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Real-Time Power Monitoring and Future Usage Prediction Using Machine Learning and IoT

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KEYWORDS

Real-time monitoring, predictive analytics, ESP32 microcontroller, smart energy meter, Internet of Things (IoT), power monitoring, machine learning, logistic regression, energy consumption prediction, and energy management system.

ABSTRACT

The increasing need for electricity together with the demand for efficient energy use makes it impossible for conventional energy meters to provide authentic time monitoring and forecasting capabilities. The research presents a Smart Energy Meter which combines Internet of Things (IoT) technology and machine learning systems to provide real-time power monitoring and future demand prediction capabilities. The system continuously monitors voltage, current, and power usage of all connected devices through an ESP32 microprocessor which operates with ACS712 current sensors and ZMPT101B voltage sensors. The system transmits measurement data to the Blynk IoT cloud platform through wireless communication while displaying results on a 16x2 LCD screen. The system develops its operational capabilities through a machine learning model which uses past energy consumption records to determine whether energy usage falls within normal limits or operates at high-risk levels. The system activates an automatic shutdown through relay-based protection which triggers visual and auditory alarms whenever it detects abnormal power consumption. The system delivers an economical energy management solution which scales easily for home use and small industrial applications while providing smart energy management features that promote safety and energy conservation and active power usage management.

INTRODUCTION

The world needs intelligent energy management systems because of rising electricity demand and increasing energy costs and environmental issues. Residential and commercial buildings use traditional energy meters which only measure total energy consumption and need manual or occasional meter readings. The systems lack real time monitoring capabilities and they fail to provide alerts for unusual usage patterns and they do not enable users to see their consumption habits. People usually do not notice their excessive energy consumption until they receive their high electricity bills. The reactionary strategy causes excessive energy consumption which leads to increased operational costs and results in equipment failures caused by electrical system overloads. Modern energy systems require intelligent solutions that can continuously monitor power usage and analyze consumption patterns to assist users in making informed decisions for energy efficiency improvements.

The Internet of Things (IoT) has brought about complete changes to how people monitor and control electrical systems. The Internet of Things enables real-time data collection and remote device access through its ability to connect sensors with microcontrollers and cloud platforms and user interfaces. Users of IoT-based smart meters receive better energy usage understanding through the system's continuous monitoring of voltage and current and power consumption during energy management activities. The current market for IoT energy meters provides predictive intelligence in the most advanced devices which only display real-time data. The systems lack analytical capabilities which prevent them from forecasting future usage patterns and detecting irregular consumption behavior. The IoT-based energy monitoring systems require intelligent data analysis methods which include machine learning to enable proactive energy management and improve system reliability according to this limitation.

The machine learning techniques extract valuable insights from raw energy data by discovering hidden patterns and trends that exist in historical consumption records. Machine learning models enable the classification and prediction of energy usage patterns which can be improved through optimization based on established historical usage patterns. The system employs predictive analytics to identify unusual consumption patterns and overloads and inefficient usage methods which allows users to take preventive action before critical situations develop. The low computational cost and quick inference time of lightweight machine learning methods, such logistic regression, make them ideal for embedded and edge devices. Smart energy meter systems use these models to automate decision making and create alerts and safety measures which enhance energy efficiency and operational safety and control.

The Smart Energy Meter project uses IoT and machine learning to predict electricity demand because it needs to monitor power usage around the clock. The system operates continuously to measure electrical characteristics through its combination of an ESP32 microprocessor and ZMPT101B voltage sensors and ACS712 current sensors. The system transmits all collected data to a cloud-based IoT platform while displaying information on an LCD screen for local access. The system uses a machine learning algorithm to classify power consumption into two categories normal and high-risk which triggers automatic relay control during detected abnormal conditions. The system promotes energy conservation through user education and advanced power management while maintaining a budget-friendly design which suits both industrial and home energy needs.

