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Design and Development of Smart Energy Meter with Real-Time Analytics.

Miss. Sayali Pravin Thoke, Miss. Pranali Bharat Patil, Miss. Pratiksha Sarjerao Patil

Student, Electronics and Telecommunication Engineering, Tatyasaheb Kore Institute of Engineering and Technology, Warananagar, Kolhapur, India

ABSTRACT:

This research presents the design and development of a cost-effective Smart Energy Meter system based on the Arduino Uno microcontroller. The system is designed to continuously monitor and display essential electrical parameters such as voltage, current, power, energy consumption, and estimated electricity cost in real-time. Key hardware components integrated into the system include the ACS712 sensor for accurate current measurement and the ZMPT101B module for precise voltage detection. A Real-Time Clock (RTC) module, specifically the DS1307, ensures accurate timekeeping for tracking daily or hourly energy usage. The acquired data is displayed using a 20x4 LCD screen equipped with an I2C interface to reduce wiring complexity and improve system efficiency.

The primary aim of this project is to enhance user awareness of electricity consumption patterns, thereby promoting more responsible energy usage. By offering real-time feedback and cost estimation, the system empowers users to identify high consumption periods and adjust their usage habits accordingly. Additionally, the low-cost and open-source nature of the design makes it accessible for educational purposes, small-scale households, and remote area applications where commercial smart meters are not feasible. Future enhancements may include wireless data transmission, mobile integration, and cloud-based data logging for extended functionality and smart grid compatibility.

1. Introduction:

Energy consumption monitoring is crucial for ensuring efficient electricity use, reducing waste, and enabling effective cost management, especially in a time when global energy demand continues to rise. Traditional analog and digital electricity meters typically display only the total cumulative energy consumed over a billing period. While this data is useful for utility providers, it offers limited value to consumers who seek insights into their real-time usage patterns or wish to identify which appliances or activities contribute most to their energy bills.

To address this gap, this project proposes the development of a Smart Energy Meter using an Arduino-based platform. The system is designed to provide continuous, real-time monitoring of electrical parameters such as voltage, current, power, and total energy consumption. It also performs dynamic cost calculation based on a predefined tariff rate, giving users immediate feedback on their electricity expenses. Unlike conventional meters, this system enhances user engagement by displaying live data on a 20x4 LCD, making energy consumption more transparent and understandable.

By leveraging low-cost and readily available components like the ACS712 current sensor, ZMPT101B voltage sensor, and DS1307 Real-Time Clock (RTC) module, the Smart Energy Meter offers a budget-friendly and scalable solution. It not only supports energy conservation efforts but also lays the groundwork for future integration with wireless communication modules, allowing for data logging, remote monitoring, and potential integration into smart home ecosystems. The project demonstrates how embedded systems and IoT technologies can be combined to create intelligent solutions for modern energy challenges.

2. Literature Review:

- **Rishabh Jain, Sharvi Gupta, Chirag Mahajan, Ashish Chauhan – "IoT Based Smart Energy Meter Monitoring and Controlling System"**

This study proposed a smart energy meter integrated with IoT capabilities, allowing users to monitor their electricity consumption remotely. The system utilizes microcontrollers and wireless modules to send real-time data to a cloud platform, enabling remote load control and efficient energy tracking. This work demonstrates the potential of integrating energy meters with smart technologies for real-time user interaction and energy savings. It is relevant to the current project as it highlights the importance of user accessibility and remote monitoring.

- **A.A. Noman, M.F. Rahaman, H. Ullah, R.K. Das – "Development of Intelligent Energy Meter for Real-Time Monitoring of Electrical Parameters"**

This research focused on extending the capabilities of conventional energy meters by enabling them to monitor key electrical parameters such as voltage, current, active power, reactive power, and apparent power. The paper emphasizes the need for comprehensive energy tracking for better power quality and efficient load management. The current project builds upon this by implementing sensors that provide real-time voltage and current measurements for improved consumption analysis.

- **Singh, R. Sharma – "Design of GSM-Based Smart Energy Meter"**

This paper presents a GSM-enabled smart energy meter that sends energy consumption readings to users via SMS. Though it lacks real-time display features, it solves the problem of accessibility in areas with limited internet connectivity. While the current project does not use GSM, it shares the same goal of delivering energy data in a user-friendly format. The paper is useful in demonstrating low-cost communication methods for remote energy data access.

- **M. Patel, D. Mehta – "Low-Cost Smart Energy Meter Using Arduino and Wi-Fi"**

Patel and Mehta designed a budget-friendly smart energy meter using Arduino Uno and an ESP8266 Wi-Fi module to transmit data to an online platform. Their system focuses on affordability, ease of construction, and suitability for rural or semi-urban regions. The current project shares similar goals of low cost and accessibility but differs by providing real-time local display of voltage, current, power, and cost through an LCD, making it useful even without internet access.

3. Methodology:

The proposed Smart Energy Meter is developed using a combination of hardware components and software programming to enable real-time monitoring and cost calculation of energy usage. The core of the system is the Arduino Uno, which acts as the main control unit responsible for data acquisition, processing, and output display.

