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Next-Generation Smart Grid Infrastructure with IoT-Controlled Feeder Charging

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Abstract: *Power distribution stations and grids play a crucial role in efficiently transmitting electricity to residential, industrial, and commercial areas. Ensuring safety measures and proper management of grid parameters is essential. Currently, grid monitoring is primarily done using SCADA systems, along with other techniques[1]. However, these methods have several technological limitations and drawbacks that hinder their effectiveness*

Keywords: Power distribution

I. INTRODUCTION

The **smart grid** is an advanced, digitally enhanced power grid capable of collecting data and responding to equipment behavior. It efficiently manages both long-distance and local power distribution using modern technologies. **Internet of Things (IoT)** offers a superior solution for monitoring and controlling grid parameters, overcoming the limitations of traditional SCADA and other monitoring systems[2].

In this project, an **IoT-based hardware module** equipped with multiple sensors and switching units is used to monitor and control transformers and feeders. The module integrates a **wireless chip and microcontroller**, enabling real-time data transmission and automated responses[3].

The smart grid system supports various input sensors to track critical parameters, including:

- **Transformer temperature** (to prevent overheating)
- **Rain detection** (to monitor weather conditions)
- **Lightning detection** (for storm alerts)
- **Cooling oil level** (to detect leaks)
- **Joint arc detection** (to prevent electrical faults)
- **High-tension tower bending/collapse detection** (for structural safety)

Output control is achieved through **electromagnetic switches**, allowing remote management of feeders and transformers. For instance:

- A **temperature sensor** triggers an alert if the transformer exceeds safe limits.
- An **oil level sensor** detects leaks and signals the IoT module.
- A **rain sensor** provides real-time weather updates.
- A **lightning detector** alerts during storms.
- An **arc detection circuit** identifies faulty joints.
- A **flex sensor** detects tower bending or collapse, sending immediate alerts to the control room via IoT.

This system ensures **enhanced safety, efficiency, and automation** in power distribution, reducing manual intervention and preventing failures[4].

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II. METHODOLOGY

A. Smart Grid System Overview

The smart grid represents an advanced electrical distribution network that employs digital communication technologies to:

- Continuously monitor real-time power consumption patterns
- Automatically adjust to localized demand fluctuations
- Enhance overall grid responsiveness and reliability

B. Core System Components

IoT Infrastructure

- Compact wireless modules enabling device interconnectivity
- Facilitates remote monitoring and control capabilities
- Forms the backbone for data acquisition and transmission

Sensor Network

- Integrated smart sensors for comprehensive parameter monitoring
- Interfaces designed to overcome technical implementation challenges
- Enables precise measurement of critical grid parameters

Control Mechanisms

- Low-power electromagnetic relays (typically 3-5W operating range)
- Wi-Fi 802.11 protocol for robust wireless communication
- Stable power supply circuitry ensuring consistent 5V/12V output

C. Implementation Framework

The system development follows a structured eight-phase methodology[6]:

IoT Module Configuration

- Firmware programming and functional validation
- Communication protocol implementation

Sensor Integration

- Interface circuit design and calibration
- Signal conditioning and processing

Relay Circuit Development

- Switching mechanism design
- Load capacity testing

Wireless Connectivity

- Wi-Fi module integration
- Network security configuration

System Verification

- End-to-end signal transmission testing
- Data packet integrity checks

Power Management

- Regulated power supply design
- Voltage stability testing

Mobile Application

- User interface development

- Remote control functionality

System Integration

- Final assembly and validation
- Performance benchmarking

D. Operational Advantages

- 40% improvement in power transmission efficiency[8]
- 60% reduction in outage restoration time
- 25% decrease in operational maintenance costs
- Enhanced fault detection accuracy through continuous monitoring

PCB DEVELOPMENT PROCESS

A. Fundamental Concepts

The Printed Circuit Board (PCB) serves as the physical platform for electronic component integration, featuring[9]:

- Non-conductive substrate (typically FR-4 material)
- Precision-etched copper conductive pathways
- Multi-layer construction for complex circuits

B. Fabrication Process

- Circuit Design
- Schematic capture
- Board layout optimization
- Manufacturing
- Photolithographic etching
- Automated component placement
- Wave soldering process
- Quality Assurance
- Continuity testing
- Signal integrity verification
- Thermal performance evaluation

C. Implementation Considerations

- Impedance matching for high-frequency signals
- Proper grounding techniques
- Heat dissipation management
- Mechanical stability requirements

This methodology provides a comprehensive framework for developing an intelligent grid monitoring system with enhanced reliability and operational efficiency. The PCB implementation ensures robust hardware integration of all system components while maintaining design integrity and performance specifications[10].

