Development of a Compact Self-System with Real-Time Fault Detection, Automated Power Distribution, and ML-Driven Predictive Analysis

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Abstract: This project presents a compact self-healing grid system designed to automate fault detection, optimize power distribution, and provide real-time notifications and data for predictive analysis. The system leverages Arduino for grid management, an LCD for real-time display of grid status, switches to simulate faults, and a buzzer for audible fault alarms. Voltage sensors and current sensors continuously monitor the power system, while a NodeMCU (ESP8266) module facilitates the sending of real-time alerts via Telegram messaging. In the event of a fault, the system detects the anomaly, reroutes power to maintain supply, and sends alerts containing detailed voltage, current, and power data. The system is further enhanced by integrating machine learning (ML), which processes this data for predictive maintenance and fault detection, enabling grid operators to anticipate and prevent failures. By combining real-time monitoring, automatic rerouting, and ML-driven predictive capabilities, this self-healing grid system improves both the resilience and efficiency of power distribution networks, offering a scalable solution for grid automation and management.

1 INTRODUCTION

The modern power grid faces increasing challenges due to growing demand, aging infrastructure, and the need for more reliable energy distribution. One promising solution is the self-healing grid system, which can automatically detect and resolve faults, ensuring a continuous power supply even in the face of failures. This project presents a self-healing grid system designed to simulate the automated monitoring, fault detection, and power rerouting of electrical grids. The system utilizes low-cost microcontrollers and components such as Arduino, NodeMCU, voltage sensors, and current sensors to provide real-time insights into grid health (Kumar, Sarath, et al. , 2021).

In traditional power grids, fault detection and resolution often rely on human intervention, leading to delays in restoring power and costly downtime. A self-healing grid overcomes these limitations by detecting faults in real-time and autonomously rerouting power through alternative pathways. When a fault occurs, it can significantly disrupt the grid's operation, causing voltage drops, power outages, and even equipment damage. The goal of the self-healing grid is to minimize these disruptions by detecting faults early, isolating the faulty section, and rerouting electricity to maintain service continuity (Lakshmi, Pavithra, et al. , 2024).

In this system, Arduino is responsible for processing sensor data and controlling relays to switch between different grid sections. A buzzer provides audible fault alarms, while an LCD display shows real-time data such as voltage levels, current, and power flow. Switches are used to simulate faults in various sections of the grid. Additionally, the system is equipped with NodeMCU to send fault notifications and grid status updates via Telegram, ensuring operators are instantly informed of issues, even when remote (Suguna, Sangeetha, et al. , 2024).

Furthermore, the system integrates machine learning for predictive maintenance and performance optimization. By collecting and analyzing data on

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voltage, current, and power fluctuations, an ML model can predict potential failures and recommend actions to prevent them, making the grid more resilient over time. This combination of real-time monitoring, automated fault handling, and predictive analysis makes the self-healing grid system a powerful tool for enhancing the reliability and efficiency of power distribution networks (Suhasini, et al. , 2022).

This project outlines the design, implementation, and operational flow of a self-healing grid system. The proposed solution is a small-scale yet scalable model, intended to demonstrate how automation, data analytics, and machine learning can transform traditional power grids into smarter, more efficient systems capable of addressing modern energy challenges (Pavithra, Nikhil, et al. , 2021).

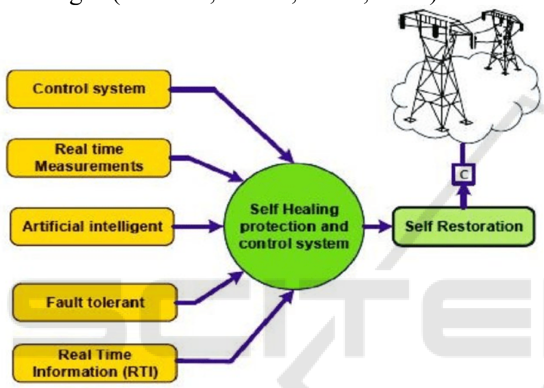

Figure 1:Architecture of the self healing smarter grids

2 LITERATURE SURVEY

The concept of a self-healing power grid has gained significant attention in recent years, especially as the global demand for reliable, uninterrupted power grows. Several studies and technological advancements have contributed to the development of self-healing grids, integrating fault detection, automated power rerouting, and predictive maintenance to enhance grid resilience. This literature survey reviews key studies, technologies, and methodologies related to self-healing grid systems, focusing on the application of microcontrollers, communication technologies, and machine learning in grid automation. The Fig. 1 shows the architecture of the self healing smarter grids [1].

