AI-Driven Self-Healing Switchgear System for Enhanced Reliability and Predictive Maintenance in Smart Grids

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Abstract—**This paper presents an AI-enabled self-healing switchgear system to guarantee reliability & efficiency of modern power systems. Through the use of AI, edge compute technology and predictive maintenance, it real-time monitors key electrical metrics that help identify faults, switching to a backup relay in case of a failure. Error detection and predictive maintenance systems are helpful, utilizing TinyML models that can be implemented in real-time on an ESP32 microcontroller with low latencies for uninterrupted operation to prevent downtime from occurring as much as possible when encountering faulty states. Self-healing through dual-relay redundancy; if the usage of backup relay is enabled, switching to it will prevent service interruption and reduce system downtime. In addition, live data is streamed into a cloud-based dashboard from which operators can do remote monitoring and receive predictive alerts. The system achieves higher resilience along with better efficiency in power grids by facilitating early detection of failure and allowing reactive component switching, which in turn contributes to reduced maintenance costs. Modern power grids can also supplement SM with AI and edge computing to support self-healing switchgear. Further advancements in the refinement of artificial intelligence models, expansion of self-healing functionality and improvements on cybersecurity pertaining to the system's capacity to meet challenges from interconnected grid environments have been anticipated.**

***Keywords— AI-driven, Edge Computing, Predictive Maintenance, Relay Status, Self-healing, Smart Grids, Switchgear*.**

I. INTRODUCTION

Power use and operation of electrical grids are vital for industrial or residential infrastructures stability which are relying increasingly on smart grid and automation; therefore, there is a major need that power systems also have high reliability. At present, electromechanical relays make up most of the commercial technology available for protection in circuits, however mechanical wear, thermal stress and arcing are all problems that this type of relay suffers from as a matter of course. When these systems start to fail, one consequence is unplanned trips, heating costs increase and operational reliability decreases. The common solution is to conduct AI and ML methods for an example, predictive maintenance, fault detection, and self-healing of the system. A failure prediction could avert those outages, allowing power grids to run with greater efficiency and economy. Decoupling reactive fault information systems from passive data-dependent ones is central to smart grid technologies and represents the present challenges in terms of privacy preserving compliance. At the same time, another breakthrough over recent years has seen AI-based condition monitoring systems that can efficiently explain faults, and make life-cycle management work for power grids. As at many times AI can have good results, intelligent fault-detection systems in the form of machine learning algorithms have been implemented through decision trees, support vector machines and deep learning models which can monitor electrical parameters as their focus is mainly on aging assets undergoing fault diagnosis and failure prediction. In an AI-based model the system is learning from past data patterns; this could mean an impending failure which goes undetected among conventional approaches. Conversion equipment with initial failure makes this development several fold less reliable. However, makes improvement in system reliability that a dramatic increase in accuracy and speed of deviation detection. Against traditional threshold protection metrics such as fault detection accuracy and response times, these techniques have proven favorable [1-4]. Also, predictive maintenance important part of modern power systems, should be established in real life to minimize the time that equipment remains idle and prolong its operational life. Think how the predictive maintenance systems, working by use of decision trees on AI systems, are keeping a continual watch over health of the system and even the most minor signs for early indications of degradation in performance because of aging parts such as induction failures. In the past, maintenance has been conducted on a time-based metric and only reactive actions taken when faults appear. This implementation allows for efficient system operation, decreased operating costs, low maintenance expenses, and long-life equipment without short lives for its parts. Such systems thus - as they discourage unnecessary maintenance or replacement [5-9]. An emerging technology for real-time monitoring and fault detection in power grids is edge computing, a revolutionary architecture that decentralizes information processing near the source of generation rather than centralizes it. Edge computing reduces the dependence of processing, especially in centralized cloud-based systems, by approximating and curing the data through embedded systems such as microcontrollers that could also offer a quicker decision with lesser latency. This is particularly relevant for real-time applications, as the whole system could become unresponsive if there is a delay in fault detection. TinyML, a subfield of machine learning specialized for low-power platforms, allows machine-learning models to be deployed on ultra-low power microcontrollers. This enables real time edge-based anomaly detection, fault prediction and maintenance for multiple industrial, e-mobility and smart grid applications. TinyML is a small-size oriented solution to execute AI-supported frameworks in limited computational power environments, which is quite helpful for edge-based models in the field of power systems [10-14]. While key advancements in AI/ML and edge computing have gone a long way, there are still open questions regarding the practicality of self-healing power systems. For instance, one major challenge requires large amounts of labeled data to train machine learning models. So even though supervised learning methods can get very accurate results, the major hurdle remains an approachable well formatted data set to be trained on. The challenge in training models to generalize well towards unseen regimes stems from the common absence of infrastructure in power systems that allows for high-throughput, low-latency data. Also, scalable architectures for low-latency or high-throughput systems for real-time fault detection by large-scale data processing are needed. However, would not be able to satisfy the requirements of real-time applications, particularly large-scale systems with existing models. Another challenge is how to integrate models for fault detection with those for self-healing. Self-healing systems switch the primary and backup relays several times during fault scenarios to provide power delivery. The trick, however, is ensuring those systems are compliant and responsive in real-time all while running in a manner that there’s never any delay or service outage. Nevertheless, fault detection and correction based on predictive maintenance models and self-healable mechanisms should be time-aligned. The time needed for the system to switch from relay to relay is a reaction time, a key performance specification when it comes to reliability and continuous power delivery. Therefore, to alleviate such challenges, the researchers inclined towards the hybrid types of formulations [13]; however, this approach includes formulating a semblance between artificial intelligence-based fault detection along with real-time self-healing competent as it is determined to reduce the responding time for the occurrence of faults and ensure uninterrupted transferring capabilities during failure scenarios across relays [14-16]. But incorporating AI into energy systems that are already operated for large parts of the day is difficult. Most of the currently existing power plants were not designed with filtering AI or edge computing applications, so substantial updates will be anticipated in order to incorporate these new advances. Legacy systems often need to be retrofitted with AI-based fault detection or self-healing hardware and software, which generally has to be funded. However, in the long run, it makes sense to make such investments because AI-based solutions provide an improved fault prediction benchmark, greater uptime and lesser maintenance costs. Data can be stored on cloud platforms where all data can be analyzed, which is really helpful in real-time applications, as a combination of cloud application would provide central point widgets for the entire system comprising predictive alerts and long-term performance status. Operators monitor the grid’s health from a distance in cloud-based systems and are automatically notified and guided on what interventions to take before a fault cascade into system-wide failure. Standardized communication protocols like IEC 61850 improve interoperability among substation automation system entities [18-20] so that AI-based fault detection algorithms and self-healing functionalities can be integrated homogeneously in diverse devices and hosts.

