

IOT-Based Solar Inverter with Intelligent Power Source Management

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Abstract

The project titled “IoT-Based Solar Inverter with Intelligent Power Source Management” focuses on the design and implementation of a smart backup power system that ensures uninterrupted electricity supply by automatically switching between the main AC supply and an inverter during power interruptions. The primary **objective** of this project is to develop a reliable and intelligent renewable energy-based solution that integrates solar energy utilization, battery storage, and automated source management while providing real-time system monitoring through IoT technology. The **methodology** adopted in this work involves the use of a solar panel connected to an MPPT charge controller to achieve efficient and safe battery charging. An Arduino Uno is utilized for monitoring battery voltage, detecting the availability of the main supply, controlling relay-based power source selection, and displaying system parameters on an LCD. In the event of a power failure, the system detects the interruption, displays a power failure message, and automatically transfers the load to the inverter without manual intervention. The inverter circuit, operating independently in analog mode, converts stored DC energy from the battery into AC power to maintain continuous supply to the connected load. An ESP32 module is incorporated to provide IoT connectivity, enabling real-time remote monitoring of battery voltage, battery level, selected power source, and protection status through a cloud-based platform. The **novelty** of the proposed system lies in the integration of intelligent automatic switching, IoT-enabled remote supervision, and built-in protection mechanisms such as overcharging and deep discharge protection to enhance battery lifespan and overall system reliability. The **findings** of this study indicate that the system effectively achieves seamless transition between power sources during outages, significantly reduces switching delay, improves solar energy utilization efficiency through MPPT operation, and maintains battery health by preventing overcharging and deep discharge conditions under varying load scenarios. The system also demonstrates stable real-time data transmission through IoT, ensuring continuous monitoring and improved user control. Therefore, the developed system provides a dependable, efficient, and intelligent power backup solution suitable for residential and small-scale renewable energy applications.

Keywords:

Solar Inverter, IoT, MPPT, Arduino, ESP32, Automatic Switching, Battery Protection, Renewable Energy

1. Introduction

The increasing demand for reliable and uninterrupted power supply has become a significant concern in modern society due to rapid industrialization, urbanization, and the growing dependence on electrical and electronic systems. In many regions, especially in developing countries, power outages and voltage fluctuations are common issues that affect both residential and commercial sectors. These interruptions not only cause inconvenience but can also lead to damage to sensitive electronic equipment and disruption of critical operations. Therefore, the need for an efficient and intelligent backup power system has become essential. Traditional backup systems such as diesel generators and conventional inverters are widely used, but they come up with limitations including fuel dependency, high operational costs, environmental pollution, and lack of automation. As a result, there is a growing interest in developing sustainable and smart energy solutions that can ensure reliability while minimizing environmental impact[1], [2].

Renewable energy sources, particularly solar energy, have emerged as one of the most promising alternatives to conventional energy systems. Solar energy is abundant, clean, and sustainable, making it an ideal choice for meeting energy demands in an eco-friendly manner. With advancements in photovoltaic technology, solar panels have become more efficient and affordable, enabling their widespread adoption in residential and small-scale applications. Integrating solar energy with backup power systems allows for the storage of energy in batteries, which can be utilized during power outages. However, efficient utilization of solar energy requires proper energy management techniques to maximize power extraction and ensure optimal battery charging. This has led to the development of technologies such as Maximum Power Point Tracking (MPPT), which enhances the efficiency of solar energy systems by continuously adjusting the operating point of the solar panel[3], [4].

In addition to renewable energy integration, the concept of automation plays a crucial role in modern power management systems. Manual switching between different power sources during outages is not only inconvenient but also prone to delays and human error. Automatic transfer systems address this issue by detecting the availability of the main supply and switching to an alternative source, such as an inverter, without human intervention. This ensures seamless power continuity and improves system reliability. The use of microcontrollers, such as Arduino, enables precise control and monitoring of system parameters, allowing for intelligent decision-making and efficient operation. By incorporating sensors and controlling logic, the system can dynamically respond to changing conditions and optimize performance[5], [6].