3 SELF-HEALING GRIDS AND AUTOMATED FAULT DETECTION

Self-healing grids, first conceptualized in the early 2000s, are based on the idea that modern grids should autonomously identify and isolate faults, reroute power, and restore service without human intervention. Early studies, such as those by EPRI (Electric Power Research Institute), highlighted the need for distributed intelligence within the grid, emphasizing the role of sensors and controllers for real-time monitoring. Thomas et al. (2005) developed a framework for integrating sensors into substations to monitor real-time voltage and current data for fault detection. This early work paved the way for automated grid restoration technologies (Manjunath, Pavithra, et al. , 2016).

More recently, Ammar et al. (2019) proposed a self-healing grid architecture using real-time communication between distributed grid components. Their work integrated fault-tolerant algorithms and communication protocols to ensure minimal downtime during failures. The study underscored the importance of rapid fault detection and communication to improve grid reliability. However, the need for cost-effective, scalable implementations remained a challenge for widespread adoption (Rajesh, Prasanna, et al. , 2017).

4 MICROCONTROLLERS AND LOW-COST SOLUTIONS FOR GRID AUTOMATION

With the advent of affordable microcontrollers such as Arduino and NodeMCU, grid automation systems have become more accessible for small-scale or experimental applications. J. Patel et al. (2018) demonstrated a self-healing grid using Arduino and relays, successfully simulating automatic fault detection and power rerouting. Their system relied on manual fault creation through switches and used LEDs to indicate power status. While effective at a basic level, their approach lacked real-time communication capabilities, such as remote monitoring and fault notifications (Pavithra, Manjunath, et al. , 2017).

Expanding on this, Bhat et al. (2020) introduced the use of ESP8266 NodeMCU for remote monitoring of power systems. Their study integrated Wi-Fi communication to send fault alerts to remote users via mobile applications. The work marked an advancement in grid management, enabling grid operators to receive real-time notifications, much like the Telegram-based notifications in the current study. This integration improved operational awareness but did not address predictive maintenance, which is crucial for long-term grid reliability (Ammar, Durra, et al. , 2019).

5 DATA MONITORING: VOLTAGE, CURRENT, AND POWER IN GRIDS

Real-time data collection for voltage, current, and power is essential for effective grid management. Several studies have explored sensor integration in grid systems to continuously monitor electrical parameters. Pandey and Tiwari (2017) employed voltage and current sensors with Arduino to measure electrical parameters in a low-voltage distribution system. They calculated power consumption and used threshold-based algorithms to detect abnormal grid behavior. This approach was effective in detecting basic grid anomalies, but lacked intelligent analytics to forecast potential failures (Pandey, Tiwari, et al. , 2017).

Similarly, Rahul et al. (2019) presented a more advanced system for real-time monitoring and control of electrical loads using voltage sensors and relays. Their work integrated communication with mobile applications to alert operators about voltage fluctuations, similar to the NodeMCU-driven Telegram notifications in the proposed system. However, their system did not incorporate machine learning for data-driven predictions, limiting its fault-prevention capabilities (Rahul, Mishra, et al. , 2019).

6 INTEGRATION OF MACHINE LEARNING IN GRID SYSTEMS

Predictive maintenance has become an emerging area of interest for grid systems, driven by advances in machine learning (ML). Chen et al. (2020) explored the use of ML models to predict grid faults by analyzing historical data on voltage, current, and power. By training predictive models using past grid events, they demonstrated how machine learning could anticipate faults and recommend preemptive actions. This approach significantly improved grid resilience, but required extensive datasets for training and a robust communication infrastructure for real-time feedback (Chen, Li, et al. , 2020).

Li et al. (2021) extended this idea by incorporating real-time sensor data with cloud-based ML systems. They proposed a hybrid model where grid data was sent to the cloud for real-time analysis and fault prediction, providing instant feedback to local controllers. Their model successfully reduced downtime by predicting equipment failures in advance. However, they noted that implementation of ML @ grid level was challenging due to data privacy, security & latency concerns.

7 COMMUNICATION TECHNOLOGIES IN GRID

Automation Effective communication is essential for a self-healing grid to function. Several studies have examined the use of IoT and cloud-based communication systems to provide real-time data transmission. Ahmed et al. (2019) explored the use of Wi-Fi-enabled modules like NodeMCU to monitor and control grid systems remotely. Their study leveraged cloud services to store data, though real-time decision-making was left to local controllers. This approach allowed for scalability but required reliable internet connectivity, a potential limitation for remote areas (Ahmed, Hassan, et al. , 2019).

