SMART SOLAR GRID SYSTEM FOR EFFICIENT ENERGY MANAGEMENT AND COST OPTIMIZATION

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Abstract:

The rapid increase in electricity demand and energy costs has created the need for efficient energy monitoring and management systems. The proposed Grid-Connected Energy Storage and Monitoring System is designed to manage energy flow between residential consumers and the utility grid using net metering concepts. The system employs a dual energy meter configuration to measure both imported and exported electrical energy. A microcontroller serves as the central control unit, continuously collecting and processing energy data to calculate net energy consumption and billing values under variable tariff conditions. A regulated power supply ensures reliable system operation, while a crystal oscillator provides precise timing for accurate measurements. Real-time energy parameters are displayed on an LCD module, enabling users to monitor energy usage effectively. The proposed system enhances billing transparency, improves utilization of renewable energy sources, reduces electricity expenses, and contributes to sustainable energy management in modern smart grid environments.

***Keywords**: Net Metering, Grid-Connected System, Energy Monitoring, Bidirectional Energy Flow, Microcontroller, Energy Meter, LCD Display, Power Management, Variable Rate Electricity, Smart Energy System, Residential Energy Management*

1. INTRODUCTION

The increasing demand for electrical energy has created a need for efficient energy management systems. Net metering has emerged as an effective method that allows consumers to both consume and supply energy to the utility grid. This requires accurate monitoring and measurement of energy flow in both directions. The proposed system uses a dual energy meter setup to track imported and exported energy. One meter records energy consumption, while the other measures energy supplied back to the grid. A microcontroller is used to collect and process data from both meters. It calculates net energy and helps in determining accurate billing. A regulated power supply ensures stable system operation. The system also provides real-time monitoring through an LCD display. This improves energy awareness and promotes efficient utilization of electrical energy.

J. Smith et al. (2018) presented the design of a smart net-metering system using a microcontroller and an Energy Meter. Their study focused on improving billing accuracy through bidirectional energy measurement. The system records both the electricity consumed from the grid and the electricity supplied back to the grid from renewable energy sources, making energy monitoring more transparent and efficient.[1]

R. Kumar and S.Singh (2019) discussed a grid-connected Solar Photovoltaic System integrated with net-metering. The research highlighted that excess solar power generated during peak sunlight hours can be exported to the grid. This helps consumers reduce electricity bills while also supporting the power grid with additional renewable energy.[2]

A. Verma and P. Sharma (2020) proposed an embedded-based energy monitoring and billing system using a Microcontroller. Their work emphasized the importance of smart monitoring technologies for efficient energy management. The system uses sensors and controllers to track real-time energy consumption and generation, enabling better decision-making for both consumers and utility providers.[3]

The Ministry of Power (2022) introduced guidelines for implementing net-metering policies for renewable energy systems. These guidelines support the integration of distributed energy resources such as solar power into the national grid. They also encourage consumers to adopt renewable energy technologies and benefit from net-metering schemes.[4]

S. Patel et al. (2024) developed a smart grid monitoring system for renewable energy applications using digital energy meters and embedded controllers. The study demonstrated that real-time monitoring of electricity generation and consumption improves grid reliability and allows consumers to optimize their energy usage.[5]

Recent research by K. Sharma et al. (2025) focused on IOT-based smart net-metering systems for grid-connected renewable energy sources. The proposed system enables remote monitoring of electricity import and export through cloud platforms. This approach helps consumers manage energy consumption efficiently while supporting utilities in maintaining accurate billing and power distribution.[6]

The conventional electricity management systems mainly depend on grid power and do not provide an efficient way to store excess energy generated from renewable sources such as solar power. In many cases, surplus energy produced during peak generation periods cannot be effectively utilized or stored, which leads to energy wastage. Moreover, traditional systems do not allow consumers to fully benefit from net metering policies and variable electricity pricing. Due to the absence of proper energy storage and management, consumers are unable to optimize energy usage or reduce electricity costs efficiently.

To address these limitations, batteries can be used as an energy storage solution. The system integrates solar photovoltaic panels, an inverter, batteries, and a bidirectional energy meter to manage energy flow between the solar source, household loads, and the utility grid. Excess energy generated by the solar system can be stored in the batteries or exported to the grid, enabling consumers to gain financial benefits through net metering. This approach improves energy efficiency, reduces dependency on grid power, and allows effective utilization of variable electricity rates .

