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An IoT-based Smart Hybrid Power Management System with Accurate Forecasting and Load Strategy

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ABSTRACT

Efficient use of renewable energy sources without limiting power consumption is the problem in demand-side energy management. This paper presents the design and implementation of an IoT-driven hybrid power management system that seamlessly integrates solar and AC power sources. Leveraging the ESP32 microcontroller, this system is engineered to prioritize solar energy as the primary power source, switching to AC only when solar output is insufficient or an overload condition occurs. This dynamic switching mechanism not only ensures a consistent power supply but also optimizes energy usage, contributing to both cost-efficiency and environmental sustainability. Proposed design allows users to track power levels, receive notifications on power source switching, and manage overload conditions remotely.

Keywords: Hybrid Power, IoT, ESP32, Solar Energy, Mobile Application, Renewable Energy

I. INTRODUCTION

People's development is greatly impacted by the economy's rapid growth, the massive energy consumption, and the growing energy shortage. Energy is the fundamental assurance for social and economic development and is essential to human existence and sustainable development [1-3]. The global shift toward sustainable energy solutions has amplified the role of renewable resources like solar power in meeting energy demands. However, the variable nature of solar power requires supplementary systems to maintain a stable power supply [4]. Hybrid systems, which integrate renewable sources with conventional energy, present a feasible solution to this challenge. An IoT-based hybrid power management system utilizes the solar and AC power sources, controlled by a microcontroller. This system is designed to favor solar energy, switching to AC as necessary to ensure continuity and protect devices during power overloads. Real-time monitoring and control through a mobile app enhance user engagement and operational efficiency [5-6]. The most crucial thing is to keep an eye on the inverter's power quality. The advent of the Internet of Things addresses real-time power quality monitoring and other safety concerns, making solar power generation a practical and efficient alternative, and increases the efficiency of supporting management decisions. In order to accomplish a fully integrated design, the building system and photovoltaic installations are currently integrated with the use of suitable computer-assisted support. The several critical

challenges like rising electricity costs, environmental sustainability, pollution, and power cuts are the major issues in this field. Increasing energy prices impose significant financial burdens on households and businesses, making cost reduction a priority. This hybrid power management system leverages solar energy, a free and renewable resource, to offset grid electricity usage, thereby lowering electricity bills. By decreasing reliance on non-renewable energy sources, the system reduces pollution and carbon emissions, contributing to a cleaner environment. The system also enhances energy security by providing a reliable power supply during grid outages. Additionally, by providing real-time monitoring and control of energy usage, the system empowers users to manage their consumption more efficiently, fostering a proactive approach to sustainable development.

The objective of this hybrid power management system project is to create a cost-effective and sustainable energy solution that integrates solar and grid power to reduce electricity bills and enhance energy efficiency. Remaining paper is organized as follows. Existing related works are described in Section 2. Hardware description is given in Section 3. Software monitoring is presented in Section 4. Results and discussion are described in Section 5.

Advantages and applications are given in Section 6. Paper is concluded in Section 7.

II. EXISTING RELATED WORKS

Different related works are discussed in this section. In [7], an Arduino microcontroller manages the energy flow in real-time, optimizing power distribution and cost. The system employs multi-function sensors and cloud-based data processing, effectively balancing load demands across various sources. Simulation and real-life results align, demonstrating efficient and cost-effective energy management, crucial for enhancing the reliability and sustainability of hybrid renewable systems.

Authors in [8] propose an Intelligent Smart Energy Management System (ISEMS) utilizing IoT and advanced machine learning techniques to manage renewable energy demand efficiently. The PSO-based SVM regression model excels in accurate energy forecasting. The system involves PV data collection, load scheduling, and remote monitoring. An experimental setup demonstrates ISEMS's power negotiation based on predicted energy availability, optimizing renewable resource utilization. Secure IoT integration enhances data monitoring and analysis, supporting effective demand-side management in smart grids with significant renewable penetration.