- To develop an AI-enabled automated fault diagnosis and recovery system for switchgear with improved reliability and fault tolerance in power grids.
- Towards edge computing with TinyML for real-time fault detection and predictive maintenance for power systems.
- It is to develop a hybrid system merging AI based fault detection with dual relay redundancy architecture for fault recovery.
- To test the system in simulation and prototype hardware to evaluate its performance in-real time.
- To power cloud-based monitoring and remote diagnostics for predictive maintenance and system health status.

II. Operation of the AI-Driven Self-Healing Switchgear System

The layout of the entire system is depicted in **Fig. 1**, which uses a microcontroller called ESP32 as CPU. The most interesting part is, the overall setup uses an ESP32 based board as the central control unit and monitors key parameters of electrical systems Such as voltage, current or temperature with basic sensors. Using TinyML based models, lightweight machine learning models that are deployed directly on microcontrollers for real-time inference to identify and diagnose anomalies and the potential for failures in data collected. Because they detect important shifts in electrical signatures that traditional threshold-based systems would miss until a problem has turned disastrous. If there is a fault or an overcurrent/overvoltage situation, **Fig. 2** shows that the system will engage a dual-relay redundancy mechanism. If relay failure occurs, a second relay is powered in order to allow delivery to the load. In order to reduce the downtime as well as provide reliability, systems are integrated so that they can work continuously and efficiently; the backup relay gives an important function in industrial and smart grid environments. The seamless and efficient transfer of control during fault scenarios with no downtime between the main relay and backup relays is essential for the system to operate properly. Simultaneously this robustness around the edges is enhanced by a cloud monitor agent that relays data in real time for remote analysis and maintenance planning so that operators can see what is happening to their systems at any point in time, which means they have a chance of being able to spot an impending failure.

