IOT-ENABLED SMART SOLAR MICROGRID FOR RURAL ELECTRIFICATION

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***Abstract*— This paper presents a new IoT-enabled P2P solar energy exchange system using a central battery bank in a DC microgrid environment. Typically, conventional standalone SHS suffers from inefficiencies of energy management due to overproduction and insufficient storage. This system provides a network of interconnected solar nodes through a DC bus for instantaneous energy exchange based on battery SoC and energy demand of each node. Every node consists of a PV source, a battery, sensor components, relays, and a control mechanism based on an Arduino Mega microcontroller. Excess energy is exchanged among the nodes or is stored in a central battery for future usage such as peak-load operation and street light application. The system performance is experimentally evaluated using the Proteus simulator and its hardware model implementation.**

***Keywords*— DC Microgrid, Peer-to-Peer Energy Sharing, Solar Home System, IoT, Centralized Battery Storage, Rural Electrification.**

I. INTRODUCTION

In rural and remote regions, the problem remains one of accessing electricity, since there are no existing power grids that could provide electricity to such locations. Accordingly, SHSs, owing to their modular nature and lack of need for central power grid support, serve as an efficient answer to this problem. In their current state, however, these units operate independently, making them highly inefficient.

When there is a lot of solar production, there is always extra energy produced which goes waste because of inadequate storage capability, and at the same time, other houses might lack energy. However, there have been developments in the area of microgrids that help integrate various energy resources, thus enhancing efficiency and stability. The use of DC microgrids would be more ideal for applications using PVs because of lower energy losses during conversion and compatibility with batteries and DC loads. PV based systems are highly compatible with DC micro-grids, owing to lower losses in conversion processes and better compatibility with battery storage and DC loads.

In addition, the energy-sharing scheme among peers enables users to engage in energy exchanges in a decentralized manner, leading to efficient energy usage. However, the conventional schemes employed in current solutions either use advanced communication infrastructure or are grid-based, and hence not suitable for low-cost rural environments. Furthermore, the fusion of centralized energy storage with P2P energy sharing is not yet extensively explored. This study develops a practical and economical multi-node solar energy sharing scheme that solves these problems by incorporating peer-to-peer energy exchanges along with centralized energy storage and load management. The solution proposed in this study has been successfully modelled and simulated as well as implemented using hardware prototypes.

II. LITERATURE SURVEY

A lot of research has been conducted on microgrids as a method to ensure more energy access and security. The system allows energy production in a localized area, which lessens dependency on central power lines. Among such systems, DC microgrids are the most favourable options in solar energy systems because they provide better performance with minimum energy loss from conversion. Peer-to-peer energy exchange is a decentralized method used to balance the energy needs and supply in various systems. Research shows that peer-to-peer energy systems are capable of increasing renewable energy usage in a flexible manner.

However, most peer-to-peer energy systems require an advanced communication network infrastructure and are usually limited to cities. Energy storage systems are essential components in the integration of renewable energy sources because of their ability to handle intermittencies and changes in demands. Although centralized storage facilities using batteries have already found extensive application in massive installations, few works have been devoted to their implementation in small-scale peer-to-peer (P2P) systems.

Additionally, Internet-of-things (IoT)-based monitoring and control systems have been instrumental in improving the performance of energy systems with their capability for data acquisition and automated decision-making. Affordable microcontrollers have made possible the design of these systems. Nevertheless, current studies mostly rely on models and simulations. Practical, inexpensive systems that integrate P2P energy exchange, centralized storage, and hardware-based controls are not yet available. This study aims to fill this void.

III. PROPOSED SYSTEM ARCHITECTURE

The system will operate as a decentralized DC microgrid composed of different SHS nodes linked through the common DC bus and powered by a central battery system. Each node corresponds to a particular household with its own photovoltaic (PV) source, local battery, sensor units, relay-switch circuitry, and a microcontroller. The DC bus acts as a medium through which energy flows from one node to another or to the central battery storage system. This connection makes it possible to transfer energy from nodes

having excess energy to other nodes facing a shortage of energy. Besides P2P energy transfers, the proposed system uses a central battery storage system that stores excess energy once all the nodes have adequate power. Each node regularly checks electrical variables such as solar voltage, battery voltage, and current consumption using sensors. These readings will be transmitted to the microcontroller (Arduino Mega) where conditions will be checked and relay switches activated accordingly.
The central storage unit provides a cushioning effect for energy and facilitates:
Energy storage when there is excess energy
Load support when there is high load
Energy generation for public utility purposes, for instance streetlighting
This system also comes with an IoT-based monitoring system using the Blynk platform.

