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Design And Development Of Electrical Machine Health Monitoring and Diagnosis System By Using Fuzzylogic

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ABSTRACT

This project involves the development of an advanced fault detection and monitoring system for a three-phase induction motor using power monitoring modules (PZEM) and other sensors to ensure operational reliability and efficiency. The system is designed to continuously monitor critical motor parameters, including voltage, current, power, temperature, and vibration, using an ESP32 microcontroller. A fuzzy logic-based analysis module is implemented to classify the motor's health status into Normal, Warning, or Critical, addressing uncertainties in real-time sensor data. The monitored data is transmitted to an IoT platform for remote visualization and historical trend analysis, providing users with insights into motor performance and potential faults. Additionally, critical fault conditions trigger SMS alerts via a GSM module, enabling timely maintenance responses to minimize downtime. Real-time local monitoring is supported by an LCD display that shows current parameters and health status. The integration of IoT connectivity, fuzzy logic, and SMS alerts ensures comprehensive and proactive motor fault management for enhanced safety and operational reliability.

Keywords: *Induction motor, fault detection, power monitoring, fuzzy logic, IoT, ESP32, GSM alerts, real-time monitoring, three-phase motor, sensor integration.*

1. INTRODUCTION

Induction motors, widely acknowledged for their durability, operational simplicity, and economic viability, constitute essential elements in industrial, commercial, and residential contexts. These motors are vital in energizing machinery, propelling pumps, and enabling automation across diverse sectors. Nonetheless, their significant function in operations demands the implementation of an effective fault detection and monitoring system to guarantee reliability, avert downtime, and prevent expensive failures. Failures in induction motors can arise from electrical, mechanical, or thermal complications, frequently resulting in diminished efficiency, heightened maintenance expenses, or total operational cessation. Therefore, the prompt identification of irregularities is crucial for sustaining optimal performance and prolonging the motor's operational lifespan.

The three-phase induction motor, being the most prevalently utilized variant, necessitates continuous surveillance of parameters such as current, voltage, temperature, and vibration to ensure efficient operation. Conventional fault detection methodologies, which frequently depend on manual examinations or fixed thresholds, prove inadequate for real-time monitoring and may overlook subtle or developing faults. These constraints underscore the necessity for the integration of advanced technologies, such as sensor networks, IoT platforms, and intelligent decision-making systems, to facilitate comprehensive and real-time assessments of motor health. By harnessing these technologies, it becomes feasible to proactively detect potential issues, minimize downtime, and decrease maintenance expenditures, thereby enhancing operational efficiency.

This project presents a robust system for the monitoring and diagnosis of faults in three-phase induction motor utilizing power monitoring modules (PZEM) alongside an array of sensors. The system employs an ESP32 microcontroller to gather real-time data from sensors measuring crucial parameters such as voltage, current, power consumption, temperature, and vibration. These parameters serve as indicators of the motor's operational health and can assist in identifying anomalies prior to their escalation into significant failures. Through the integration of IoT technologies, the collected data is transmitted to a remote platform, allowing users to visualize real-time motor performance and analyze historical trends from any internet-connected device.

Health monitoring and fault detection in induction motors are essential for ensuring operational efficiency and minimizing downtime in industrial applications. Various researchers have utilized advanced techniques, including fuzzy logic, machine learning, and hybrid models, to enhance the accuracy and reliability of fault diagnosis systems.

Rian et al. [1] proposed an Android-based health monitoring application that uses fuzzy logic to analyze parameters such as pulse rate and oxygen saturation. Their work highlighted the potential of fuzzy logic in providing real-time condition analysis through mobile platforms. Similarly, Patil et al. [2] demonstrated the application of fuzzy logic in the online condition monitoring of induction motors using MATLAB. They utilized linguistic variables to describe motor health states, such as 'good' or 'overloaded,' and built a knowledge base to support fuzzy inference systems.

Kudelina et al. [3] introduced a neuro-fuzzy framework for fault prediction in electrical machines, focusing on vibration analysis for detecting bearing faults. Their study showed that integrating fuzzy logic with neural networks improved the validation accuracy to 99.40%, outperforming traditional neural network approaches. This hybrid model combines the decision-making capabilities of fuzzy logic with the pattern recognition strengths of neural networks, making it highly effective in handling complex fault scenarios.

