

Hardware Implementation of Smart Metering System for Peer-to-Peer Microgrid Energy Management

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Abstract: *The increasing demand for electricity and the integration of renewable energy resources have led to the development of microgrid systems. Peer-to-peer (P2P) energy trading allows consumers to become prosumers, enabling them to generate and exchange energy locally within a microgrid. This paper presents the hardware implementation of a smart metering system designed for P2P microgrid energy management. The system employs INA219 current sensors and ESP32/ESP8266 microcontrollers to measure electrical parameters such as voltage, current, and power consumption in real time. The collected data is transmitted via Wi-Fi to a centralized monitoring platform for energy exchange management. Experimental results demonstrate that the proposed system improves transparency, efficiency, and reliability in energy trading among users in a microgrid environment.*

Keywords: Smart metering, Peer-to-peer energy trading, Microgrid, ESP32, INA219, IoT, Renewable energy

I. INTRODUCTION

The modern power system is gradually shifting from centralized generation to decentralized energy systems. Microgrids have emerged as an effective solution for integrating renewable energy sources such as solar and wind power. A microgrid is a localized energy network consisting of distributed energy resources, battery storage systems, and local loads that can operate independently or in coordination with the main grid [1].

Peer-to-peer (P2P) energy trading is a concept that allows individuals to generate electricity using renewable energy systems and trade excess energy with nearby consumers [3]. For such a system to operate efficiently, accurate monitoring of energy production and consumption is necessary. Smart metering technology plays a significant role in enabling real-time monitoring and communication between different participants in a microgrid [2].

This paper presents the design and hardware implementation of a smart metering system for P2P microgrid energy management. The system uses INA219 current sensors for measuring voltage, current, and power, along with ESP8266 microcontrollers as distributed sensing nodes and an ESP32 microcontroller as the central master node. The measured data is transmitted wirelessly via Wi-Fi to a monitoring platform for analysis and energy distribution management.

II. LITERATURE REVIEW

Several studies have explored the development of smart grid technologies and microgrid energy management systems. Lasseter [1] introduced the concept of microgrids as self-contained power systems capable of operating in both grid-connected and islanded modes. Mengelkamp et al. [2] proposed a blockchain-based energy market for the Brooklyn Microgrid, demonstrating the feasibility of decentralized energy trading among prosumers.

Tushar et al. [3] presented a comprehensive framework for transforming energy networks through P2P trading, emphasizing the role of signal processing and communication technologies. Parag and Sovacool [4] discussed the



design of electricity markets tailored for the prosumer era, highlighting regulatory and technical challenges. Zhang et al. [5] reviewed existing P2P energy trading projects and identified key requirements for hardware monitoring infrastructure.

Research also highlights the importance of IoT-enabled communication systems for continuous monitoring of energy generation and consumption. Technologies such as Wi-Fi, ZigBee, and GSM are used to create communication networks within microgrids [7]. However, developing cost-effective and scalable hardware architectures for microgrid monitoring remains an important area of research [8].

III. PROPOSED SYSTEM ARCHITECTURE

The proposed system architecture integrates sensing units, microcontroller-based processing units, wireless communication modules, renewable energy sources, and energy storage components. The architecture is designed to enable real-time monitoring, data communication, and efficient energy management within the microgrid network.

INA219 current sensors are installed at each node to continuously monitor voltage, current, and power consumption. These sensors communicate with ESP8266 microcontrollers via the I2C interface. The ESP8266 modules function as distributed slave nodes responsible for collecting and transmitting sensor data wirelessly to the ESP32 master node using Wi-Fi. The ESP32 aggregates data from all connected nodes, performs analysis, and forwards the processed data to a central monitoring platform.

A solar panel serves as the renewable energy source, a battery provides energy storage, and a potentiometer simulates variable load conditions for testing. A transformer regulates voltage levels for safe distribution. Fig. 1 illustrates the complete system architecture.

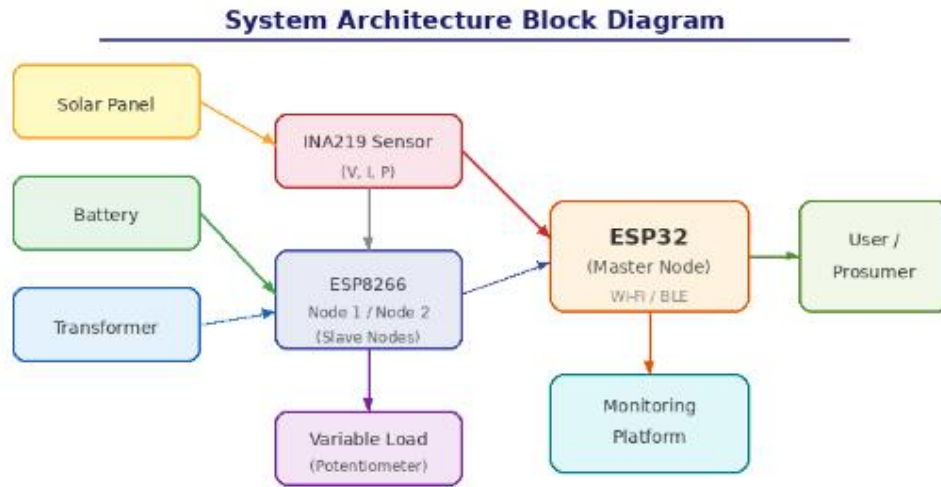


Fig. 1: System Architecture of P2P Microgrid Energy Management System.