The advancement of the Internet of Things (IoT) has further revolutionized the way power systems are monitored and managed. IoT technology enables real-time data collection, remote monitoring, and control of devices through internet connectivity. In the context of power systems, IoT allows users to monitor parameters such as battery voltage, charge level, power source status, and system performance from anywhere in the world. This not only enhances user convenience but also improves system maintenance by providing timely alerts and diagnostics. The integration of IoT with power backup systems adds a layer of intelligence, making them smarter and more efficient compared to conventional systems[7], [8].

Battery storage is a critical component of any backup power system, as it stores energy for use during power outages. The performance and lifespan of the battery depend on proper charging and discharging practices. Overcharging and deep discharge can significantly reduce battery life and lead to system failure.

Therefore, implementing battery protection mechanisms is essential to ensure safe and reliable operation. Modern systems incorporate features such as voltage monitoring, charge control, and load management to prevent damage and optimize battery performance. The use of MPPT charge controllers further enhances battery efficiency by ensuring that the maximum available power from the solar panel is utilized for charging[9], [10].

The inverter plays a vital role in converting the stored DC energy into AC power suitable for running household appliances. Inverter circuits can be designed using various topologies, ranging from simple square wave inverters to more advanced sine wave inverters. In this project, the inverter operates in analog mode, ensuring continuous power supply without relying on microcontroller intervention. This separation of control and power circuits enhances system reliability and reduces complexity. The inverter ensures that the load receives a stable AC output during power outages, maintaining uninterrupted operation of connected devices[11], [12].

An important aspect of modern power systems is the integration of intelligent control mechanisms that can manage multiple energy sources efficiently. Intelligent power source management involves selecting the most appropriate power source based on availability and system conditions. For instance, when the main AC supply is available, the system should prioritize it while simultaneously charging the battery using solar energy. During a power outage, the system should automatically switch to the inverter without delay. Such intelligent switching not only ensures continuity of power supply but also optimizes energy usage and reduces dependency on non-renewable sources[13], [14].

The implementation of this project involves the use of an Arduino Uno microcontroller for system control and monitoring. The Arduino continuously checks the status of the main supply and battery voltage, controls the relay for source switching, and updates system information on an LCD display. An ESP32 module is used to provide IoT connectivity, enabling real-time monitoring through a cloud platform. The combination of Arduino and ESP32 offers a powerful and flexible solution for building intelligent energy systems. The hardware components are integrated in a way that ensures efficient operation, ease of implementation, and scalability for future enhancements[15], [16].

Despite the advancements in power backup systems, several existing solutions still face limitations. Many traditional systems lack proper integration of renewable energy sources, resulting in inefficient energy utilization. Automatic switching mechanisms in conventional systems may not be fast or reliable enough to prevent power interruptions. Additionally, the absence of real-time monitoring makes it difficult for users to track system performance and detect faults. Battery management is often inadequate, leading to reduced lifespan and increased maintenance costs. Furthermore, most systems do not incorporate IoT technology, limiting their ability to provide remote access and intelligent control. These gaps highlight the need for a more advanced and integrated solution that combines renewable energy, automation, and IoT capabilities[17], [18].

The proposed system addresses these challenges by integrating solar energy with intelligent power source management and IoT-based monitoring. The benefits of this approach include improved energy efficiency through MPPT-based solar charging, seamless automatic switching between power sources, and enhanced battery protection mechanisms. The inclusion of IoT enables real-time monitoring and remote control,

providing users with greater visibility and convenience. The system reduces dependency on conventional power sources, promotes the use of renewable energy, and contributes to environmental sustainability. Additionally, the modular design allows for easy expansion and customization based on user requirements. Overall, the proposed work offers a reliable, efficient, and intelligent solution for modern power backup needs, making it suitable for residential and small-scale applications[19], [20].