Using a hybrid approach that combines the Honey Badger Algorithm (HBA) with Density Clustering and Graph Neural Network (DCGNN), an Internet of Things (IoT)-enabled energy management system (EMS) is presented for grid-connected solar PV-fed DC residential buildings [9]. By optimizing power flow between the grid, battery storage, and solar PV system, the HBA-DCGNN technique seeks to lower electricity bills without sacrificing comfort. Capabilities for real-time monitoring and control improve resource use and reduce expenses and energy use [10]. The study demonstrates the feasibility and effectiveness of this system in residential settings, promoting renewable energy adoption and setting the stage for advancements in IoT-based EMS for smart energy consumption [11-12].

III. HARDWARE IMPLEMENTATION

The hardware implementation of our proposed system has been presented in this section. The ESP32 microcontroller continuously monitors power levels, switching to AC if solar power drops below 8V or in overload conditions. During overloads (21V or higher), the system shuts down to prevent damage. This setup ensures efficient energy use and device protection, while the mobile app provides remote monitoring. Figure 1 shows the overall block diagram of our proposed system.

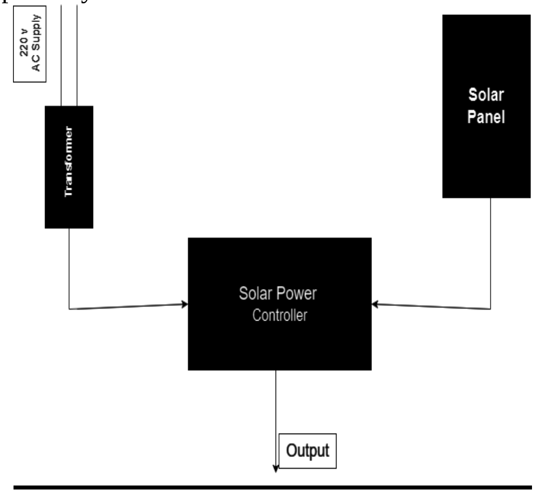

Fig1: Block diagram of proposed system

Circuit diagram of proposed system is presented in Fig. 2. The IoT-based hybrid power management system includes various components that ensure efficient switching between solar and AC power. The ESP32 microcontroller is the central control unit, supported by essential components like a transformer, bridge rectifier, voltage regulator, diodes, relays, and sensors. The snapshot of our model in working condition is shown in Fig. 3.