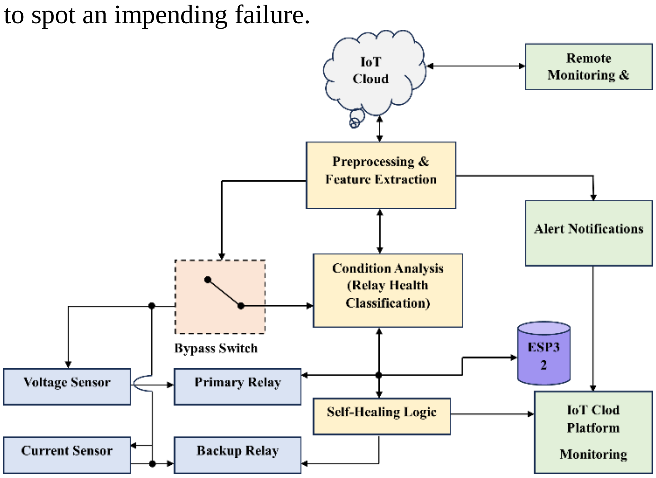


Fig. 1. Block Diagram of the AI-Driven Self-Healing Switchgear System.

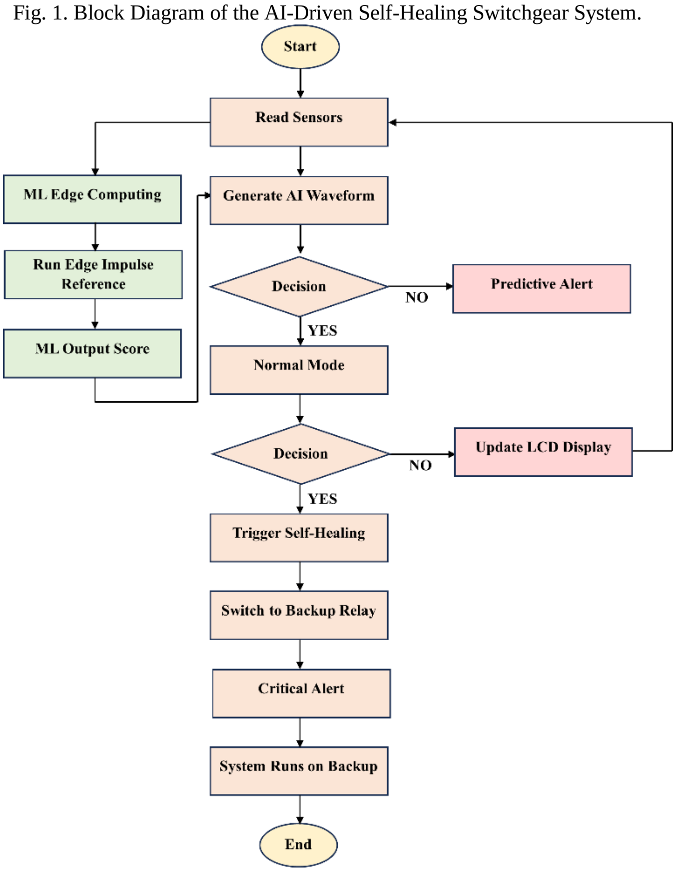


Fig. 2. Flowchart of the AI-Based Relay Condition Monitoring.