2. Methodology

The system integrates a solar panel, MPPT charge controller, battery, inverter, and control unit to ensure continuous power supply. The solar panel generates energy, which is optimized by the MPPT controller and used to charge the battery. An Arduino Uno monitors battery voltage and the availability of the main supply and controls a relay for automatic source switching. When the main supply is present, the load is powered directly and the battery charges; during power failure, the system instantly switches to the inverter. The inverter converts DC from the battery into AC for the load. An ESP32 module enables IoT-based real-time monitoring of system parameters through a cloud platform.

2.1 Working

a) Main mode:

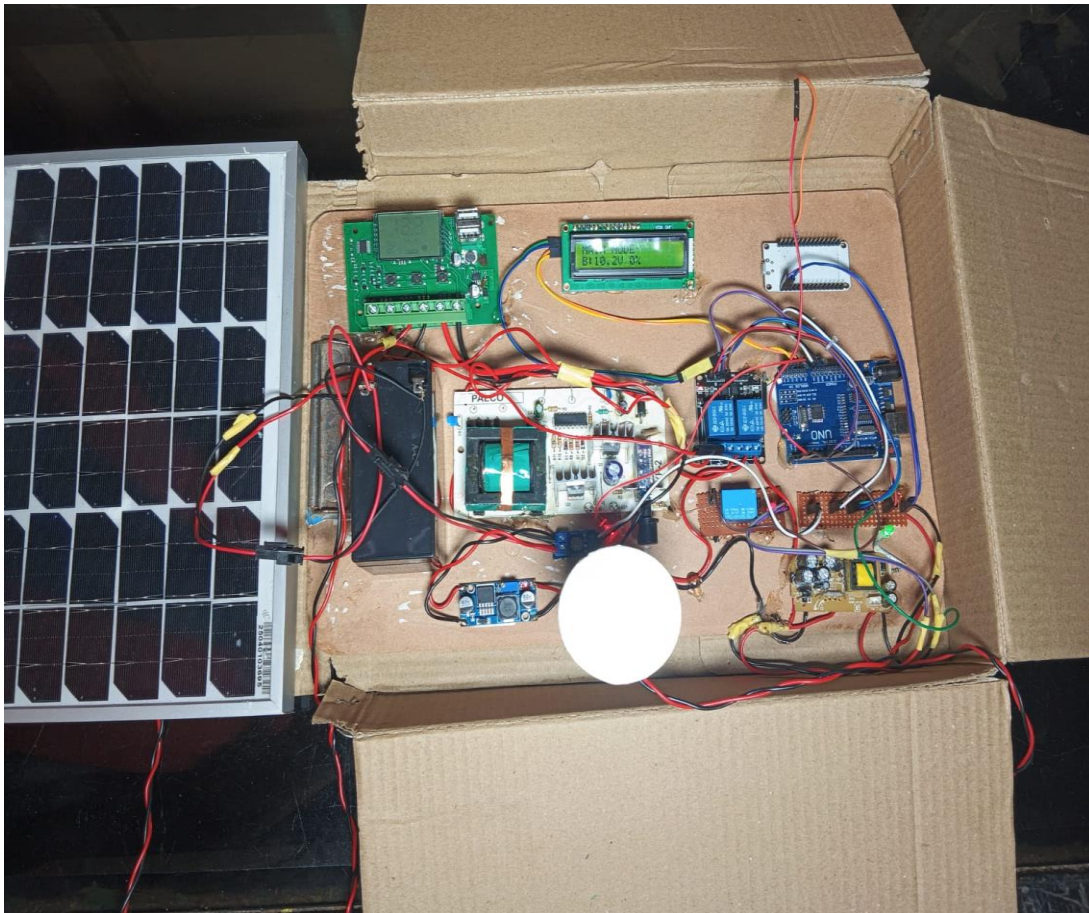


Fig 1. Main mode

Figure 1 illustrates the operation of the proposed system under normal conditions when the main AC supply is available, and the system functions in what is referred to as the main power mode. In this mode, the electrical load is directly powered by the grid supply through a relay-based switching mechanism, which is controlled by the Arduino Uno microcontroller. The system continuously monitors the availability of the AC supply using sensing circuitry, and as long as the supply remains stable, the relay maintains its default position, ensuring that the load is connected to the main power source. At the same time, the solar panel plays a significant role in energy generation by converting sunlight into electrical energy, which is then fed into the MPPT charge controller. The MPPT (Maximum Power Point Tracking) algorithm ensures that the solar panel operates at its optimal efficiency regardless of environmental conditions such as varying sunlight intensity and temperature. The regulated output from the MPPT controller is used to charge the battery efficiently while preventing overcharging through controlled voltage and current regulation. The battery, therefore, remains in a fully charged or optimal condition, ready to provide backup power during interruptions. The Arduino Uno monitors key parameters such as battery voltage, charging current, and system status, and displays this information on the LCD screen in real time, allowing the user to have direct visual feedback about system performance.