A. *Working Principle*

The working process of the recommended system is based on dynamic energy management, which takes into account real-time measurements and prearranged control strategies. Several operating modes can be considered, which are defined by available solar energy, battery state-of-charge (SOC), and load demand. First, during daytime, if energy is produced from solar cells, energy is first consumed to satisfy the needs of the local load. Any additional energy is then directed to the local battery and when its SOC level reaches the upper limit, energy is distributed among interconnected nodes via the DC bus.
When energy levels at all interconnected nodes are high (SOC level is high), energy is redirected to the central battery energy storage. Such strategy allows avoiding losses in energy and ensures the highest level of efficiency. At the same time, during low sun activity and nighttime, the proposed system works in a mode involving battery energy usage. Energy from a local battery satisfies the demands of the local load and when SOC reaches the lower limit, energy is acquired from peer nodes or battery storage facilities.
Under high loads, where there is more demand than a pre-determined amount, the centralized storage system supplies extra power. In addition to this, the centralized storage system is used to automatically supply power for street lighting loads through an LDR-based control system.
The energy flow system adopted here helps achieve optimal use of available energy sources, minimize waste, and improve reliability.

B. *Control Algorithm*

The designed system uses a rule-based control algorithm in the microcontroller to regulate the energy transfer among the components.
The control rules depend on the following scenarios:

- Solar Power Availability:

In case the solar power exceeds the minimum value, the system tries to feed the loads using the solar power
If the battery SOC is below the upper limit (e.g., 90%), excess solar energy is used to charge the battery.

- Energy Sharing Condition (P2P Mode):

In case the battery is charged to the maximum SOC level, excess power can be shared with other nodes via the DC bus.

- Central Storage Charging Condition:

If all nodes' SOC values are high, then the excess power can be channeled to the centralized battery storage system.

- Battery Discharge Mode:

Under conditions of insufficient solar irradiance, the battery discharges its power to supply the load until the SOC falls below a predetermined value (for example, 40%).

- Load Demand Support Mode

In situations where the demand by the load surpasses a predetermined limit, power is supplemented by the centralized storage unit.

- Street Light Operation Mode:

At night, the centralized storage unit operates street lights based on the input from an LDR sensor.

The above algorithm guarantees intelligent energy distribution and efficient performance of the microgrid system.

C. *Mathematical Modeling*

Basic electrical relations are utilized for determining the parameters related to power, energy, and battery SOC for analysis and regulation of system behavior.

- Power Calculation:

The instantaneous load power is calculated as:

$P=V\times I$
Where:
P = Power (W)
V = Voltage (V)
I = Current (A)

This relation is utilized for monitoring the load requirement and identifying high load conditions.

- Battery State of Charge (SOC):

Since the actual determination of SOC is difficult, it can be determined by measuring battery voltage as:

$$SOC \approx \left(\frac{V_{battery}}{V_{max}}\right) \times 100$$

Where:
$V_{battery}$= Measured battery voltage
V_{max}= Fully charged battery voltage

This approximation is used to determine charging, discharging, and sharing decisions.

IV. IOT-BASED MONITORING SYSTEM

A. Blynk System Integration

In the suggested design, there will be an Internet of Things (IoT) monitoring system based on the Blynk app that can visualize real-time data and supervise the whole system from afar. The microcontroller (ESP32/Arduino Mega) is connected to the Blynk cloud server via Wi-Fi, which enables constant transmission of all the parameters within the system. The ESP32 (or the Wi-Fi module connected to the Arduino) retrieves information such as the voltage level of the battery, solar power, and the current flowing from the load, and sends it to the Blynk cloud platform.

Such connectivity makes it possible to monitor the performance of the system remotely using either the smartphone or web-based dashboard without any need for direct physical interaction with the hardware components.

B. Parameters Monitored

The IoT platform is utilized to observe the critical parameters necessary for efficient energy management and analysis. The parameters monitored are as follows:

- Battery State of Charge (SOC):

This shows the current state of energy in the battery and enables us to determine if the system needs charging or discharging.

- Solar Panel Percentage:

This monitors the amount of energy generated by the solar panels at any moment and indicates whether there is energy generation.

- Energy Sharing Status:

This monitors whether there is energy transfer between nodes or whether there is energy coming from the central energy storage system.

These parameters provide a complete overview of system operation and energy flow conditions.