LITERATURE SURVEY

According to current research, IoT-based smart energy meters serve two purposes, which include monitoring energy usage and providing users with information. The researchers study low-cost solutions which use ESP32 and ESP8266 microcontrollers together with voltage and current sensors to achieve accurate electrical parameter measurements [1], [2]. Blynk and Firebase and MQTT-based dashboards enable customers to access remote viewing capabilities and data logging functions, which improve their interaction with the system [3], [4]. The systems dedicate their resources to real-time monitoring instead of building predictive intelligence capabilities. The studies on AC mains measurement show that researchers must solve three main obstacles, which include noise filtering and ADC resolution and sensor calibration problems [5]. The methods provide better visibility of energy consumption; however, their success in preventing energy waste and overload conditions remains restricted because they lack systems that can forecast future usage patterns and detect unusual behavior [6].

The researchers studied how edge computing and cloud computing work together to enhance smart energy system performance and scalability. The researchers propose edge-cloud systems which use cloud servers for advanced data analysis and storage while microcontrollers handle immediate data collection tasks [7] [8]. The communication standards MQTT and HTTP are used to achieve reliable data transmission with minimal latency according to established industry practices [9]. Recent studies have placed a strong emphasis on security and privacy issues, such as encrypted communication and authenticated access [10]. The prediction accuracy of a model depends on feature engineering methods and time-series data pipelines according to the research findings [11]. The majority of cloud-based systems increase operational expenses and system delays which makes them unsuitable for residential applications that depend on immediate local control decisions [12].

Machine learning functions as a powerful instrument which enables researchers to measure and predict energy usage patterns. The study evaluates advanced algorithms such as random forest extreme learning machines and LSTM networks against the performance of standard models which include logistic regression and linear regression [13] [14]. Deep learning models achieve better forecasting accuracy but they need extensive data and high computational resources [15]. Embedded systems should use lightweight models like logistic regression because they provide easy operation and result explanation with quick inference times according to research [16]. The research suggests hybrid methods which combine cloud-based training with edge-level categorization to achieve both accuracy and efficiency results [17]. The results demonstrate that researchers can use logistic regression to identify abnormal resource usage patterns in smart energy meters which operate under limited resource conditions.

Intelligent energy management systems require safety and protection mechanisms as fundamental components of their design. Research shows that using rule-based thresholds together with machine learning predictions enhances overload detection reliability according to study [18]. The combination of visual indications with buzzers and relay-based shutdown mechanisms and mobile notifications creates an effective system to warn users and prevent equipment damage according to research findings [19]. The predictive warning system provides a faster response time than standard meters based on tests that used actual loads which included motors and heaters and lighting systems as testing equipment [20]. Most existing systems today require either complete user involvement or they do not possess any automatic protection functions. The combination of predictive analytics with automatic load control systems provides enhanced system protection and ensures safe operations during periods of unexpected power usage.

The 2021 to 2025 evaluations show future developments for smart energy metering because they establish links between electric vehicle charging infrastructure and renewable energy systems. The research team used explainable machine learning models to enhance user trustworthiness and make their system more transparent according to their findings. Cost-effectiveness and scalability remain vital assessment factors for both home use and small industrial operations according to research studies. The existing literature provides substantial backing for developing intelligent energy meters which use Internet of Things technology and built-in machine learning systems. The research supports the proposed system design which combines automatic protection with predictive analytics and real-time monitoring to achieve efficient energy management.

PROPOSED METHODOLOGY

The system development process will use real-time sensing and intelligent data processing and Internet of Things-based remote monitoring to create a unified intelligent energy management solution. The system first collects electrical data through sensors which connect to supply lines by measuring voltage and current. The system uses a ZMPT101B voltage sensor to measure supply voltage with galvanic isolation whereas an ACS712 current sensor detects the load current. The ESP32 microcontroller's analog-to-digital converter receives the analog signals produced by these sensors in proportion to the electrical parameters. The ESP32 system uses electrical equations to determine power consumption while it performs noise filtering and calibration and continuously measures sensor data. This process ensures the system maintains accurate and continuous monitoring of energy use at the device level.

The second phase of the methodology focuses on two main areas which include local user engagement and embedded data processing. The ESP32 computes the voltage, current, and power values in real time by processing the digital sensor data. The system displays these calculated metrics on a 16x2 LCD to provide users with immediate visual information about their energy usage. The microcontroller firmware predefines threshold settings for safe operation. The system signals possible abnormal circumstances when monitored parameters get close to or surpass specified limits. The system achieves quick response times through local computing power which decreases its need for continuous cloud connection. The system maintains its essential monitoring functions by executing them at the edge during temporary network disruptions.