In addition to local monitoring and control, the system integrates IoT capabilities through the ESP32 module, which enables seamless communication between the hardware system and a cloud-based platform. During the main power mode, the ESP32 continuously transmits real-time data such as battery voltage levels, battery percentage, and current operating mode to the IoT dashboard, as shown in the monitoring interface. This allows users to remotely observe system behavior from anywhere using a smartphone or computer, enhancing convenience and control. The inverter circuit remains inactive in this mode, thereby conserving energy and reducing unnecessary power conversion losses. Furthermore, protective mechanisms such as overcharging protection are actively enforced to ensure battery longevity and system safety. The coordination between solar energy harvesting, battery management, and intelligent control ensures that energy is utilized efficiently while maintaining system reliability. This mode highlights the system's ability to prioritize grid supply while simultaneously optimizing renewable energy usage, thereby reducing dependency on conventional power sources and improving overall energy efficiency. The seamless integration of hardware and IoT technology ensures that the system operates in a stable, efficient, and user-friendly manner under normal operating conditions.

b) Inverter mode

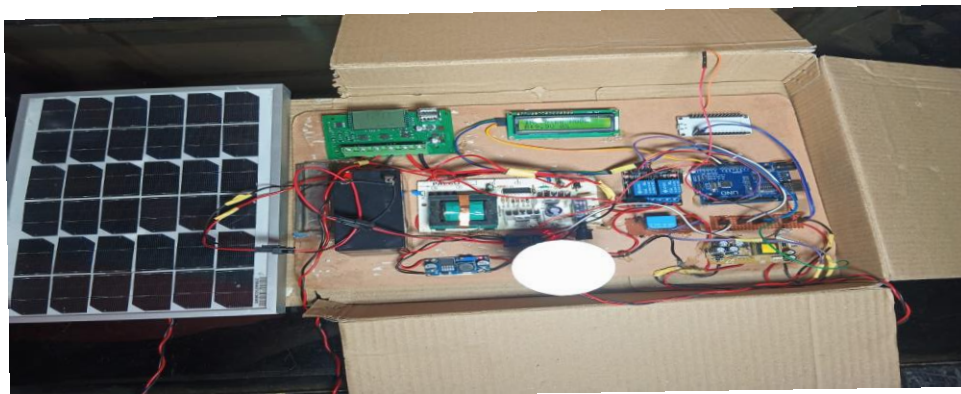


Fig 2. Inverter mode

Figure 2 represents the operation of the system during a power outage, where the main AC supply becomes unavailable and the system automatically switches to inverter mode. In this condition, the Arduino Uno continuously monitors the presence of the main supply, and upon detecting a failure, it triggers the relay module to change its position, disconnecting the load from the grid and connecting it to the inverter output. This transition occurs rapidly, ensuring minimal interruption to the connected devices and maintaining continuity of power supply. The battery, which was charged during the main power mode through the solar panel and MPPT charge controller, now becomes the primary source of energy. The stored DC energy in the battery is fed into the inverter circuit, which converts it into AC power suitable for running household appliances or low-power loads. The inverter circuit is designed using analog components, allowing it to operate independently of the microcontroller for power conversion, thereby enhancing system reliability even in case of microcontroller failure. The LCD display updates immediately to indicate the power failure condition and provides real-time information about battery voltage and discharge status, enabling users to understand the current state of the system.