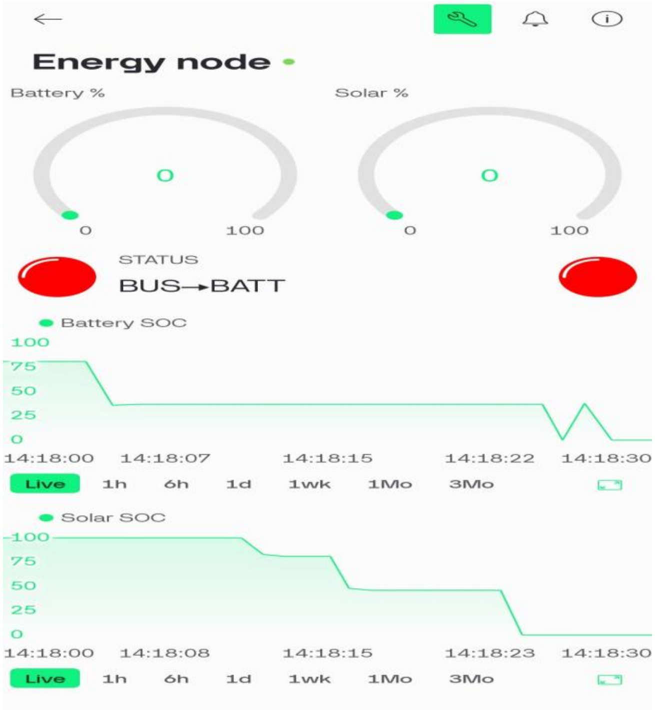

Fig: Dashboard Visualization

V. HARDWARE IMPLEMENTATION

A. Components Used

A hardware prototype of the proposed system design is created by using inexpensive and readily available components to ensure its practicability. The key components employed in the design include the following:

- Solar Panel (DC Source):

This component represents photovoltaic energy generation. In this case, a DC source is employed in place of the solar panel to simulate solar energy.

- Lithium-ion Battery:

It is used as an energy storage facility in each of the nodes and central battery storage.

- Voltage Sensors:

They are used to monitor the voltage generated by the solar panels and that stored in the batteries.

- Relay Modules:

These are used for switching between the various power routes such as solar to the load, solar to battery, battery to load, peer-to-peer sharing on DC bus.

- ESP32 / Wi-Fi Module:

These components facilitate IoT communications with the Blynk platform.

- DC Loads (Bulbs/LEDs):

They represent household loads.

These components are selected to ensure cost-effectiveness, ease of implementation, and suitability for rural deployment.

B. *Circuit Connections*

The hardware circuit will allow flexibility of energy routing in the system using relay switches. In each solar node, there will be a photovoltaic cell, battery, sensor units, and control unit connected using relay switches. The photovoltaic cells will be connected to both the load and battery through relay switches; this will allow the controller to choose whether to give out energy straight to the load or charge the battery. Battery connection is linked to the load through relays to facilitate power feeding from the battery when solar energy is lacking.

DC Bus connects several nodes and also the centralized battery bank together. Relay switches are used to enable the exchange of energy from node to DC bus and vice versa; this allows peer to peer exchange of energy between the nodes. Relay switches are also used for charging and discharge operations of the centralized battery. Voltage sensors are connected across the photovoltaic cells and batteries terminals. These parameters are applied in estimating battery SOC and determining modes of operation. The ESP32 (or Wi-Fi module) is programmed using a controller that sends data to the Blynk cloud platform. The LDR sensor is wired for detecting environmental light and controlling the operation of street lights.

In general, the circuit provides secure transfer of energy between all components as well as different modes of operation.

C. *Prototype Implementation*

The physical model of the system is designed to verify the real-time operation and performance of the system. The model comprises two solar nodes connected by a DC link. The nodes have been mounted on the breadboard with components like ESP 32, relay circuits, sensors, and battery pack.

The prototype verifies the following operations during operation:

Supplying power from the solar panel to load

Charging and discharging batteries

Sharing energy between nodes

Monitoring of the IoT platform with Blynk verifies system operation by presenting real-time system parameters such as battery state of charge, solar voltage, and energy sharing.