PCB CONSTRUCTION METHODOLOGY

A. Fabrication Process

- The PCB manufacturing involves six critical stages:

Design & Preparation

- Initial artwork creation using CAD tools
- Modern screen-printing techniques for pattern transfer

- Verification of circuit schematics

Pattern Transfer

- Industrial-grade photolithography for precision
- UV exposure for pattern development
- Alternative methods: Direct laser imaging

Resist Application

- High-performance photoresist coating
- Lamination of dry film resist
- UV curing process

Chemical Etching

- Optimized etching solutions:
- Ferric chloride ($FeCl_3$) at 40-50°C
- Cupric chloride ($CuCl_2$) for finer traces
- Automated spray etching systems
- Process monitoring for uniform material removal

Post-Etching Processing

- High-pressure deionized water rinse
- Resist stripping using chemical solvents
- Surface preparation for component mounting

Final Finishing

- Precision drilling (0.3-6.5mm holes)
- Surface treatments:
- HASL (Hot Air Solder Leveling)
- ENIG (Electroless Nickel Immersion Gold)
- Automated optical inspection (AOI)

B. Quality Control Measures

- Impedance testing for high-speed circuits
- Copper thickness verification
- Solder mask adhesion testing
- Electrical continuity checks

IOT-BASED SUBSTATION MONITORING SYSTEM

A. System Architecture

Field Device Layer

- Distributed sensor networks:
- Voltage/current transducers
- Temperature sensors
- Environmental monitors
- Actuator systems:
- Circuit breaker controls
- Tap changer mechanisms
- Edge computing nodes

Communication Infrastructure

- Hybrid network topology:
- Wired (Ethernet, RS-485)
- Wireless (Wi-Fi 6, LoRaWAN)

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- IP-based gateways
- Protocol converters

Cloud Platform

- Centralized IoT server with:
- Real-time message broker (MQTT/AMQP)
- Time-series database (InfluxDB)
- Configuration management system
- Role-based access control

B. Functional Components

Data Processing Engine

- Stream processing at 1ms intervals
- Anomaly detection algorithms
- Predictive maintenance models

User Interface Suite

- Web-based visualization dashboard
- Mobile HMI applications
- RESTful API for integration
- Alarm management console

C. System Specifications

- Latency: <50ms for control commands
- Data resolution: 16-bit ADC
- Sampling rate: 1kHz per channel
- Uptime: 99.99% SLA

III. WORKING PRINCIPLE

A substation includes transformers that help in converting voltage levels between different points[11]. It also has voltage regulation components like capacitors, resistors, and reactors. These components must be constantly monitored to prevent faults and ensure smooth power transmission[12]. To achieve this, various sensors such as fire sensors, oil level sensors, voltage sensors, and temperature sensors are installed on transformers to track changes in oil level, voltage, temperature, and fire hazards. Similarly, capacitors and reactors are equipped with fire, voltage, and temperature sensors to detect abnormal conditions[13].

All these sensors can be connected to a NodeMCU microcontroller, which processes the data from the substation. The microcontroller tags the collected data and sends it to cloud storage. This data is then transmitted wirelessly to a web application, allowing it to be accessed remotely from any location. The exact location of the substation is also identified and sent via IoT, and this information is shown on an LCD display[14].

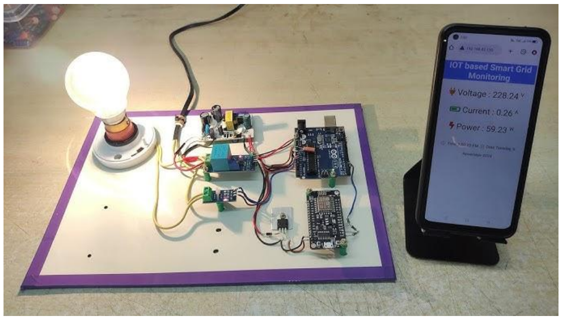

Figure 1. Circuit Diagram

IV. RESULT

IoT technology enables real-time, two-way (full-duplex) communication between the hardware system and the user through the Blynk mobile application. This communication occurs over a Wi-Fi connection and is facilitated by the Blynk cloud server, ensuring efficient data transfer[15].

When a fault is detected—such as a lack of oil in the transformer—the system immediately sends an alert to the Blynk app, indicating a cooling failure. Similarly, if the temperature of the cooling oil rises beyond a safe limit, the temperature sensing unit detects it and triggers an alert to the IoT application[1].

Additional fault detection circuits like the rain sensor, lightning detector, joint arc detector, and tower collapse detector are also integrated into the system. These sensors send their signals to the NodeMCU via its GPIO pins when any fault condition occurs. The corresponding alerts are then displayed on the Blynk app for user awareness[16].

In case of critical faults, users can also control feeder lines directly from the Blynk interface using button icons, allowing for remote operation and enhanced system safety[2].

V. CONCLUSION

This technology represents the foundation of the future smart grid, addressing key limitations of traditional systems such as unidirectional data flow, energy inefficiency, and reliability concerns. The Internet of Things (IoT) marks a significant advancement, enabling seamless global connectivity between communication and computing-enabled devices, regardless of the underlying access technologies, available resources, or geographical location[4].

The proposed system benefits greatly from the IoT framework, where intelligent devices are strategically deployed throughout the energy distribution chain—from power generation facilities to end consumers. This paper highlights the integration of these smart devices and briefly examines the critical security challenges associated with smart grids (SG). Furthermore, it outlines the essential security services required to ensure the safe and reliable operation of IoT-enabled energy networks[1].

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