Baviskar et al. [4] explored machine learning algorithms, including Random Forest and Naïve Bayes, for predictive maintenance and fault diagnostics. They emphasized the integration of IoT devices for real-time monitoring, which facilitates data-driven decision-making and enhances equipment reliability. Similarly, Kudelina et al. [5] provided a comprehensive review of machine learning algorithms like support vector machines and decision trees, highlighting their effectiveness in feature extraction and fault classification in electrical machines.

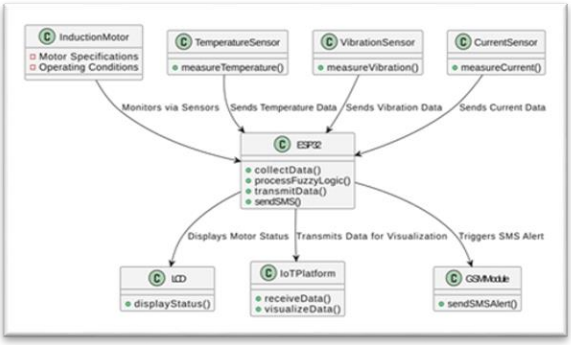
Samanta et al. [6] developed a fuzzy logic-based fault detection methodology for single-phase induction motors by analyzing harmonic distortions in voltage and current signals. Their approach demonstrated the potential of fuzzy logic in distinguishing between faults caused by internal motor problems and external distortions, providing a robust framework for condition monitoring.

This body of work underscores the growing adoption of intelligent diagnostic techniques, particularly fuzzy logic and machine learning, in advancing the field of induction motor fault detection and health monitoring. These approaches address the limitations of traditional methods by offering improved accuracy, real-time monitoring, and predictive capabilities.

2. WORKING PRINCIPLE AND METHODOLOGY

2.1 Working

The proposed system operates by continuously monitoring critical parameters of a three-phase induction motor, ensuring reliable and efficient fault detection. At its core, the system leverages sensors and advanced algorithms to collect, analyze, and interpret real-time data, facilitating early detection of faults and enabling proactive maintenance.



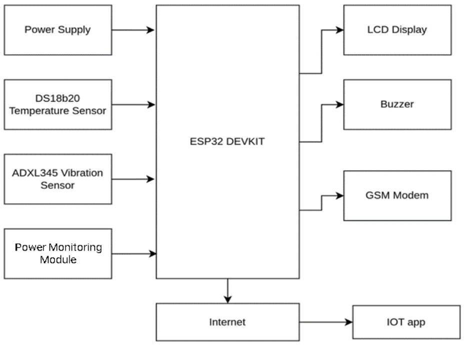


Fig 2.1 Work flow **Fig 1.2 Block Diagram**

The process begins with data acquisition through power monitoring modules (PZEM) and additional sensors. These sensors measure key parameters such as voltage, current, power, temperature, and vibration. The data is transmitted to a central microcontroller, typically an ESP32, which serves as the hub for processing and managing the collected signals. By capturing real-time measurements, the system provides a comprehensive view of the motor's operational status.

Signal processing is a critical step in the system's operation. The raw data is preprocessed to remove noise and extract meaningful patterns. Key indicators such as harmonic distortion, power factor, and frequency are calculated to identify deviations from normal operating conditions. This preprocessing ensures that the analysis remains accurate and reliable, even in noisy environments.

A fuzzy inference system is employed to detect faults and classify the motor's health status. Fuzzy logic is particularly effective in this context because it can handle uncertainties and nonlinear relationships in the sensor data. Based on predefined rules, the system categorizes the motor’s condition into states like "Normal," "Warning," or "Critical." For example, a combination of high temperature and abnormal vibration levels may indicate an impending mechanical fault, while irregular current readings might suggest electrical issues.

When a fault is detected, the system initiates a decision-making process to determine the appropriate response. In critical scenarios, a GSM module is used to send SMS alerts to maintenance personnel, ensuring prompt notification and rapid intervention. This feature minimizes downtime and prevents extensive damage to the motor.