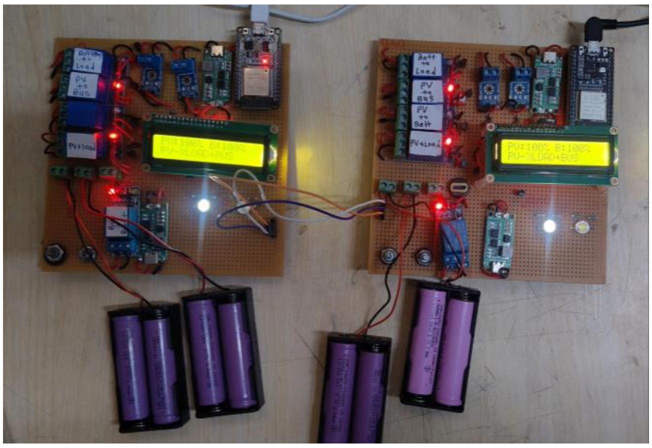

Fig: Circuits

VI. SIMULATION

A. *Proteus Setup*

The designed system will be simulated using Proteus Design Suite for checking the control mechanism and energy flow characteristics prior to actual hardware implementation. Proteus Design Suite creates an appropriate platform where one can combine the microcontroller-based control with circuitry simulation together. This simulation model will have two solar nodes that communicate with each other via a shared DC link and battery storage system. These two nodes will consist of an Arduino Mega microcontroller, relay circuits, DC voltage sources representing solar cells, and batteries.

The Arduino Mega will be programmed in embedded C language (Arduino IDE) and incorporated in the Proteus software to control relay operation according to some logic. Simulation includes virtual devices like voltage probes and LCD screen to observe the behaviour of the system parameters during simulation. Simulation conditions will mimic actual working conditions by changing inputs and output loads.

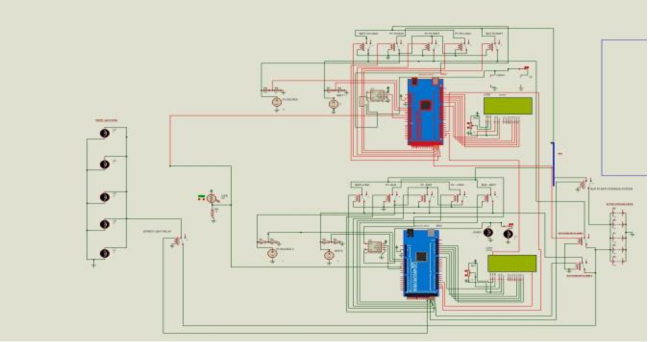

Fig: Proteus design overview

VII. RESULTS

A. Performance Analysis

Peer-to-peer energy sharing and storage help enhance energy efficiency compared to individual solar home systems. Energy loss was common because of insufficient storage capacity in traditional systems. The new approach helps redistribute or store any excess energy efficiently.

Simulation and prototype results indicate that:

Traditional SHS energy efficiency ≈ **60–70%**

P2P energy sharing efficiency ≈ **80–85%**

Centralized storage efficiency ≈ **90–95%**

These results show that there is significant enhancement in energy efficiency through improved distribution and storage.

