monitoring purposes, including transformer health assessment, environmental sensing, smart metering, and large-scale data collection. These systems have clearly improved access to operational data and enabled remote supervision through cloud and edge computing platforms. In practice, however, their function is mostly limited to observation, visualization, and offline analysis. Essential protection requirements (such as fast response, reliable fault isolation) are rarely addressed. Therefore, although monitoring capabilities continue to improve, they do not directly translate into protection-level performance or increased operational safety [3], [9],[19], [20], [21].

4.2 Limitations of IoT-Based Protection Implementations

In many published works, IoT-based protection is implemented only as a supporting feature rather than as an independent and complete protection system. Fault detection methods are often based on simple thresholds or basic rule-based logic, even when conventional protection concepts like overcurrent or differential protection are mentioned. Important aspects such as selectivity, coordination between relays, and interaction with upstream and downstream devices are frequently simplified or ignored. For this reason, IoT is typically added on top of existing protection systems instead of being integrated into standardized protection architectures [21].

4.3 Communication Dependency and Reliability Challenges:

A large number of proposed IoT protection schemes depend on communication networks for centralized processing, remote decision-making, or assisted tripping. While this design offers flexibility and easier system expansion, it also makes protection performance highly sensitive to network delay, packet loss, and cybersecurity threats. In protection applications, even small disturbances in communication can lead to incorrect or delayed responses, which may compromise system stability. For this reason, communication-dependent IoT schemes are more appropriate for backup protection, supervision, or operator support, rather than for primary protection tasks that require very fast and deterministic operation [1], [15], [21], [22].

4.4 Role of Smart and Data-Driven Methods

In [15], the authors demonstrate that integrating IoT platforms with intelligent techniques such as machine learning, pattern recognition, and data analytics has attracted increasing research interest, especially for fault diagnosis and fault location. These methods can potentially improve decision accuracy and provide deeper insight into system behavior. Nevertheless, most existing studies remain at the simulation or laboratory stage and are rarely tested under real operating conditions. In addition, there is still no clear framework for integrating these data-driven methods with established protection coordination and logic. As a result, intelligent IoT-based approaches are currently better suited for advisory and diagnostic functions than for direct use in critical protection tasks.

4.5 Research Gaps

Based on the comparative analysis, the following key research gaps are identified:

- The lack of standard-compliant IoT-based protection schemes aligned with established protection principles and industry standards.
- Insufficient validation under real-time and real-fault conditions, particularly regarding response time, selectivity, and coordination.
- There is a significant integration gap between IoT platforms and conventional numerical protection relays.
- Still there are unresolved protection-oriented IoT systems issues related to the communication reliability, latency, and cybersecurity.

4.6 Discussion Summary

Overall, IoT technologies have achieved a high level of maturity in substation monitoring applications, whereas their adoption in protection functions remains relatively limited. Advancing beyond this imbalance will require the development of hybrid protection architectures that combine the proven reliability of conventional protective relays with the flexibility, scalability, and data-processing capabilities offered by IoT technologies and edge intelligence. To be viable in real-world power system environments, such architectures must be designed in compliance with established protection standards and validated through comprehensive experimental studies and field deployments to ensure reliable and dependable operation.

V. CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

This paper reviews recent research on IoT-based monitoring and protection systems for power substations. The literature studied shows that IoT technologies have been widely and successfully used to improve monitoring functions, such as monitoring the state of transformers, monitoring the environment, smart metering and collecting data at the system level. Such applications have significantly improved data availability, real-time awareness and remote supervision capabilities in modern substations. In contrast, the integration of IoT into protection systems remains limited and immature. Most IoT-supported protection approaches focus on basic fault detection, communication-assisted functions or advisory decision support instead of protection-grade implementations. Essential protection requirements such as deterministic response, selectivity, coordination and compliance with established protection standards are rarely satisfied. As a result, IoT is mostly used as a support layer right now, not as a main part of substation protection systems. From the comparative analysis and the identified research gaps, several future research directions can be outlined.

First, there is a clear need for IoT-based protection designs that are aware of standards, follow standard protection principles, and work well with numerical protection relays. **Second,** strict testing in real-time and real-fault situations is necessary to check protection performance metrics and make sure they are reliable in practice. **Third,** future work should address communication latency, reliability and cybersecurity challenges which directly affect the suitability of IoT technologies for time-critical protection functions. **Fourth,** the development of hybrid protection designs which integrate the reliability of classic protective relays with the flexibility and data-handling power of IoT and edge intelligence is a potential method to make these systems useful in real life.

In general, IoT has already shown that it can be very useful for monitoring substations, but its significance in protection systems is still an open question for researchers. To make the next generation of smart substations' intelligent and dependable protection systems work, we need to fix the problems that were found by using integrated design, following standards, and realistic validation.

Author Contributions: Conceptualization, A.K.A., and M.F.A; Methodology, A.K.A, T.M.R., and M.F.A.; Validation, T.M.R.; Writing Original Draft Preparation, A.K.A.; Writing Review & Editing, M.F.A, and T.M.R.; Supervision, M.F.A and T.M.R.

Conflict of Interest: The authors declare that there is no conflict of interest.

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