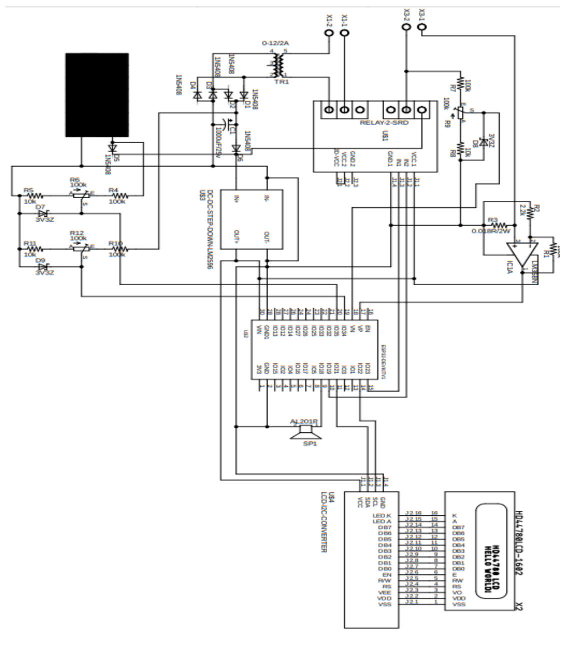

Fig2: Circuit diagram of proposed system

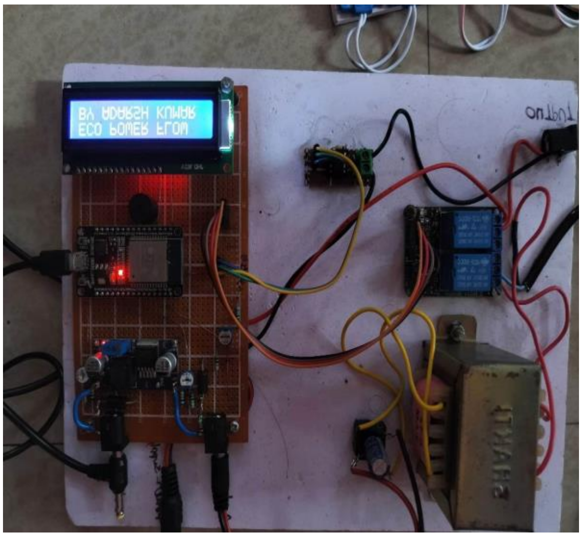

Fig3: Snapshot of working status of proposed system

Key Components used: The following major hardware components are required to design our project.

ESP32 Microcontroller: Manages switching between power sources, monitoring voltage levels, and communicating with the mobile app for remote control.

Solar Panels and AC Power Supply: Solar panels serve as the primary energy source, while AC acts as a backup, ensuring continuous power during low sunlight or overload.

0-12/2A Transformer and Bridge Rectifier: Steps down and converts AC to DC voltage, providing stable power for the system.

Two-Channel Relay Module: Controlled by the ESP32, this module automatically switches between solar and AC power based on voltage and load conditions.

Current Sensor and Buzzer: Monitors load current and triggers alerts for overloads, protecting the system and connected devices.

IV. MONITORING THROUGH SOFTWARE

The software for the hybrid power system includes programming the ESP32 with the Arduino IDE, Firebase integration for data storage, and a mobile app built with MIT App Inventor for remote monitoring.

ESP32 Programming: The Arduino IDE is used to set up system operations, including Wi-Fi connectivity, voltage and load monitoring, and control logic for switching between solar and AC power.

Firebase Integration: Logs real-time power data, allowing users to access historical data and monitor system performance remotely.

Mobile Application (MIT App Inventor): The app provides a user-friendly interface for real-time monitoring and control, allowing users to view power levels, receive alerts, and manage power source switching from anywhere. The system features real-time monitoring and control through a mobile application developed with MIT App Inventor [13]. In the next section, working principle has been described in the following.

V. RESULTS AND DISCUSSIONS

The hybrid power management system operates by continuously monitoring solar and AC power levels, as well as the current load. Based on these readings, the ESP32 microcontroller decides which power source to use and protects the system in overload situations. Here's a brief overview of the system's functionality under different load cases:

Case 1 - Normal Load (Working on Solar): When the solar panel generates sufficient power (voltage above 8V) and the load is within the safe limit, the system uses solar energy as the primary power source. This optimizes energy usage by prioritizing renewable energy. Figure 4 shows the status during normal load (during solar power). Fig. 4a shows the mobile snapshot, Fig. 4b shows the actual model snapshot.