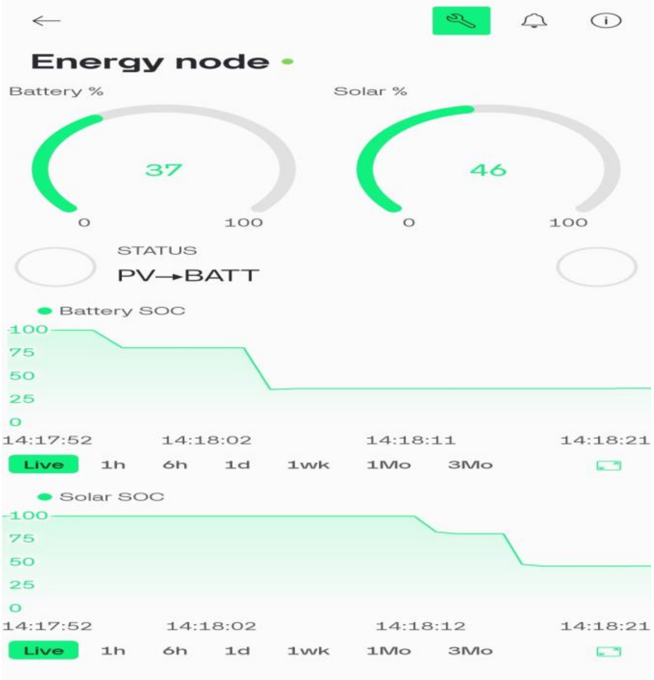

Fig: IOT Monitoring Results

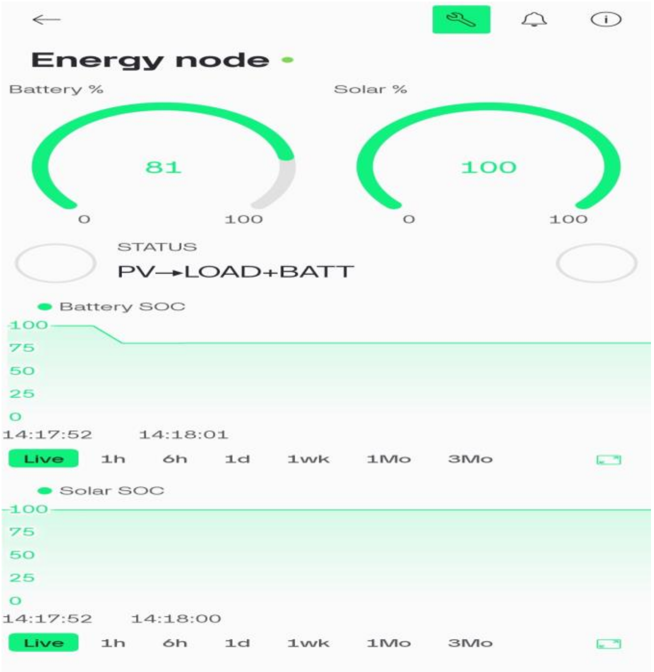

Fig: IOT Monitoring Results

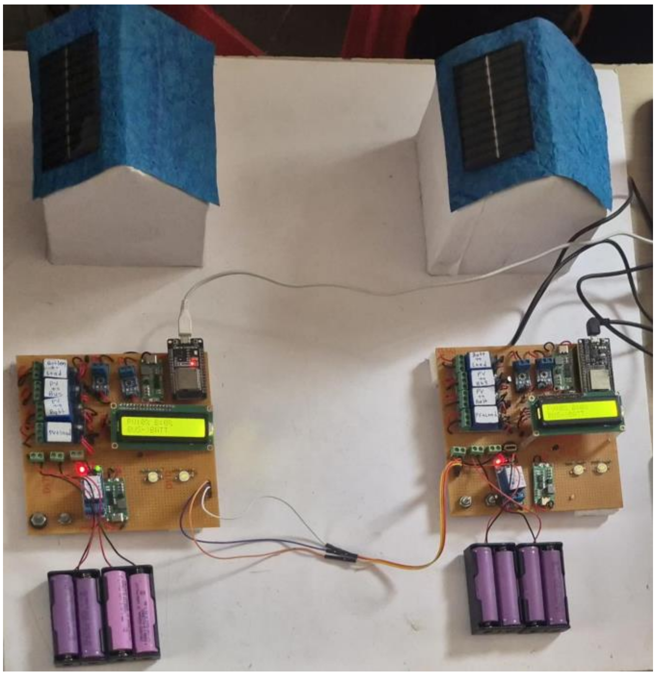

Fig: Actual Prototype

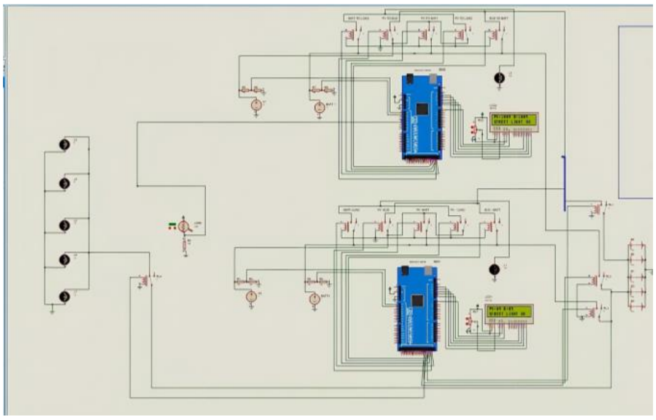

Fig: Proteus Results

VIII. FUTURE SCOPE

The system can be further enhanced with the following improvements:

Integration of MPPT Techniques

Use of Solid-State Switching Devices

Advanced Battery Management System (BMS)

AI-Based Energy Optimization

Scalability to Larger Microgrids

IX. CONCLUSION

The above paper introduced a novel concept on how an IoT-based peer-to-peer solar energy sharing system with centralized battery storage can be implemented in DC microgrids. It is evident that the system facilitates efficient energy transfer from one node to another through a DC bus without much wastage of energy. From the results obtained, the system performs well with respect to different modes, which include energy sharing, use of central storage, and power management. By implementing IoT-based monitoring, functionality of the system can be enhanced with the availability of live information.

The proposed approach makes the system more energy-efficient, reliable, and cost-effective compared to conventional approaches.

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