During inverter mode, the system also incorporates intelligent battery management and protection mechanisms to ensure safe and efficient operation. As the battery discharges to supply power, the Arduino Uno continuously monitors its voltage level to prevent deep discharge, which can significantly reduce battery lifespan. If the battery voltage drops below a predefined threshold, the system can trigger protective actions such as load disconnection or alert notifications. Meanwhile, the ESP32 module continues to provide IoT connectivity, transmitting real-time data to the cloud platform, including battery status, inverter operation, and power source changes. This allows users to remotely track system performance even during power outages, ensuring transparency and improved control. The integration of automatic switching, inverter functionality, and IoT monitoring demonstrates the system's capability to provide an uninterrupted and intelligent power supply solution. This mode emphasizes the reliability and responsiveness of the system in handling power interruptions while maintaining user awareness and system safety through continuous monitoring and protection features.

c) IoT real-time monitoring



Fig3. IoT real time monitoring

Figure 3 presents the IoT-based real-time monitoring interface of the proposed solar inverter system, implemented using a cloud platform. The displayed graphs represent critical system parameters such as battery voltage, battery percentage, and power mode status over time. The ESP32 module acts as the communication bridge between the hardware system and the cloud server, collecting data from the Arduino Uno and transmitting it via Wi-Fi. The battery voltage graph shows variations in voltage levels over different time intervals, reflecting charging and discharging cycles based on system operation. Similarly, the battery percentage graph provides a clear visualization of the battery's state of charge, enabling users to understand how efficiently the solar energy is being stored and utilized. The power mode graph indicates whether the system is operating in main power mode or inverter mode, allowing users to track transitions between power sources. These visual representations make it easier to analyze system performance, identify trends, and detect potential issues in real time. The IoT platform ensures that all data is updated continuously, providing accurate and up-to-date information to the user.

The integration of IoT technology significantly enhances the functionality and usability of the system by enabling remote monitoring and control. Users can access the system data from anywhere using a smartphone, tablet, or computer, eliminating the need for physical presence near the hardware setup. This is particularly beneficial in scenarios where the system is installed in remote or inaccessible locations. Additionally, the IoT platform can be configured to generate alerts or notifications in case of abnormal conditions such as low battery voltage, power failure, or system faults, thereby improving system reliability and user awareness. The real-time data transmission also facilitates performance analysis and optimization, allowing users to make informed decisions regarding energy usage and system maintenance. By integrating IoT capabilities with intelligent power management, the proposed system not only ensures uninterrupted power supply but also provides a smart and interactive user experience. This combination of automation, monitoring, and data visualization represents a significant advancement in modern renewable energy systems, making the solution highly efficient, reliable, and suitable for practical applications in residential and small-scale energy systems.

2.2 Operation

The operation of the “IoT-Based Solar Inverter with Intelligent Power Source Management” system is centered on ensuring a continuous and reliable power supply by intelligently managing multiple energy sources, namely the main AC supply and the solar-powered inverter system. The block diagram illustrates the overall structure, where the system integrates sensing, control, power conversion, and communication modules. The operation begins with the availability of the main power supply, which is fed into a transformer and rectifier unit. This unit steps down the voltage and converts the AC supply into a suitable DC level required for control circuits. The processed power is then supplied to the Arduino Uno, which acts as the central controller of the system. Simultaneously, the main power supply is also monitored using a voltage sensor that continuously checks its availability and condition. The Arduino receives this sensed data and determines whether the main supply is present or not, forming the basis for intelligent switching decisions.