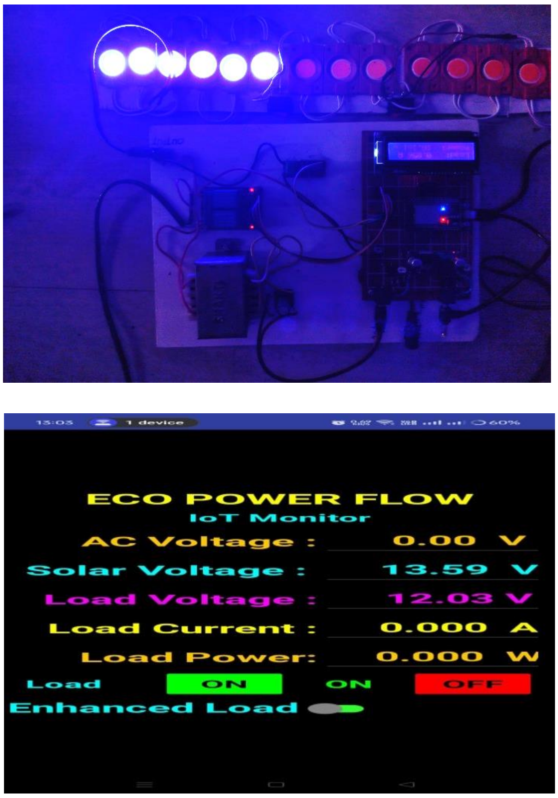

Fig 4: Case 1 – Normal Load (Working on Solar) a) mobile snapshot, b) model snapshot

Case 2 - Max Load (Switched to AC): If the load approaches the maximum safe limit (load at 12V) or the solar power drops below the required threshold (below 8V), the system automatically switches to AC power. This ensures uninterrupted power supply even when solar energy is insufficient. Figure 5 shows the status during maximum load (during AC power). Fig. 5a shows the mobile snapshot, Fig. 5b shows the actual model snapshot.

Fig 5: Case 2 – Max Load (Switched to AC) a) mobile snapshot, b) model snapshot

Case 3 - Overload (System Shutdown):
When an overload condition occurs (load exceeding 21V), the system shuts down to prevent damage to connected devices. An audible alert is triggered to notify the user of the shutdown, ensuring system safety. Figure 6 shows the status during overload (during shutdown). Fig. 6a shows the mobile snapshot, Fig. 6b shows the actual model snapshot.

Fig 6: Case 3 – Overload (System Shutdown) a) mobile snapshot, b) model snapshot

VI. ADVANTAGES AND APPLICATIONS

Solar power systems offer significant benefits, including reduced energy costs and enhanced reliability through seamless switching between solar and AC power, ensuring uninterrupted service. Their automatic overload protection safeguards devices from damage while promoting energy efficiency and sustainability. Users can conveniently monitor and control their systems remotely via apps, receiving real-time alerts for any issues. Access to historical data allows for informed energy management decisions, extending system longevity and decreasing environmental impact. Additionally, these modular systems can integrate other renewable sources, fostering energy independence and inspiring community commitment to sustainable practices.

The applications of solar power systems span a wide range of sectors, enhancing energy management and promoting sustainability. In residential settings, these systems optimize energy use by seamlessly transitioning between solar and grid power, leading to reduced electricity bills. They also serve remote and off-grid locations, ensuring reliable power where grid access is limited. During emergencies, such systems provide backup power, maintaining operations during outages. In commercial buildings, educational institutions, and agricultural settings, they help manage energy consumption and lower operational costs. Additionally, they support telecommunication towers, public infrastructure, electric vehicle charging stations, and industrial applications by ensuring continuous power supply and enhancing efficiency. Integration with smart home devices further maximizes renewable energy use, while community energy projects encourage collective management of resources. Lastly, these systems facilitate renewable energy research by providing practical setups for testing and improving power management technologies.

VII. CONLUSION:

The hybrid power management system has several limitations that affect its performance. Its efficiency depends on variable solar power availability, influenced by weather, geography, and seasons. Without energy storage, the system cannot store excess solar energy for nighttime or cloudy days, limiting reliability. It also relies on stable WiFi for real-time monitoring, making it less effective in areas with poor connectivity. Regular maintenance of components is necessary to ensure optimal function, and significant power demand increases may require extensive upgrades. Additionally, frequent overloads can lead to inconvenient system shutdowns, necessitating better load management. By prioritizing the use of renewable solar energy and ensuring a seamless switch to grid power, when necessary, the system aims to decrease reliance on non-renewable resources, promote sustainable development, and lower carbon emissions. This work seeks to empower users with real-time monitoring and control of their energy usage, fostering awareness and proactive energy management for a more sustainable future.

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