III. Results and Discussion

In **Fig. 3**, AI predictive dashboard, primary interface for real-time status monitoring of self-healing switchgear system Operators will have full visibility on their system health with this dashboard structured to reflect as such. These parameters include the server status panel, which displays a number of important parameters including health index, relay status, voltage and current values as well temperature. This is just summary for operators to see the performance and health of system. The extreme left side of the health index, shown in large red letters here, is an alert for outliers or divergent values that may indicate a problem, which allows for early intervention, before pieces of a problem grow up into severe defects, such application is very useful on deep diagnostics scenarios, or in long-term performance monitoring where engineers need to check trends, anomaly detection or simply generate a report. In Fig. 4, which shows the operational data in the table format, depicts key parameters such as temperature, humidity, current and voltage plus sound level so much more readable information is available. The format allows operators to track the behaviour of the system over time, and to check for oscillations or spikes in variables that could be signifying impending failure. By monitoring these metrics in real time, you can intervene when needed to maintain the system within reasonable limits. By identifying trends early, engineers find issues before they occur. Doing so allows systems to them fail less and ensures minimizing unforeseen downtime. Such would be a system trained on further tests data save it could learn to behave in known scenarios then adapt albeit predictively when something unknown presents. In **Fig. 5,** the prototype hardware for the ESP32 microcontroller-based self-healing system complete with relay modules and sensors. The things to keep in mind till data is against it are dual relay design system switch between primary and backup relays during the fault execution. That redundancy is essential to the uptime of the system, its ability to continue functioning despite a failed relay. This is important for systems that must be very reliable and have very few downtimes. Critical infrastructure use, for example. Lastly, **Table I** provides necessary information about the system design parameters including ESP32 microcontroller, sensors and relay modules with operational conditions such as relay switching time, logging capacity and power consumption. These types of parameters are crucial for the functioning of the system but also to perform appropriate fault detection.

TABLE I. Design Parameters of the AI-Driven Self-Healing Switchgear System

S.No.	Parameter	Description	Value	Justification
1	Microcontroller	The main processing unit of the system.	ESP32	Controls AI-based relay monitoring and self-healing logic.
2	LCD Display	Displays real-time data and alerts.	16x2 LCD	Shows monitoring information and system status.
3	Relay Switching Time	Time taken for switching between primary and backup relay.	0.5	Critical for ensuring minimal downtime during failures.

4	Data Logging Capacity	Storage for real-time data collection.	512 KB	Stores health index, voltage, current, etc.
5	Operating Voltage	Voltage range for proper operation of the system.	3.3 - 5.0 V	ESP32 operates within this range.
6	Power Consumption	Energy usage of the microcontroller and system components.	250 mA	Relates to the power efficiency of the system.
7	Temperature Range	Operating temperature for the system.	0 - 70 °C	Ensures reliability across

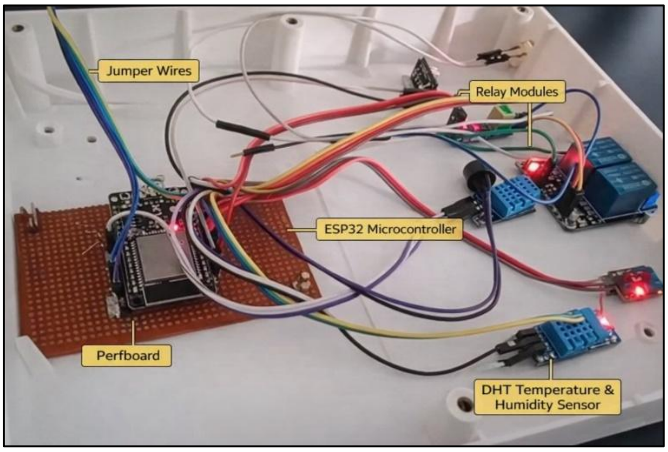


Fig. 2. Prototype Hardware of the AI-Driven Relay System.

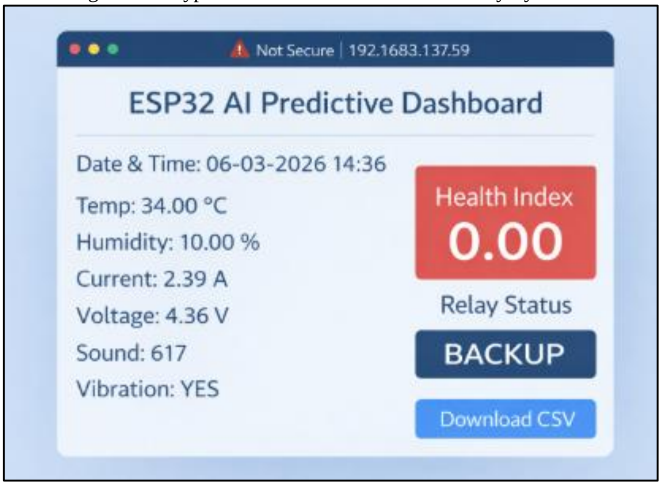
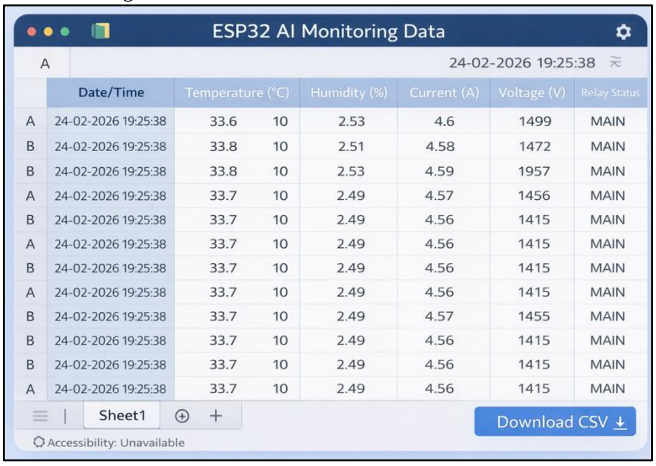