During normal operating conditions, when the main AC supply is available, the system prioritizes this source to power the load. The Arduino processes input from the main voltage sensor and keeps the relay in a position that connects the load directly to the main supply. At the same time, the solar panel generates

energy, which is passed through the MPPT charge controller to ensure maximum power extraction. The MPPT optimizes the voltage and current levels to charge the battery efficiently without losses. The battery stores this energy for later use during power outages. A separate voltage sensor continuously monitors the battery voltage and sends real-time data to the Arduino. The Arduino then displays this information on the LCD, such as battery voltage, charging status, and power source. Additionally, the ESP32 module transmits this data to a cloud platform, allowing users to monitor the system remotely through IoT.

When a power failure occurs, the system detects the absence of the main supply through the voltage sensor. This signal is immediately processed by the Arduino, which triggers the relay control mechanism to switch the load from the main supply to the inverter. This switching process is designed to be fast and seamless, ensuring minimal disruption to the load. The inverter, which is powered by the battery, converts the stored DC energy into AC power suitable for operating electrical appliances. The inverter operates independently in analog mode, ensuring that it continues to function even if there are minor delays in the control system. Once the inverter is activated, the load continues to receive power without noticeable interruption, demonstrating the system's ability to maintain continuity.

The battery plays a crucial role during inverter mode operation, as it serves as the primary energy source. The battery is charged using solar energy when sunlight is available, and it discharges when the inverter is supplying power to the load. The system includes protection mechanisms to prevent battery damage due to overcharging or deep discharge. The Arduino continuously monitors the battery voltage using the voltage sensor and compares it with predefined threshold values. If the battery voltage exceeds the safe charging limit, the system restricts further charging to avoid overcharging. Similarly, if the battery voltage drops below a critical level during discharge, the system can disconnect the load or provide an alert to prevent deep discharge. This intelligent battery management ensures longer battery life and improved system reliability.

The relay and controlling unit serve as the switching interface between different power sources. The relay receives control signals from the Arduino based on the availability of the main supply and the condition of the battery. It physically switches the load connection between the main supply and the inverter output. The relay operation is synchronized with the sensing and control logic to ensure smooth transitions. The use of relays provides electrical isolation between control and power circuits, enhancing safety and reliability. In addition to switching, the system may also incorporate current sensing at the load side, which helps in monitoring power consumption. This data can be used to analyze load behavior and optimize system performance.

The integration of IoT through the ESP32 module adds an advanced layer of functionality to the system. The ESP32 collects data from the Arduino, including battery voltage, load status, power source selection, and protection conditions. This data is transmitted to a cloud platform, where it can be accessed by the user in real time. Users can monitor system performance, check battery levels, and receive alerts in case of faults or abnormal conditions. This remote monitoring capability enhances user convenience and enables proactive maintenance. For example, if the battery voltage drops significantly, the user can take action before the system shuts down. The IoT feature transforms the system from a conventional inverter into a smart energy management solution.

The overall operation of the system demonstrates a well-coordinated interaction between renewable energy generation, energy storage, intelligent control, and communication technologies. The system efficiently utilizes solar energy for charging, prioritizes the main supply when available, and seamlessly switches to the inverter during outages. The use of sensors ensures accurate monitoring, while the Arduino provides reliable control and decision-making. The inverter guarantees uninterrupted power supply, and the IoT module enables real-time monitoring and control. This integrated approach not only improves system efficiency and reliability but also promotes the use of renewable energy. As a result, the project successfully achieves its objective of providing an intelligent, automated, and sustainable power backup solution suitable for modern residential and small-scale applications.