The system intelligence development process requires predictive analytics which uses machine learning techniques during its third implementation stage. The system develops a logistic regression model which identifies standard power consumption patterns and high-risk usage patterns through his training on historical energy usage records. The trained model operates on ESP32 for real-time inference to handle incoming sensor data while predicting unusual consumption patterns. The technology alerts users through LED lights and a buzzer when the system identifies a dangerous situation. The predictive technique detects overloads and wasteful usage patterns which enables organizations to take preventive actions before major equipment failures happen.

The last step of the methodology implements automated security measures together with Internet of Things connectivity. The ESP32 transmits its projected and current power consumption information to the Blynk IoT cloud platform through Wi-Fi which enables users to monitor their energy consumption using a mobile application. Users receive immediate alerts about abnormal situations. A relay-based control system automatically disconnects the load when the user fails to respond during the established safety period. The system ensures protection for electrical equipment and infrastructure. The system delivers a complete solution that scales up and provides intelligent features to manage energy consumption through its combination of real-time monitoring and predictive analytics and remote access capabilities and automatic shutdown functions.

A. System Architecture

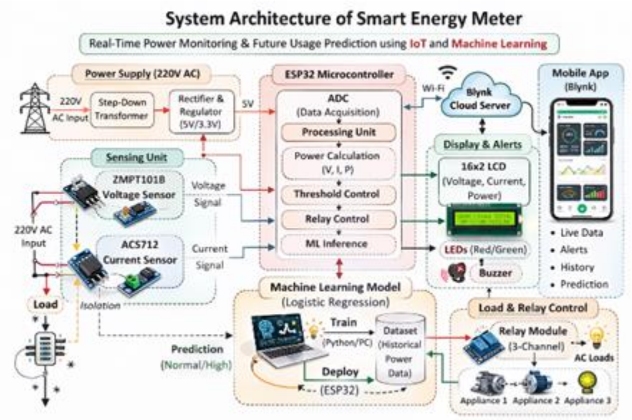

Fig 1 System Architecture

B. Methodology

Acquiring Power Data in Real Time Through Sensor-Based Measurement

The first stage of the methodology aims to achieve precise real-time measurement of electrical parameters directly from the supply line. The system employs a ZMPT101B voltage sensor to capture supply voltage data and an ACS712 current sensor to track current consumption of active loads. The sensors produce analog signals which represent current and voltage values at all times while ensuring electrical isolation and protecting human safety. The sensors maintain continuous monitoring capabilities because their series and parallel configurations enable power delivery to the load without any interruptions. The calibration process of the sensors eliminates offset errors together with AC signal-induced noise and fluctuations. The system achieves dependable measurement results which reflect actual electrical conditions present in both residential spaces and small industrial facilities.

The ESP32 microcontroller's analog-to-digital converter (ADC) interfaces with the analog outputs produced by the voltage and current sensors. The ESP32 monitors sensor data through continuous sampling which operates at a fixed time interval to track voltage and current fluctuations. Digital filtering techniques enable the system to achieve stable measurements while it reduces background noise. The system uses digitized readings to calculate current electrical parameters. The system achieves low-latency monitoring and eliminates the need for constant cloud connectivity by carrying out computations locally at the edge device. The system maintains operations without interruption because it can function during times of network disruption.

The ESP32 utilizes standard electrical equations to compute actual power consumption by using its voltage and current measurements. The system performs continuous updates to its power assessment calculations to adapt to changing load conditions. This continuous sensing method enables the detection of unusual consumption patterns together with overload situations and sudden changes in power usage. The gathered data functions as the foundation for subsequent machine learning-based predictive analysis and decision-making processes. The technology develops an essential data acquisition system for smart energy management through its combination of real-time processing and accurate measurement capabilities.

Implementation of Control Logic, Local Display, and Embedded Processing

The second phase of the methodology investigates how local interaction systems function and how embedded processing systems operate. The ESP32 microcontroller acts as the central processing unit which handles all computing tasks and control logic operations and sensor data collection. The system displays real-time measurements on a 16x2 LCD after it calculates voltage and current and power readings. Users can track their energy usage through the local display which provides immediate information without requiring extra devices. The built-in firmware system presents power parameters in a seamless manner which continuously updates the display throughout the entire time.