Hardware Components Used:

- Arduino Uno: Functions as the central microcontroller for interfacing sensors, processing input data, and controlling the display.
- ACS712 Current Sensor: A Hall-effect-based sensor used to measure the real-time current flowing through the load.
- ZMPT101B Voltage Sensor Module: Used for detecting and measuring AC mains voltage with accuracy and safety.
- RTC DS1307: A Real-Time Clock module that provides precise time and date for logging and time stamping energy usage.
- 20x4 LCD Display with I2C Module: Displays live voltage, current, power, energy consumed, and cost, reducing pin usage on the Arduino.
- Resistors, Connectors, and Breadboard: Supporting components used for circuit integration and prototyping.

Software and Tools Used:

- Arduino IDE: Primary platform used for writing, uploading, and debugging the code on the Arduino Uno.
- Wire and LiquidCrystal_I2C Libraries: Used for communication with the RTC module and the I2C-based LCD display.
- EEPROM Library (optional): For storing historical energy data or cumulative values across power cycles.

4. Working Process:

1. **Sensor Initialization:**

Upon powering up, the Arduino initializes all connected modules and libraries, including the voltage and current sensors, RTC, and LCD.

2. **Data Acquisition:**

The ACS712 measures the instantaneous current, while the ZMPT101B measures the voltage. These analog signals are read continuously by the Arduino's ADC (Analog-to-Digital Converter).

3. **Power and Energy Calculation:**

The Arduino calculates instantaneous power ($P = V \times I$) and integrates it over time to determine total energy consumed ($E = P \times t$).

4. **Real-Time Clock Synchronization:**

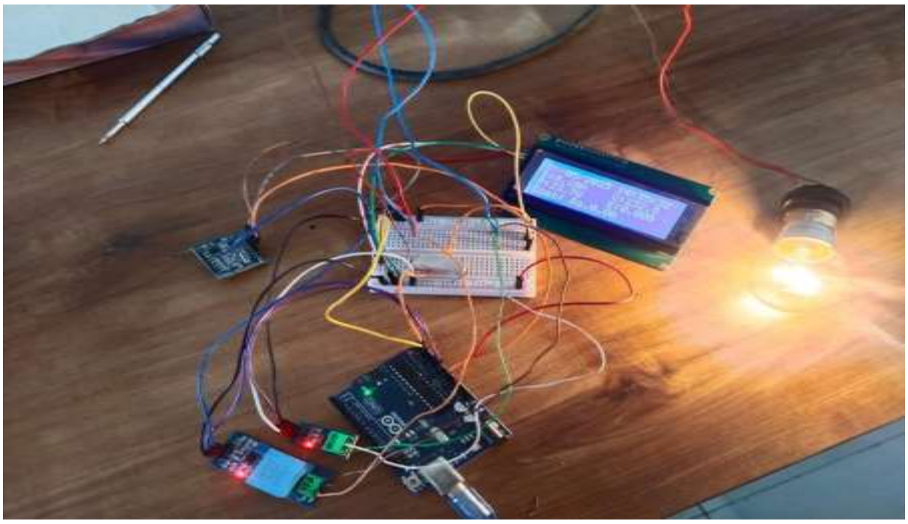
The RTC module provides time and date information, which is used to associate energy data with specific timestamps, enabling time-based tracking.

5. **Cost Estimation:**

A fixed electricity tariff (e.g., cost per kilowatt-hour) is predefined in the code. The Arduino multiplies the energy consumed with the tariff to estimate the current cost of usage.

6. **Data Display:**

All live and computed values, including voltage, current, power, energy, time, and cost, are displayed on the 20x4 LCD using the I2C communication protocol.



5. Results:

The Smart Energy Meter prototype was successfully developed and tested under controlled conditions. The system accurately measured real-time voltage and current values using the ZMPT101B and ACS712 sensors, respectively. These readings were processed by the Arduino Uno to calculate instantaneous power consumption, which was then integrated over time to determine total energy usage. The cost of energy consumption was computed based on a fixed tariff rate embedded in the code. All measured and calculated values, including voltage, current, power, energy (in kWh), real-time clock data, and cost, were clearly displayed on the 20x4 LCD module. During testing, the system demonstrated stable performance, with voltage and current readings closely matching those from standard multimeter equipment. The real-time display updated at regular intervals, providing users with continuous and accurate feedback. The inclusion of the RTC module ensured time-accurate energy tracking, which can be useful for daily or hourly consumption analysis. Overall, the results confirmed the system's effectiveness in providing reliable, real-time monitoring and cost estimation of energy usage in a compact and low-cost setup.

6. Applications:

- Residential energy usage tracking
- Laboratory projects and prototypes
- Educational demonstration for embedded systems
- Precursor to smart home energy management

7. Conclusion:

The Smart Energy Meter based on Arduino Uno presents a reliable, affordable, and efficient approach to real-time energy monitoring and cost estimation. By integrating essential sensors and modules, such as current sensors, voltage dividers, and wireless communication systems, the meter provides accurate data on power consumption, helping users make informed decisions about energy usage. Its modular design ensures flexibility and scalability, making it suitable for both household and educational applications. Furthermore, the project encourages hands-on learning for students and enthusiasts in the fields of electronics, embedded systems, and sustainable energy. Overall, this solution not only promotes energy efficiency but also supports the broader goals of smart grid development and environmental sustainability.

8. Future Enhancements:

- Wi-Fi integration using ESP8266

- ESP32Mobile app for remote tracking
- Data logging and cloud storage
- Overload protection and auto shut-off features

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