2.3 Advantages

- **Uninterrupted Power Supply**
Provides continuous electricity by automatically switching between the main supply and inverter during power failures without delay.
- **Utilization of Solar Energy**
Uses solar power as a primary energy source, reducing dependence on conventional grid electricity.
- **Improved Energy Efficiency (MPPT)**
The MPPT charge controller ensures maximum power extraction from the solar panel, improving overall system efficiency.
- **Real-Time IoT Monitoring**
Enables live tracking of system parameters such as battery voltage, power mode, and status using ESP32 and a cloud platform.
- **Battery Protection Mechanism**
Prevents battery damage by implementing overcharging and deep discharge protection techniques.
- **Automatic Intelligent Switching**
Eliminates the need for manual intervention by automatically detecting power failure and switching sources.
- **Enhanced System Reliability**
Ensures stable and dependable operation under varying conditions through integrated control and protection features.
- **Remote Access and Control**
Allows users to monitor system performance from anywhere using mobile or web applications.
- **Reduced Electricity Costs**
Minimizes electricity bills by utilizing free and renewable solar energy for power generation.
- **Eco-Friendly Operation**
Reduces carbon emissions and environmental impact by promoting clean energy usage.
- **Modular and Scalable Design**
The system can be easily expanded or upgraded with additional components as per requirement.
- **LCD-Based Local Display**
Provides instant on-site information about system status, battery level, and operating mode.

2.4 APPLICATIONS

- **Residential Homes**
Provides reliable backup power for households during power outages, ensuring uninterrupted daily activities.
- **Small Offices and Shops**
Maintains continuous power supply for essential equipment, reducing downtime and business interruptions.
- **Rural and Remote Areas**
Offers an effective solution in areas with unstable or limited grid access by utilizing solar energy.
- **Solar-Based Smart Homes**
Integrates with modern smart home systems for efficient energy management and automation.
- **Educational Institutions**
Useful for demonstration, research, and learning purposes in engineering and renewable energy projects.
- **Hospitals and Clinics**
Supports basic backup power for critical devices during emergencies or power failures.
- **Telecom Systems**
Ensures uninterrupted power for communication infrastructure, improving network reliability.
- **Small-Scale Industrial Setups**
Helps manage power supply for low-power industrial operations and equipment.
- **Solar Street Lighting Systems**
Can be adapted for powering street lights using solar energy with battery backup.
- **IoT-Based Smart Energy Systems**
Enables real-time monitoring and intelligent control in modern energy management applications.

3. Conclusion

The “IoT-Based Solar Inverter with Intelligent Power Source Management” system successfully demonstrates an efficient and reliable solution for ensuring uninterrupted power supply by integrating renewable energy, intelligent control, and IoT technology. The project effectively combines solar energy generation, battery storage, and automatic power source switching to provide a continuous and stable power supply to the connected load. By utilizing a solar panel along with an MPPT charge controller, the system maximizes energy extraction and ensures efficient battery charging, thereby improving overall system performance. The implementation of the Arduino Uno as the central control unit enables accurate monitoring of system parameters such as battery voltage and main supply status, and based on these inputs, the system performs automatic switching between the main power supply and the inverter using a relay mechanism, eliminating the need for manual intervention and reducing switching delays. The inverter circuit ensures continuous operation by converting stored DC energy into usable AC power during power outages, while battery protection mechanisms such as overcharging and deep discharge prevention enhance battery lifespan and overall system reliability. A key feature of the project is the incorporation of IoT through the ESP32 module, which allows real-time monitoring of system parameters via a cloud

platform, providing users with remote access, improved control, and timely maintenance. The system also displays important parameters locally through an LCD, ensuring user awareness. Overall, the proposed system offers a smart, efficient, eco-friendly, and reliable power backup solution suitable for modern residential and small-scale applications while promoting the use of renewable energy.

4. Future Scope

The future scope of the “IoT-Based Solar Inverter with Intelligent Power Source Management” system can be further enhanced by integrating advanced technologies to improve performance and scalability. The system can be upgraded by incorporating artificial intelligence and machine learning algorithms for predictive analysis, enabling better energy management and fault detection. Integration with smart grid systems can allow dynamic power sharing and improved efficiency in large-scale applications. The use of higher-capacity batteries and more efficient inverter designs can support larger loads and industrial applications. Additionally, mobile application development can provide a more user-friendly interface for real-time monitoring and control. The system can also be expanded to include multiple renewable energy sources such as wind or hybrid systems. Implementing advanced communication protocols and data analytics can further improve system reliability, security, and performance, making it suitable for future smart energy infrastructures and sustainable development.

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