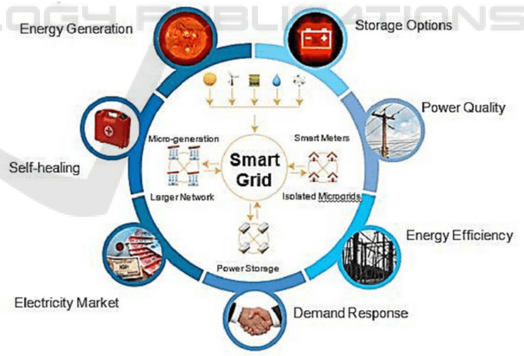

Figure 2:Smart grid's salient features [1]

The salient features of the smart grid is shown int he Fig. 2 [1]. Telegram-based notifications, as proposed in the current system, provide a simple, user-friendly communication method. Khan et al. (2022) implemented a Telegram API in a home automation system to send alerts and receive user commands, demonstrating its effectiveness in grid-related applications. By extending this communication channel to grid systems, real-time fault alerts and updates can be delivered to operators anywhere, enhancing situational awareness (Khan, Rasool, et al. , 2022).

8 MATHEMATICAL MODEL DEVELOPMENT

Mathematical Model for Edge-Enabled Self-Healing Smart Grid is developed as follows. This model provides a high-level mathematical representation of an Edge-Enabled Self-Healing Smart Grid that includes fault detection, predictive maintenance, and real-time adaptation. Each component can be further expanded and tuned based on real-time data, edge computing capabilities, and specific grid requirements. The optimization problem aims to minimize costs associated with energy loss, delays, and maintenance while ensuring system reliability and efficient fault recovery. Mathematical model is used for the simulation & experimentation purposes

9 EQUATIONS FOR REAL-TIME MONITORING

Voltage Monitoring Equation is given by

$$V(t) = V_{nom} - \Delta V(t)$$

where

$V(t)$: Instantaneous voltage at time t

V_{nom} : Nominal voltage level

$\Delta V(t)$: Voltage fluctuation at time t

10 CURRENT MONITORING EQUATION IS GIVEN BY

$$I(t) = I_{nom} - \Delta I(t)$$

where

$I(t)$: Real-time current at time t

I_{nom} : Nominal current level

$\Delta I(t)$: Current deviation at time t

11 GRID REPRESENTATION

Represent the smart grid as a graph $G(V,E)$, where

V : Set of nodes, representing substations, power generation units, consumers, and edge computing devices.

E : Set of edges, representing transmission and distribution lines between nodes.

12 EDGE COMPUTING NODES

Edge devices are placed at critical locations to collect and process data locally, reducing latency. Let X_i represent the processing capability of the edge node iii, with X_i including (Hayder, Manjunath, et al. , 2025)

Data processing rate, P_i (in data units per second). Storage capacity, S_i.

13 POWER FLOW EQUATIONS

Use AC Power Flow or DC Power Flow equations to represent the power distribution between nodes. The power balance at each node iii is given by

$$P_i = \sum_{j \in N_i} Y_{ij} V_i V_j \cos(\theta_i - \theta_j)$$

where:

Y_{ij} : Admittance between node i and j.

V_i, V_j : Voltage magnitudes at nodes i and j.

θ_i, θ_j : Phase angles at nodes i and j.

14 FAULT DETECTION

Define fault indices such as line current or power quality metrics. Let F_{ij} denote a binary variable that indicates the state of line (i , j)

$$F_{ij} = \begin{cases} 1, & \text{if fault is detected on line } (i, j) \\ 0, & \text{otherwise} \end{cases}$$

Real-time fault detection is often represented using a state-space model or a machine learning-based classifier. A state-space model can be used for predicting grid stability as

$$x(t+1) = Ax(t) + Bu(t) + w(t)$$

$$y(t) = Cx(t) + v(t)$$

where

$x(t)$: State vector representing grid parameters (e.g., voltage, current).

$u(t)$: Control input (e.g., switching actions).

$w(t)$, $v(t)$: Noise terms.

15 PREDICTIVE MAINTENANCE

Use time-to-failure (TTF) models for predicting equipment failure. Assume $R_i(t)$ represents the reliability of equipment i as

$$R_i(t) = e^{-\lambda_i t}$$

where λ^i is the failure rate of component I & the predictive maintenance schedules can be optimized using [22]

$$\min \sum_i C_i(t) \quad \text{s.t. } R_i(t) \geq R_{\min}$$

where $C_i(t)$ is cost associated with maintaining component i.