To enhance accessibility and usability, the system is integrated with an IoT platform. Real-time data and historical trends are transmitted to the cloud, allowing users to remotely monitor the motor's performance and analyze patterns over time. This remote access capability facilitates predictive maintenance by identifying potential issues before they escalate into serious faults.

2.2 METHODOLOGY

The proposed project for fault detection and monitoring of a three-phase induction motor follows a systematic methodology involving multiple stages of design, implementation, and integration of advanced technologies. The detailed methodology is as follows:

A. System Design and Requirements Specification

The first step in the project involves defining the system's objectives, operational requirements, and the selection of suitable hardware and software components. The primary objectives of the system are to ensure reliable fault detection, minimize downtime, and enable efficient remote monitoring of the three-phase induction motor. Achieving these objectives requires a combination of advanced sensors, a capable microcontroller, communication modules, and an effective display interface.

The system employs PZEM power monitoring modules to measure critical electrical parameters such as voltage, current, power, and frequency. These are complemented by temperature sensors to monitor thermal conditions and vibration sensors to detect mechanical anomalies. Together, these sensors provide a comprehensive data set for accurate analysis of the motor's health.

An ESP32 microcontroller is chosen for its computational capabilities and IoT connectivity, making it well-suited for managing sensor data and facilitating communication with remote monitoring systems. For alert mechanisms and real-time updates, the system integrates a GSM module for sending SMS notifications during critical fault conditions and employs IoT protocols such as MQTT or HTTP to transmit data to cloud platforms for advanced analysis and visualization.

Additionally, the system includes an LCD interface to display real-time motor parameters and fault statuses locally. This ensures on-site operators have immediate access to the motor's operational data, enabling quick responses to emerging issues. By combining these components, the system is designed to deliver robust and reliable performance, meeting the specified objectives effectively.

B. Data Acquisition and Hardware Setup

The implementation of the system begins with the strategic placement of sensors to ensure accurate and comprehensive monitoring of the motor's health. Power monitoring modules are installed to measure voltage, current, power, and frequency, while temperature sensors are positioned to detect thermal changes. Vibration sensors are strategically placed to capture mechanical anomalies, ensuring that critical parameters are recorded effectively for fault detection and analysis.

These sensors are interfaced with the ESP32 microcontroller, which acts as the central hub for data collection and processing. Proper wiring and calibration are essential to ensure accurate readings from the sensors. Signal conditioning techniques are employed to filter out noise and enhance the quality of the transmitted data. This ensures that the information received by the microcontroller reflects the true operational status of the motor.

The ESP32 microcontroller is programmed to collect data from the sensors continuously at predefined intervals. To maintain data reliability, error-checking mechanisms are incorporated during data transmission, preventing inaccuracies caused by noise or signal interruptions. This real-time measurement and data handling process ensure that the system provides precise and actionable insights into the motor's performance.

C. Signal Processing and Feature Extraction

The implementation of the system involves strategically placing sensors to accurately monitor the motor's health.

Power monitoring modules are installed to measure voltage, current, power, and frequency, while temperature sensors detect thermal variations and vibration sensors capture mechanical anomalies. These sensors are connected to the ESP32 microcontroller, which acts as the central hub for data acquisition and processing. Proper wiring, calibration, and signal conditioning are critical to ensuring accurate and noise-free data transmission from the sensors. The ESP32 is programmed to collect sensor data continuously at predefined intervals, with error-checking mechanisms in place to ensure data integrity during transmission. This setup enables precise real-time monitoring and reliable insights into the motor's performance.

D. Fuzzy Logic-Based Fault Classification

The implementation of the system begins with strategically placing sensors to ensure accurate monitoring of the motor's operational health. Power monitoring modules are deployed to measure voltage, current, power, and frequency, while temperature sensors are positioned to detect thermal changes, and vibration sensors are used to capture mechanical anomalies. These sensors are integrated with the ESP32 microcontroller, which serves as the central hub for data collection and processing. Ensuring proper wiring, calibration, and signal conditioning is essential to achieve accurate and noise-free data transmission. The ESP32 is programmed to continuously collect data from the sensors at predefined intervals, with built-in error-checking mechanisms to maintain data integrity during transmission. This comprehensive setup ensures precise real-time monitoring and provides reliable insights into the motor's performance, facilitating effective fault detection and maintenance.