2. BLOCK DIAGRAM

The block diagram For Smart Energy Monitoring and Control System for Grid-Connected Renewable Energy Integration as shown in Fig.1

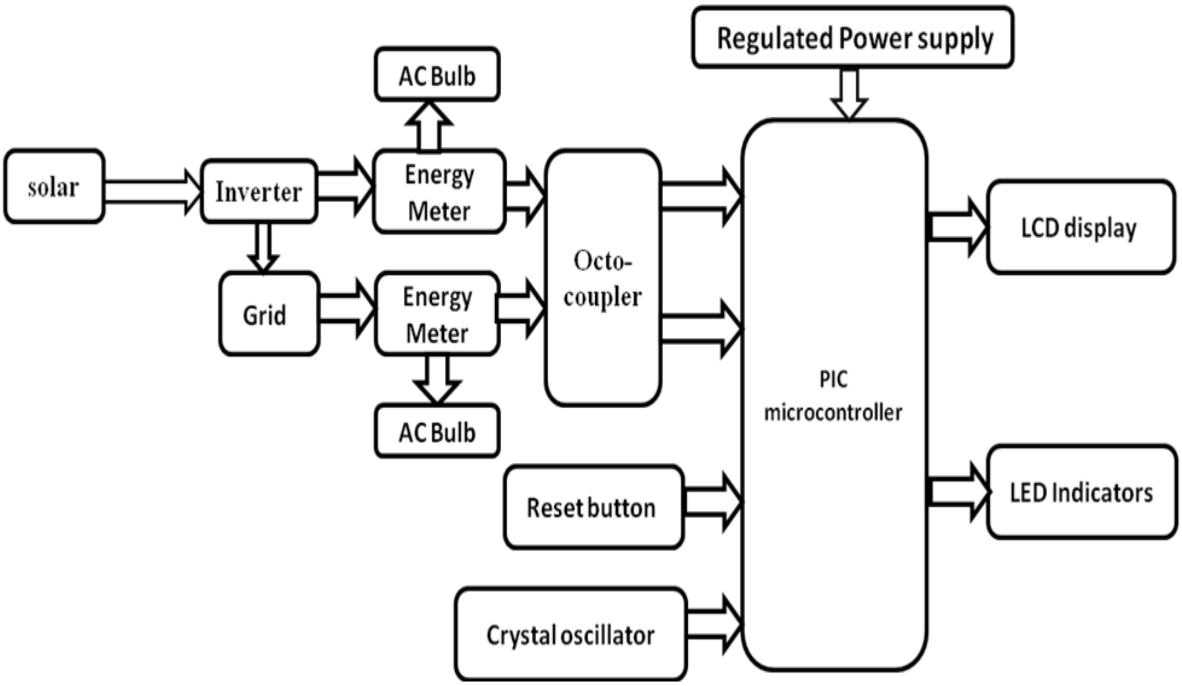

Fig.1 Block Diagram

Solar Panel: The solar panel converts sunlight into electrical energy in the form of DC power. It acts as the main renewable energy source in the system. The generated DC power is supplied to the inverter for further conversion.

***Inverter*:** The inverter converts DC power from the solar panel into AC power. This AC power can be used by household loads. It also allows the system to interact with the grid supply.

Energy Meter: The energy meter measures the amount of electrical energy flowing in the system. It records both imported energy from the grid and exported energy from the solar system. This measurement is important for net metering calculations.

Grid: The grid represents the utility electricity supply. When solar power is not sufficient, electricity is taken from the grid. Excess solar energy can also be sent back to the grid.

Opto-Coupler: The opto-coupler transfers signals from the energy meter to the microcontroller. It provides electrical isolation between high-voltage and low-voltage circuits. This helps protect the microcontroller from damage.

PIC Microcontroller: The PIC microcontroller acts as the main control unit of the system. It processes the signals received from the energy meter. It controls system operations and sends information to the display.

Regulated Power Supply**:** The regulated power supply provides a stable DC voltage to all electronic components. It protects the circuit from voltage fluctuations. This ensures reliable system operation.

LCD Display: The LCD display shows the system information to the user. It displays parameters such as energy consumption and system status. This helps in monitoring the system performance.

LED Indicators: LED indicators show the operating status of the system. They indicate conditions such as power availability or system operation. This provides quick visual information to the user.

Reset Button**:** The reset button is used to restart the microcontroller. It helps reset the system during errors or abnormal conditions. This ensures proper functioning of the system.

Crystal Oscillator*:* The crystal oscillator provides the clock signal required for the microcontroller. It ensures accurate timing and synchronization. This helps the system operate correctly.

AC Bulb (Load)*:* The AC bulb acts as a load in the system. It consumes the electrical power generated from solar or grid supply. It is used to demonstrate and test the working of the system.

When the system is powered on, the PIC microcontroller initializes all the components and starts monitoring the energy flow in the system. The solar panel generates electrical energy and the inverter converts DC power into AC power for household loads. The energy meters measure the power flow between the solar system, grid, and load, and the microcontroller processes this information and displays the system status on the LCD display.

And in these we have three cases:

Case 1: Grid energy greater than household load

Case 2: Grid energy less than household load

Case 3: Grid energy equal to household load

3. HARDWARE MODULE

The hardware module is shown in the Fig.2.