16 SELF-HEALING MECHANISM

The restoration strategy for the self-healing process can be represented as an optimization problem to minimize load shedding and quickly restore service. Define L_i as the load demand at node i and R_{ij} as a decision variable indicating whether line (i , j) is restored as

$$\min \sum_{i \in V} L_i (1 - R_i)$$

$$\text{s.t.} \quad P_i = \sum_{j \in N_i} Y_{ij} V_i V_j \cos(\theta_i - \theta_j) \quad \forall i \in V$$

$$R_{ij} = 1 \quad \text{if edge } (i, j) \text{ is successfully restored}$$

17 EDGE PROCESSING AND COMMUNICATION DELAY

Let D_i represent the total delay at edge node i, which is the sum of processing delay $D_{p,i}$ and communication delay $D_{c,i}$ as

$$D_i = D_{p,i} + D_{c,i}$$

To minimize latency, define an objective function for optimal edge placement

$$\min \sum_{i \in V} D_i$$

18 FAULT AND MAINTENANCE STRATEGIES

Utilize ML models for predicting faults and maintenance needs, integrated into the optimization framework.

19 OBJECTIVES

In this section, we present the main objectives of the project work that is being implemented by us [17].

20 AUTOMATE FAULT DETECTION AND RECOVERY

Develop an automated system that can detect faults in different sections of the grid using voltage and current sensors and reroute power to maintain continuous supply, thereby minimizing downtime and human intervention.

21 REAL-TIME DATA MONITORING AND DISPLAY

Implement real-time monitoring of electrical parameters such as voltage, current, and power using sensors, and display this data on an LCD screen for easy visualization of grid health and status.

22 IMMEDIATE FAULT INTIMATION VIA TELEGRAM NOTIFICATIONS

Utilize a NodeMCU (ESP8266) module to send real-time fault alerts and grid status updates to operators or users via Telegram, enabling remote monitoring and quick responses to grid issues.

23 INTEGRATE PREDICTIVE MAINTENANCE WITH MACHINE LEARNING

Collect voltage, current, and power data and feed it to a machine learning model to predict future faults, identify patterns of potential grid failures, and optimize grid performance through predictive maintenance.

24 PROVIDE AUDIBLE FAULT ALERTS

Integrate a buzzer to provide immediate audible alerts in the event of a fault, ensuring quick attention to grid issues by on-site personnel.

25 LOW-COST, SCALABLE DESIGN

Design a self-healing grid system using affordable and easily available components like Arduino, NodeMCU, and sensors, making it scalable for various small to medium-scale grid applications.

26 ENHANCE GRID RESILIENCE AND RELIABILITY

Improve the overall resilience of the grid by implementing an intelligent, self-healing system capable of quickly isolating faults, restoring service, and continuously learning from historical data to prevent future failures.

27 PROBLEM STATEMENT

As power grids become more complex and demand increases, the ability to ensure continuous and reliable electricity distribution is crucial. Traditional grid systems are prone to faults, which can result in power outages, equipment damage, and prolonged downtime, often requiring manual intervention for fault detection and resolution. The lack of real-time monitoring, slow response times, and insufficient data analytics capabilities limit the efficiency of traditional grid systems, particularly in handling unexpected faults. Moreover, existing solutions for grid automation and fault detection are often expensive and difficult to implement at a smaller scale. Most systems lack integration with predictive maintenance technologies like machine learning (ML), which could anticipate faults before they occur, thereby preventing major disruptions. Additionally, communication delays between grid systems and operators, especially in remote areas, can result in delayed responses to grid issues, exacerbating the problem [18].

28 BLOCK DIAGRAM

The Fig. 3 shows the complete block-diagram of the project developed which consists of the power supply, voltage sensors, current sensors, switches, Arduino board, LCD displays, relays, buzzers, ML model & the power supply circuit which supplies power to all the electronic parts. The proposed self-healing grid system is designed to detect faults, reroute power, and provide real-time notifications while also integrating machine learning (ML) for predictive maintenance. The methodology to develop and implement this system involves several steps, from hardware setup to data transmission and predictive analytics.

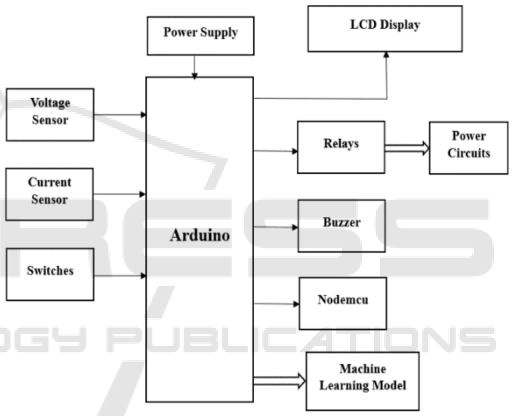

Figure 3: Complete block-diagram of the project developed

29 SYSTEM DESIGN AND HARDWARE SETUP

Arduino Microcontroller : Acts as the central control unit responsible for managing inputs from sensors, processing data, and controlling the output components such as relays, buzzer, and LCD display.