IV. HARDWARE COMPONENTS

Component	Specification	Function
ESP32	Dual-core, Wi-Fi + BLE	Master node; data aggregation and control
ESP8266	Single-core, Wi-Fi	Slave nodes; local data collection
INA219	I2C, $\pm 1\%$ accuracy	Voltage, current, and power measurement
Solar Panel	5V/6V, polycrystalline	Renewable energy generation source



Battery	3.7V Li-ion	Energy storage system
Transformer	Step-down, 230V to 12V	Voltage regulation
Potentiometer	10kΩ variable resistor	Simulates variable load conditions

Table 1: Hardware Components Used in the Proposed System

The ESP32 microcontroller functions as the master node, equipped with built-in Wi-Fi and Bluetooth capabilities suitable for IoT applications. It receives real-time data from multiple ESP8266 slave nodes. The INA219 sensor provides high-precision measurement of both voltage and current simultaneously via the I2C interface, enabling accurate power calculation at each node.

V. DATA FLOW AND COMMUNICATION

The data flow in the proposed system follows a hierarchical structure. At the lowest level, INA219 sensors measure voltage, current, and power parameters and transmit the readings to ESP8266 nodes via I2C communication. Each ESP8266 node performs local processing and wirelessly transmits the data to the ESP32 master node using Wi-Fi. The ESP32 aggregates data from all nodes and forwards it to the monitoring platform for visualization and analysis. Fig. 2 illustrates the data flow.

VI. HARDWARE IMPLEMENTATION

The hardware prototype was assembled by connecting INA219 sensors to ESP8266 modules via I2C (SDA and SCL pins). Each ESP8266 node measures local electrical parameters and transmits data wirelessly to the ESP32 master node. A solar panel is connected as the renewable energy source, and a Li-ion battery serves as the energy storage element. A potentiometer is used to simulate variable load conditions for testing purposes. A step-down transformer regulates voltage levels for safe operation of electronic components. Fig. 3 shows the hardware connection overview.

VII. EXPERIMENTAL RESULTS

The proposed system was tested under varying load conditions to evaluate its performance. The INA219 sensors successfully measured voltage and current values with high accuracy. The ESP8266 nodes transmitted data reliably to the ESP32 master node via Wi-Fi, and the monitoring platform displayed real-time electrical parameters with minimal latency.

Load Condition	Voltage (V)	Current (mA)	Power (mW)
Low Load	4.98	120.5	600.1
Medium Load	4.85	245.3	1189.7
High Load	4.72	480.1	2266.1

Table 2: Experimental Results under Different Load Conditions

The results demonstrate that the system accurately monitors electrical parameters across different operating conditions. The voltage remained stable within acceptable limits, and the current and power readings scaled proportionally with load increases, confirming reliable sensor performance.



Hardware Connection Overview

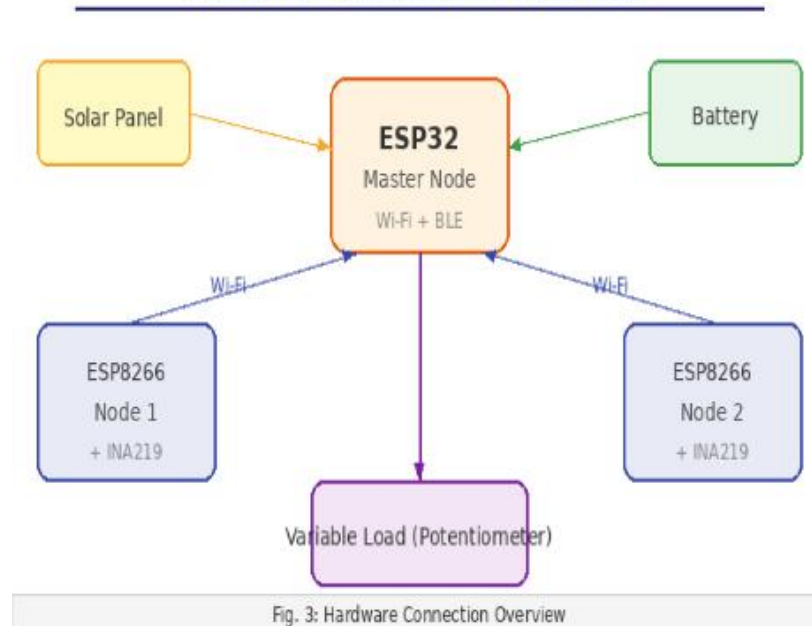


Fig. 3: Hardware Connection Overview

VIII. ADVANTAGES AND APPLICATIONS

The proposed system offers several advantages: real-time monitoring of energy consumption, high-accuracy measurement of voltage, current, and power parameters, improved transparency in P2P energy trading, support for renewable energy integration, and cost-effective hardware design using commercially available components. Applications include residential microgrids with rooftop solar panels, smart homes for real-time energy optimization, commercial buildings sharing electrical infrastructure, community-based energy sharing systems, and smart grid infrastructure supporting decentralized prosumer trading.

IX. CONCLUSION

This paper presented the hardware implementation of a smart metering system for peer-to-peer microgrid energy management. The system employs INA219 sensors and ESP32/ESP8266 microcontrollers to monitor voltage, current, and power consumption in real time. Wireless data transmission via Wi-Fi enables continuous monitoring and efficient energy distribution within the microgrid. Experimental results confirm the system's capability to accurately measure electrical parameters under varying load conditions. Future work will focus on integrating blockchain-based transaction mechanisms, advanced communication protocols, and expanding the system for large-scale microgrid deployments.

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