E. Decision-Making and Alerting

The system is designed to provide both local and remote responses to ensure timely and effective fault management. Locally, it displays real-time parameters and fault statuses on an LCD, allowing on-site operators to monitor the motor's performance at a glance. In the event of warnings or critical faults, the system triggers visual or audible alerts to immediately draw the operators' attention to potential issues. For remote alerts, the system integrates a GSM module to send SMS notifications to maintenance personnel whenever a critical fault is detected. These alerts are designed to include actionable insights, such as the type of fault and its urgency level, enabling the maintenance team to respond promptly and effectively to mitigate risks and prevent downtime. This dual-response mechanism ensures comprehensive monitoring and swift intervention during fault conditions.

F. IoT Integration for Remote Monitoring

The system incorporates advanced data transmission and visualization capabilities to facilitate effective monitoring and decision-making. Processed sensor data is transmitted to an IoT platform using protocols such as MQTT or HTTP, ensuring seamless communication between the motor and the remote monitoring infrastructure. To maintain the integrity and confidentiality of the data, secure channels such as TLS encryption are employed, protecting the information from unauthorized access during transmission.

For visualization and analytics, a cloud-based dashboard is developed to display real-time motor parameters alongside historical trends. This dashboard provides users with an intuitive interface to monitor the motor’s performance and detect anomalies over time. By enabling users to analyze data trends, the system supports predictive maintenance, allowing for informed decision-making and proactive management of potential faults. This comprehensive approach enhances the system's ability to optimize motor reliability and efficiency

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3. HARDWARE AND SOFTWARE IMPLEMENTATION

3.1 PCB Fabrication

The printed circuit board (PCB) acts as a linchpin for almost all of today's modern electronics. If device needs to do some sort of computation-such as is the case even with the simple digital clock. Chances are there is the PCB inside of it. PCBs bring electronics to life by routing electrical signals where they need to go to satisfy all of the device's electronic requirements.

Parts of PCB

- **Substrate:** The first, and most important, is the substrate, usually made of fiberglass. Fiberglass is used because it provides core strength to the PCB and helps resist breakage. Think of the substrate as the PCB's "skeleton".
- **Copper Layer:** Depending on the board type, this layer can either be copper foil or a full-on copper coating. Regardless of which approach is used, the point of the copper is still the same — to carry electrical signals to and from the PCB, much like your nervous system carries signals between your brain and your muscles.
- **Solder Mask:** The third piece of the PCB is the solder mask, which is a layer of polymer that helps protect the copper so that it doesn't short-circuit from coming into contact with the environment. In this way, the solder mask acts as the PCB's "skin".
- **Silk screen:** The final part of the circuit board is the silkscreen. The silkscreen is usually on the component side of the board used to show part numbers, logos, symbols switch settings, component reference and test points. The silkscreen can also be known as legend or nomenclature.

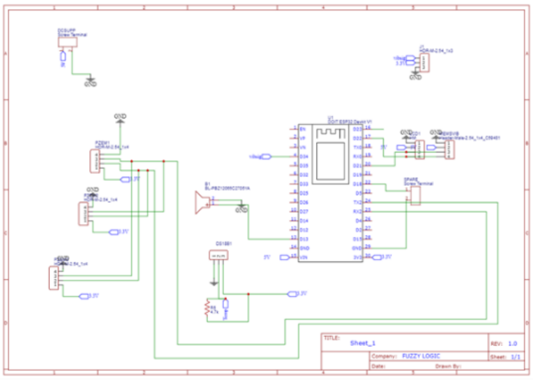

Fig. 3.1 schematic and the pin Diagram

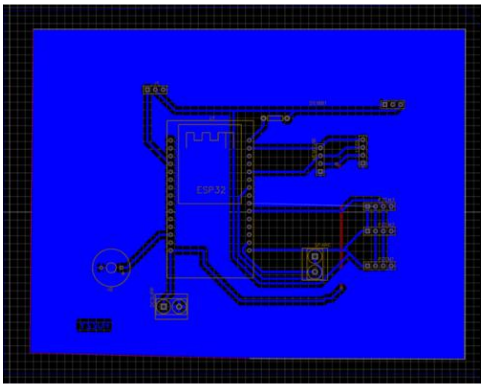

Fig. 3.2 PCB Layout

3.2 Algorithms

1. WiFi Connection Setup

Input:

- SSID (WiFi name)
- Password (WiFi password)

Output:

- ESP32 connected to the WiFi network
- Connection status displayed on the LCD and serial monitor

Steps:

1. Initialize the serial communication (Serial.begin) for debugging.

2. Initialize the LCD screen and display a message ("Connecting to WiFi...").
3. Call WiFi.begin(ssid, password) to start the WiFi connection.
4. Check WiFi.status() in a loop:

   If not connected, print a message ("Connecting...") to the serial monitor and wait 1 second.
5. Once connected, print "WiFi Connected" to the serial monitor.
6. Display "WiFi Connected" on the LCD.

2. MQTT Setup and Reconnection

Input:

- MQTT server address
- MQTT port

Output:

- Active MQTT connection
- Data sent to the MQTT broker

Steps:

1. Initialize the PubSubClient with the MQTT server and port.
2. In the main loop, check client.connected():
   - If the client is disconnected:
     - Attempt to reconnect using client.connect("Client_ID").
     - Print success or failure messages to the serial monitor.
     - Wait 2 seconds before retrying if the connection fails.
3. Once connected, call client.loop() to maintain the connection.

3. Fuzzy Logic Setup

Input:

- Voltage and current readings from sensors
- Fuzzy rules for fault evaluation

Output:

- Fuzzy fault level: "Normal," "Warning," or "Critical"

Steps:

1. Define fuzzy input variables:
   - Voltage: Define sets for "Low Voltage," "Normal Voltage," and "High Voltage."
   - Current: Define sets for "Low Current," "Normal Current," and "High Current."
2. Define fuzzy output variables:
   - Fault Level: Define sets for "Normal," "Warning," and "Critical."
3. Create fuzzy rules:
   - Rule 1: If Voltage is Low and Current is Low, Fault Level is Normal.
   - Rule 2: If Voltage is Normal and Current is Normal, Fault Level is Warning.
   - Rule 3: If Voltage is High or Current is High, Fault Level is Critical..

4. Sensor Data Acquisition (PZEM Sensors)

Input:

- RX and TX pins for each PZEM sensor

Output:

- Voltage, Current, and Power readings for each phase

Steps:

1. Initialize three PZEM sensor objects, each representing a phase.
2. Read sensor data using:
   - pzem.voltage() for voltage.
   - pzem.current() for current.
   - pzem.power() for power.
3. Check for invalid data (e.g., -1 returned by the library) and handle errors appropriately.
4. Store the readings for further processing.

5. Fuzzy Logic Evaluation

Input:

- Voltage and current readings for each phase
- Predefined fuzzy rules

Output:

- Fault Level (Numerical and Categorized as "Normal," "Warning," or "Critical")

Steps:

1. Pass the voltage and current readings for a phase to the fuzzy system using setInput().
2. Run the fuzzification process to evaluate the inputs based on defined fuzzy sets.
3. Apply the fuzzy rules to derive a fault level.
4. Defuzzify the output to compute a numerical fault level.
5. Categorize the fault level:
   - <50: Normal
   - 50-80: Warning
   - 80: Critical

6. Display Fault Level on LCD

Input:

- Fault Level
- Sensor readings (Voltage, Current, Power)

Output:

- Real-time fault status displayed on the LCD

Steps:

1. Clear the LCD display.
2. Set the cursor to the desired position.
3. Display the fault level (Normal, Warning, or Critical) on the first line.
4. Optionally, display voltage, current, and power values for each phase on subsequent lines.

7. Publish Data to MQTT

Input:

- Sensor readings for each phase
- Fault Level

Output:

- JSON payload sent to the MQTT broker

Steps:

1. Format the sensor data and fault level into a JSON string.
2. Use client.publish(topic, payload) to send the data to the MQTT broker.
3. Print success or failure messages to the serial monitor.
4. Retry publishing if the transmission fails.