Fig. 3. ESP32 AI Predictive Dashboard Screenshot.



ESP32 AI Monitoring Data

A 24-02-2026 19:25:38

	Date/Time	Temperature (°C)	Humidity (%)	Current (A)	Voltage (V)	Relay Status
A	24-02-2026 19:25:38	33.6 10	2.53	4.6	1499	MAIN
B	24-02-2026 19:25:38	33.8 10	2.51	4.58	1472	MAIN
B	24-02-2026 19:25:38	33.8 10	2.53	4.59	1957	MAIN
A	24-02-2026 19:25:38	33.7 10	2.49	4.57	1456	MAIN
B	24-02-2026 19:25:38	33.7 10	2.49	4.56	1415	MAIN
A	24-02-2026 19:25:38	33.7 10	2.49	4.56	1415	MAIN
B	24-02-2026 19:25:38	33.7 10	2.49	4.56	1415	MAIN
A	24-02-2026 19:25:38	33.7 10	2.49	4.56	1415	MAIN
B	24-02-2026 19:25:38	33.7 10	2.49	4.57	1455	MAIN
B	24-02-2026 19:25:38	33.7 10	2.49	4.56	1415	MAIN
B	24-02-2026 19:25:38	33.7 10	2.49	4.56	1415	MAIN
A	24-02-2026 19:25:38	33.7 10	2.49	4.56	1415	MAIN

Sheet1 Download CSV

Accessibility: Unavailable

Fig. 4. ESP32 AI Monitoring Data in Spreadsheet Format.

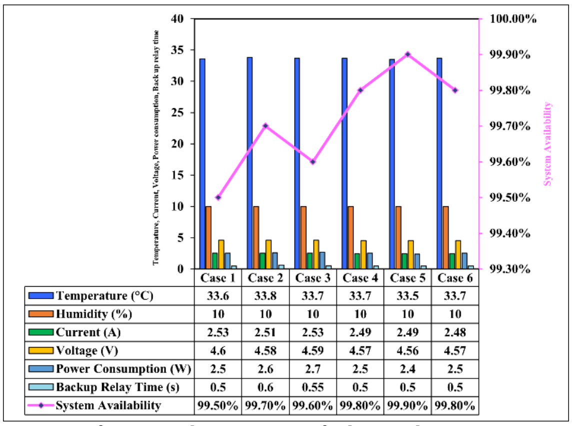


Fig. 5. Performance characteristics of relay condition monitoring.

IV. CONCLUSION

The developed machine preprocessing support will improve the reliability and operational efficiency of power continuity as well as resilience by accurate fault accident detection techniques, predictive maintenance smarter self-healing switchgear system using AI based techniques for fault conditions, relay system fault prediction and automatic switching to Back up relay eliminates downtime and ensures continuous power supply. Moreover cloud-based dashboards allow operators to monitor the health of these systems in real-time and take actions proactively. Larger datasets or a more complicated machine learning approach is probably the key to improving upon the initial models developed, which will be explored in future work. This will lead to a more redundant and self-healing global system, further increasing the robustness. Scaling the system to larger, more complex power grids, particularly under renewable scenarios. Furthermore, system will have to fend off a new class of cyber threats as which operate in the hybrid grids or steady-state power systems; securing the cyber front ends of your system would be critical. This research serves as a foundation for the development of intelligent, self-regulating and fault-tolerant systems that have the potential to increase stability and energy efficiency in today's power grids.

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