The inbuilt control logic establishes safe operating levels for voltage, current, and power in addition to displaying data. The microcontroller memory contains these threshold values, which can be changed in accordance with the needs of the application. The system detects possible problematic conditions when the measured parameters get close to predetermined limitations. This rule-based logic facilitates quick local decision-making and serves as the first line of defense. The system achieves better reliability through local checks which also enable faster response times.

The built-in control system regulates the activation of output components which include LEDs and buzzers and relay modules. The system activates red LEDs and buzzers when it detects dangerous consumption patterns, while green LEDs indicate normal operational conditions. The relay module interrupts power supply to the load after unsafe conditions persist for their designated time limit. The embedded decision-making system protects user safety and prevents equipment damage while maintaining energy efficiency without requiring ongoing human monitoring.

Predicting Power Consumption and Classifying Risk Using Machine Learning

The third stage of the project uses artificial intelligence to enhance system intelligence through predictive analysis. Power consumption data is collected over different time periods and then organized into two categories which include standard usage patterns and exceptional usage patterns. The dataset is used to train a logistic regression model which was selected because it provides clear explanations and requires minimal computing resources and can be used in different deployment environments. The model establishes a relationship between power consumption data and risk situations to identify two distinct energy usage patterns which include normal usage and high-risk usage.

After training the machine learning model, its deployment occurs on the ESP32 microcontroller for live inference execution. The system uses its trained model to assess incoming sensor data until it reaches vital threshold limits, which enables detection of potential anomalous usage patterns. The system uses its predictive feature to generate early alerts, which function independently from threshold violation detection. The lightweight design of logistic regression enables real-time embedded applications to achieve fast inference speeds while using minimal memory resources.

The technology advances from reactive monitoring to proactive energy management by combining machine learning with sensor data. Users can reduce energy waste and avoid overload-related failures by taking proactive action thanks to predictive notifications. The intelligent classification system enhances system efficiency and safety together with dependability especially in environments that experience variable and unpredictable load patterns.

Automated Power Management, Remote Monitoring, and IoT Integration

The final stage of the methodology investigates two primary areas which include IoT connectivity and remote monitoring. The ESP32 device transmits both current energy data and predicted energy data to the Blynk IoT cloud platform through its built-in Wi-Fi system. Users can now monitor voltage and current and power consumption and system performance through a mobile application from any location. The cloud platform enables users to access historical usage data which they can use to monitor current conditions and receive alerts about abnormal situations.

The technology enables remote alert creation which functions as a monitoring tool. The user receives messages through the mobile application when the machine learning model or integrated logic identifies high-risk consumption. The system enables improved response capabilities while providing users with immediate important information. Remote access enables users to make data-driven decisions which optimize energy usage and enhance their experience.

The system uses a relay-based power control system to ensure automated processes and safety functions. The system immediately disconnects the load if the user doesn't reply to alarms within a specified amount of time. The protection system automatically safeguards against electrical damage while it boosts system resilience. The complete energy management solution combines IoT connectivity with predictive analytics and automated control systems.

RESULTS

The smart energy meter which has been installed demonstrated its ability to show exact real-time electrical measurements when tested under different load conditions. The ESP32 microprocessor monitored continuous power measurements from ZMPT101B and ACS712 sensors which displayed results on a 16x2 LCD screen with minimum time delay. The research demonstrated that stable sensor performance together with accurate power assessment needed to be tested through experiments using DC motors and LED lights and variable resistive elements. The system achieved successful operation by tracking power usage when loads were activated or deactivated which proved that both the embedded processing system and the sensor modules operated accurately. The system demonstration shows that it can precisely monitor energy usage in both residential homes and small industrial environments.

The machine learning prediction system demonstrated good performance at detecting energy consumption patterns which were not typical. The logistic regression model successfully categorized energy consumption into two groups, which were normal and high-risk, during its actual operation after learning from historical power consumption patterns. The system successfully generated early alerts before the selected limits were exceeded during testing situations with sudden power demand changes and excessive load conditions. The predictive capabilities of this system provided faster emergency response times when compared to standard systems which relied on fixed threshold limits. The study results demonstrate that embedded systems which use lightweight machine learning models demonstrate both responsive performance and operational efficiency on ESP32 devices.