3.3 Flowchart

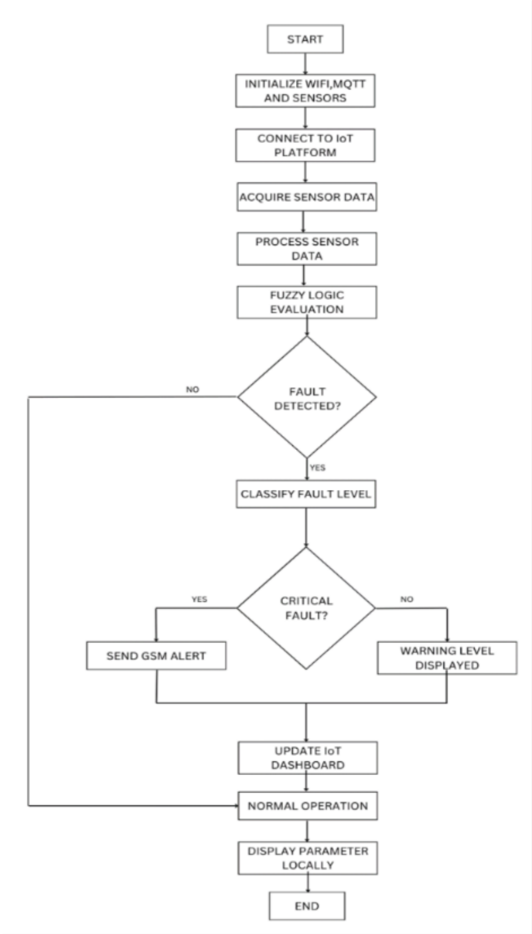

Fig 3.3 Flowchart

3.4 Implemented Snapshot of the model

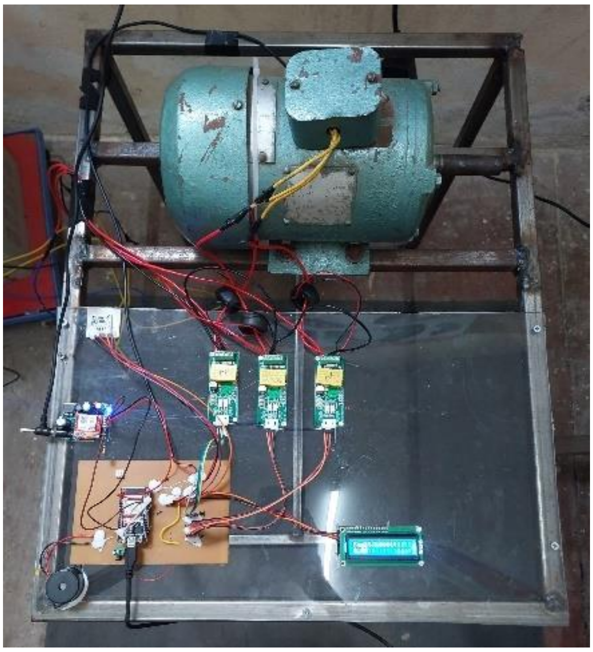

Fig 3.4 Model,

4. Result

TEMPERATURE IN °C	VIBRATION IN M/S	CURRENT IN AMP	FOULT LEVEL	MOTOR STATUS	CONDITION
52.8	0.032238	0.162	0.01	NORMAL	NO-LOAD
31.4	0.054712	0.572	3.14	WARNING	LOAD
35.5	3.046429	0.867	6.50	CRITICAL	FULL-LOAD

5. Conclusions

The development of an advanced fault detection and monitoring system for three-phase induction motors using fuzzy logic and IoT technologies has demonstrated a robust and effective solution for ensuring operational reliability. By integrating sensors for real-time data acquisition, fuzzy logic for precise fault classification, and IoT platforms for remote monitoring, the system enables proactive maintenance and reduces downtime. The inclusion of GSM alerts ensures timely intervention, while the LCD display provides local insights into motor health. This holistic approach not only addresses the limitations of traditional fault detection methods but also enhances the overall efficiency and lifespan of induction motors. The project exemplifies the potential of combining advanced algorithms and modern communication technologies to meet the needs of industries reliant on motor-driven systems.

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