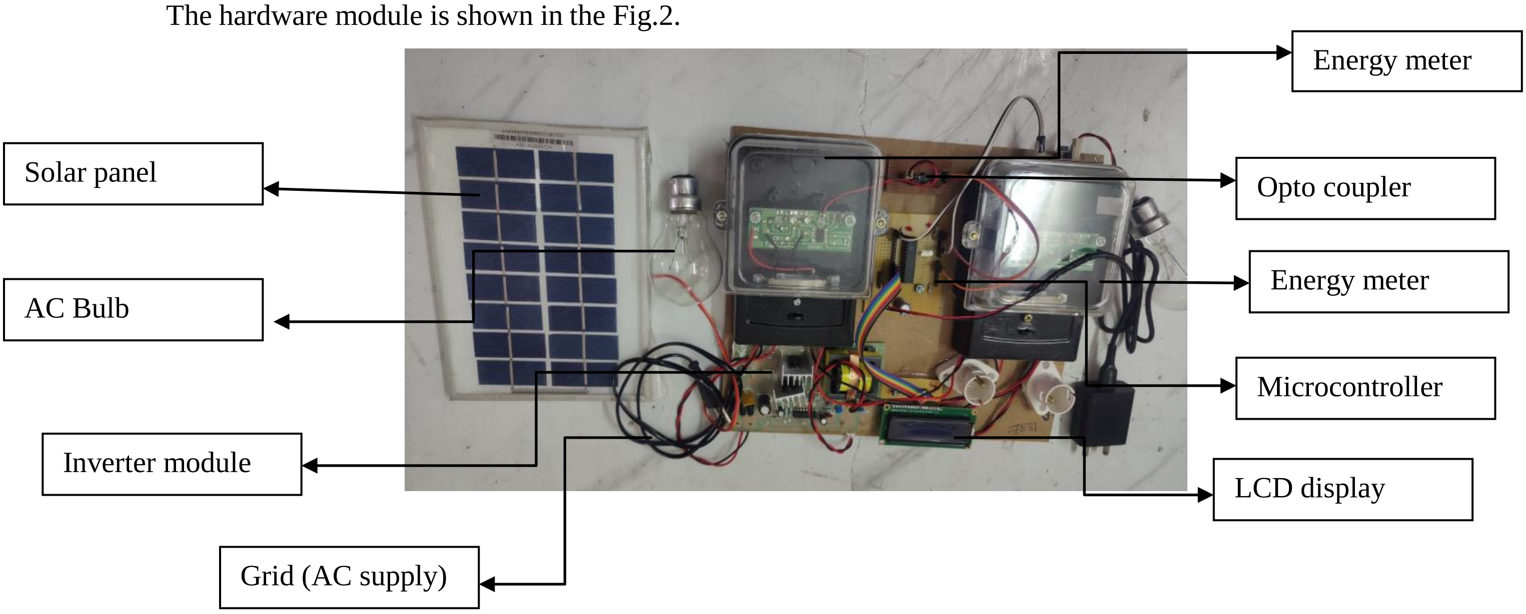

Fig.2 Hardware Module

The block diagram represents a solar-based energy monitoring system connected to the utility grid. Solar energy is converted into electrical energy and supplied to an inverter, which converts DC power into AC power for AC loads. The generated power and grid supply are measured using energy meters, and their outputs are given to an optocoupler for electrical isolation.

The signals are then sent to the PIC microcontroller, which processes the data and calculates the energy consumption or generation. The system operates with the help of a regulated power supply and crystal oscillator for stable operation. Finally, the processed information is displayed on an LCD display, and LED indicators show the system status.

4. RESULTS

4.1 Case study table

Table: Case study table

Case	Consumption	Generation	Grid	Export energy	Bill
Grid > Solar	95.4 kWh	45 kWh	50.4 kWh	0	₹252
Grid < Solar	27 kWh	45 kWh	0	0	-₹90
Grid = Solar	45 kWh	45 kWh	0	0	₹0

The above table 4.1 explains the operation of a grid-connected solar energy system under net metering for three different cases. In Case-1, the load consumption is 95.4 kWh and solar generation is 45 kWh; since the load is higher, the remaining 50.4 kWh power is imported from the grid and no energy is exported. In Case-2, the load consumption decreases to 27 kWh while solar generation remains 45 kWh, so the excess 18 kWh solar energy is exported to the grid and no grid power is required. In Case-3, both load consumption and solar generation are 45 kWh, therefore the generated solar energy fully meets the demand with zero grid import and export. Hence, the power is imported when load exceeds generation, exported when generation exceeds load, and balanced when both are equal, demonstrating efficient utilization of solar energy through net metering.

5. CONCLUSION

The proposed grid-connected energy system demonstrates the effective utilization of solar energy along with the utility grid through net metering. It ensures continuous power supply by exporting excess energy to the grid and importing energy when required. The system also enables proper monitoring of energy usage and exchange, making it efficient and reliable.

Overall, the project highlights the benefits of net metering and variable rate electricity in reducing electricity costs and improving energy efficiency. It provides a practical and sustainable approach for better energy management and promotes the use of renewable energy sources. It also demonstrates how energy flow can be balanced between generation and consumption under different operating conditions, and serves as a simple prototype for real-time applications of smart and sustainable energy solutions.

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