The IoT system which performed remote monitoring and control functions maintained its reliability throughout all testing periods. The system transmitted energy data and alerts to the Blynk cloud platform without any time delays which were displayed through the mobile application. The system maintained its operational integrity during emergency situations because relay-based load control and buzzer alerts and LED indications performed according to their expected behavior. The protective mechanism proved effective when loads automatically disconnected during extended periods of high-risk situations. The proposed system successfully unifies remote control with predictive intelligence and real-time monitoring to create an effective smart energy management system.

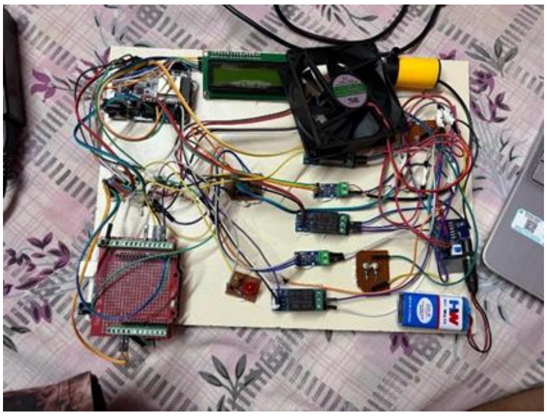

Fig 2: The Smart Energy Meter Prototype's Experimental Hardware Implementation

The complete hardware design of the proposed smart energy meter system which was developed for energy forecasting and continuous power monitoring functions is displayed in the diagram. The system uses an ESP32 microcontroller as its main processing unit to monitor power usage from different electrical loads through ACS712 current sensors and ZMPT101B voltage sensors. The system uses relay modules for automatic load management and it uses visual alarms through LEDs and auditory alarms through a buzzer to detect unusual situation. The 16x2 LCD display presents local voltage and current and power measurement results. The prototype system operates with actual electrical loads which include a DC motor and cooling fan and LED lights and it uses controlled power supply modules for operation.The system's viability and performance verification process includes integrated wiring and modules which demonstrate successful system operation through complete sensing and processing and communication and control functions.

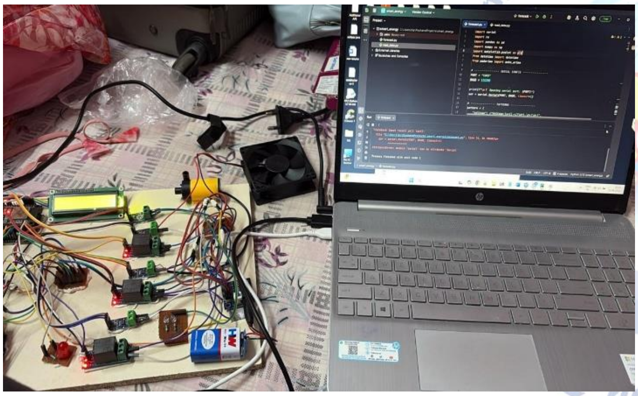

Fig 3: Testing and Monitoring of the Smart Energy Meter System in Real Time

The proposed intelligent energy meter design which combines both hardware and software solutions operates experimentally in real time testing. The hardware prototype consists of an ESP32 microcontroller together with voltage and current sensors and relay modules and LCD display and alarm indications which operate through actual power system testing. The system enables real-time power consumption data visualization and debugging through its connection to a laptop that runs machine learning prediction and data processing software. The LCD displays real-time sensor data while the system shows both relay status and alarm indications which respond to load changes. The experimental setup demonstrates that the system can efficiently measure power consumption while performing predictive analysis and controlling energy consumption through its ability to establish uninterrupted communication between embedded hardware and machine learning algorithms and monitoring software.