Voltage and Current Sensors : Sensors are placed in various sections of the grid to continuously monitor the voltage and current levels. These sensors are connected to the Arduino to provide real-time measurements. Example: Voltage sensor (e.g., ZMPT101B) and current sensor (e.g., ACS712) are used for detecting grid parameters.

Switches : Simulate faults in the grid by triggering disconnections or abnormal current/voltage conditions. Each section of the grid has a switch that, when triggered, activates the fault detection mechanism.

Relays : Used to reroute power supply when a fault is detected. The Arduino controls these relays to isolate the faulty section and restore power through alternate routes.

LCD Display : Provides real-time information on voltage, current, and power for visual monitoring of the system's operation.

Buzzer : Sounds an audible alert when a fault is detected, providing immediate on-site notification.

30 FAULT DETECTION AND POWER REROUTING

The system continuously monitors the voltage and current data from sensors. If the sensor readings fall below or exceed predefined thresholds (indicating a fault), the Arduino triggers the following actions:

Isolate the Faulty Section : The relay switches off the faulty section to prevent further damage or power loss.

Reroute Power : The relays are programmed to find an alternate route for the power supply, restoring service to the unaffected sections.

Trigger Audible and Visual Alerts : The buzzer is activated to alert nearby personnel, and the LCD displays information about the fault.

31 REAL-TIME NOTIFICATIONS VIA NODEMCU

NodeMCU (ESP8266) : A Wi-Fi module that is connected to the Arduino to enable remote communication. When a fault is detected, the Arduino sends a signal to the NodeMCU, which then communicates with the Telegram API [19].

Telegram Notifications : The NodeMCU sends real-time alerts about the grid's status, fault location, voltage readings, and rerouting status to a preconfigured Telegram chat or group. This allows remote monitoring and quick responses by grid operators.

Notification Content : The message includes data such as the voltage level, current measurement, section affected, and the action taken (rerouting or isolation).

32 ML INTEGRATION FOR PREDICTIVE MAINTENANCE

Data Preprocessing : The collected data (voltage, current, and power values) is preprocessed to remove noise and anomalies. This ensures that only clean, accurate data is used for training the machine learning model [20].

Feature Extraction : Key features such as voltage dips, power fluctuations, or current spikes are extracted from the data, as these could indicate early signs of grid failure or stress.

ML Model Development : A machine learning model (such as a decision tree, random forest, or neural network) is trained on the historical grid data to identify patterns that precede faults. The model learns to predict when and where a fault is likely to occur based on input features.

Real-Time Predictions : Once the model is trained, it is integrated with the system to provide real-time predictions. The grid data is fed into the model continuously, and if the model predicts a potential fault, the system alerts operators via Telegram, enabling pre-emptive action.

33 CONCLUSIONS

The development of a self-healing grid system using low-cost microcontrollers and sensors demonstrates a significant step toward improving the resilience and reliability of modern power distribution networks. By combining Arduino, NodeMCU, voltage and current sensors, and machine learning (ML), the proposed system successfully automates fault detection, power rerouting, and predictive maintenance.

In conclusion, the VIDYUT project demonstrates an effective and innovative approach to enhancing power grid resilience through an edge-enabled, self-healing smart grid system. By leveraging a combination of Arduino for grid management, NodeMCU for real-time communication, and voltage and current sensors for continuous monitoring, the system effectively automates fault detection and power rerouting. The integration of machine learning further enriches the project by facilitating predictive maintenance and enabling grid operators to proactively manage potential failures. The use of real-time data transmission via Telegram ensures that operators receive immediate notifications of faults, supported by detailed analytics on voltage, current, and power metrics.

This project's design highlights a cost-effective solution that combines hardware components and advanced software algorithms to optimize power distribution, improve response times, and maintain energy supply even during disruptions. The incorporation of real-time monitoring, automatic rerouting, and ML-driven analysis makes this system a scalable and adaptable tool for modern power networks. Future enhancements could include refining the machine learning algorithms for greater predictive accuracy, utilizing cloud-based data storage for long-term performance analysis, and extending the deployment to more complex and expansive grid infrastructures. This advancement in smart grid technology lays the foundation for more resilient, self-sustaining, and intelligent power management systems.

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