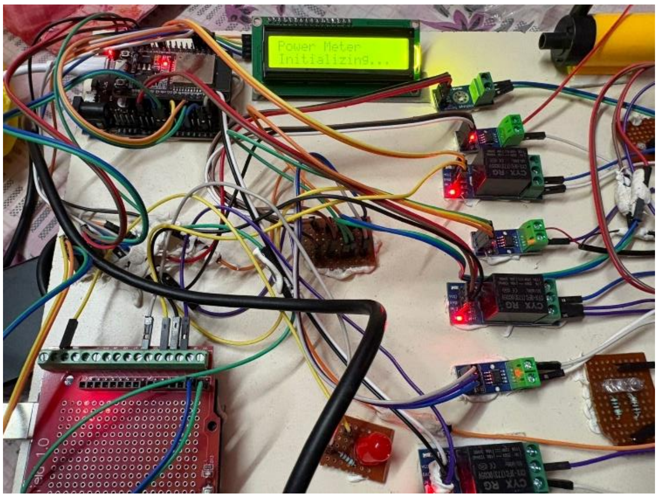

Fig 4: Setup and Multi-Load Management of the Intelligent Energy Meter System

The image shows the startup process and multimode operational capability of the proposed smart energy meter prototype. The 16×2 LCD display shows "Power Meter Initializing" which indicates that the ESP32 microcontroller begins to set up all connected devices when the system receives power. The testing process confirms that all components which include the microcontroller and sensors and display module and relay units have established successful communication. The interfacing of multiple relay modules to distinct electrical loads enables the system to perform selective switching and protection functions. The relay boards use status LEDs to display the current operating state of each load channel. The embedded control logic functions properly because the system components which include sensors and processing units and actuation devices are connected in an organized manner. The system setup and relay operation test create a system that supports predictive analysis and safe energy management and real-time monitoring across different load conditions.

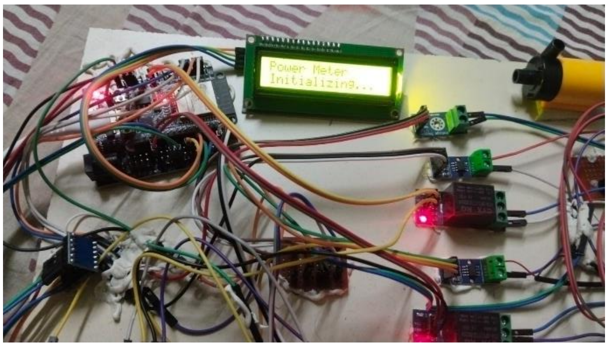

Fig 5: Verification of the Smart Energy Meter's Embedded Control and System Initialization

CONCLUSION

The research paper examined the development and implementation process of a smart energy meter which applies Internet of Things technology together with machine learning methods for the real time monitoring of electricity usage and smart energy management. The system design uses voltage and current sensors together with an ESP32 microprocessor to monitor and process electrical data which includes voltage and current and power measurements. The system uses local LCD displays together with visual indicators and audio alerts to enhance user awareness which enables them to respond effectively to changing load conditions. The experimental results demonstrate that the sensor interface and embedded processing logic together with the communication modules provide reliable performance across various load scenarios. The system provides a practical solution which enables continuous energy monitoring at an affordable price for use in residential and commercial spaces.

The primary contribution of this research work lies in its development of a predictive analytics system which uses machine learning methods for operation in embedded energy monitoring systems. The ESP32 system achieves early detection of unusual power consumption patterns through its use of a logistic regression model. The predictive capabilities of this system enable users to manage their energy usage through proactive measures which help them avoid overloads and dangerous situations. The chosen machine learning model maintains prediction accuracy through its lightweight design which requires minimal computing resources. The system demonstrates that intelligent decision-making can operate at the edge through processing capabilities which do not rely exclusively on cloud computing.

The system's operational capacity and user experience enhancements result from the implementation of automated control systems and Internet of Things connectivity. The mobile application enables users to monitor systems remotely while receiving alarm notifications and conducting historical data analysis through real-time data transmission to the Blynk cloud platform. The relay-based automated load control system safeguards equipment by disconnecting loads when dangerous conditions persist for extended periods. The energy management system achieves intelligent operation through its secure components and scalable design. The proposed solution improves safety and energy efficiency while enabling sustainable power usage, making it an ideal choice for future smart grid and smart house applications.

Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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