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SMART SOLAR EV CHARGING STATION ADAPTIVE CONTROL AND GRID POWER BALANCE FOR DC STABILITY

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Abstract:

The Smart Solar Electric Vehicle (EV) Charging Station with Adaptive Control and Grid Power Balancing provides an integrated approach to maximizing renewable solar energy utilization in modern EV charging systems. The design combines solar panels, voltage sensors, battery storage units, a bidirectional DC-DC converter, and a voltage source inverter to ensure stable DC voltage and efficient energy flow. Solar panels generate DC power that is continuously monitored to maintain appropriate charging conditions, while the bidirectional converter manages the flow of energy between the solar array, the storage battery, and the EV charging port. When solar generation exceeds immediate demand, surplus energy is stored for later use, improving overall system efficiency and reducing renewable energy wastage. The converter also regulates power delivered to the EV, ensuring that the vehicle battery receives stable voltage for safe and reliable charging. The system seamlessly shifts between direct solar charging and stored-energy operation based on real-time conditions. In addition, a voltage source inverter connects the station to the electrical grid, enabling excess renewable energy to be exported when onsite charging and storage needs are met. This grid interactive capability enhances power balancing, supports energy stability, and strengthens the integration of distributed renewable resources. Through adaptive control strategies and coordinated grid support, the system reduces dependence on conventional grid electricity, enhances operational flexibility, and promotes sustainable electric mobility. This concept offers a resilient, efficient, and environmentally responsible charging solution that supports long-term clean transportation development.

Key Words: Solar EV Charging, Adaptive Control, Bidirectional Converter, DC Voltage Stability, Grid Power Balancing, Renewable Energy Integration.

1. Introduction:

The rapid expansion of electric vehicle (EV) adoption across the world has increased the demand for charging infrastructure that is efficient, reliable, and environmentally sustainable. Traditional grid-based EV charging stations often contribute to peak load challenges, higher operational costs, and increased dependence on non-renewable energy sources. As global initiatives continue to emphasize carbon reduction and clean-energy integration, the incorporation of solar power into EV charging systems has emerged as a practical and forward-looking solution. However, effective integration requires advanced control mechanisms that can manage variable solar output, ensure voltage stability, and coordinate energy flow between multiple subsystems. Without such intelligent management, renewable-based charging stations may suffer from instability, energy imbalance, and reduced performance under fluctuating conditions. The Smart Solar EV Charging Station with Adaptive Control and Grid Power Balancing provides a comprehensive framework to address these challenges through an integrated renewable energy architecture. The system incorporates solar panels for primary energy generation, voltage sensors for continuous monitoring, an energy storage unit for buffering surplus power, a bidirectional DC-DC converter for adaptive energy transfer, and a voltage source inverter for grid interaction. Solar generated DC power is monitored in real time to maintain safe charging conditions while ensuring that the system responds efficiently to variations in sunlight and EV charging demand. When excess solar energy is available, it is stored in the battery through the bidirectional converter, enabling later use during low-generation periods. This improves energy utilization and reduces waste, enhancing the overall performance of the charging station. A key capability of the system is its grid-interactive operation, enabled by the voltage source inverter. The inverter exports excess renewable energy to the electrical grid when local charging and storage requirements are met, supporting broader grid stability and enabling effective power balancing. During periods of insufficient solar generation, the grid can also supply supplementary power, ensuring continuous operation. Adaptive control algorithms coordinate all subsystems by regulating voltage, managing power flow, and adjusting operating modes based on real-time conditions. These capabilities allow the station to operate efficiently in diverse environmental and load scenarios. Overall, the Smart Solar EV Charging Station represents a sustainable, resilient, and technologically advanced solution for the future of electric mobility. By combining renewable energy utilization, intelligent control, energy storage, and grid support, the system enhances charging efficiency, reduces dependence on conventional electricity, and supports long-term environmental and energy-efficiency goals.

2. Literature Review:

In the study titled "Solar-Based Smart EV Charging Station with Smart Battery Management System", V. Rama Ramalakshmi, R. Muniraj, K. J., and T. Jarin (2024) present the design and development of a solar-powered electric vehicle (EV) charging station integrated with an intelligent battery management system (BMS). The authors emphasize the increasing demand for renewable-powered EV infrastructure due to rising electricity consumption and EV adoption. The proposed system integrates solar photovoltaic (PV) generation with a smart BMS that continuously monitors battery parameters such as state of charge (SOC), temperature, and charge-discharge cycles. This enables efficient energy utilization while preventing battery degradation. Power electronic converters are employed to regulate voltage and control energy flow between PV panels, batteries, and EV loads. The system demonstrates improved adaptability to fluctuating solar irradiance and varying load conditions. Simulation and prototype results confirm enhanced charging efficiency, extended battery lifespan, and reliable system performance, making it a scalable solution for sustainable EV charging applications.

Similarly, in “Smart Electric Vehicle Charging Station Using Solar Power”, M. Ulagammai (2024) proposes a solar-based EV charging station aimed at reducing dependency on conventional grid electricity. The study presents a PV-integrated charging architecture capable of delivering stable DC power to EVs through regulated converters. The author highlights key challenges such as solar intermittency, shading effects, and unpredictable charging demand, and addresses them using techniques like Maximum Power Point Tracking (MPPT), voltage regulation, and controlled energy distribution. The integration of battery storage is also discussed as a means to stabilize energy supply and ensure uninterrupted charging during low irradiance conditions. The system incorporates safety mechanisms to prevent overcharging and thermal issues. Simulation results demonstrate improved efficiency and reliability, indicating that the proposed design is suitable for both rural and urban deployment with minimal infrastructure requirements.

In another important work, “Integration of EV Charging Station and On-Grid Solar PV for Power System Reliability Increasing”, T.-T. T. Dang, A.-T. Vu-Thi, Q.-V. Thai, and K.-P. Tran (2023) investigate the impact of integrating solar PV systems with grid-connected EV charging stations. The authors propose a coordinated energy management framework where solar generation, grid supply, and EV loads operate in a synchronized manner to improve system reliability. The study analyzes different operating scenarios, including peak charging demand and variable solar generation, and demonstrates how solar integration can reduce grid stress, improve voltage stability, and enhance power quality. Advanced power electronic converters ensure smooth transitions between energy sources. Simulation results show reduced transformer loading, improved voltage profiles, and enhanced reliability indices. The study concludes that such integrated systems are essential for supporting large-scale EV adoption while maintaining grid stability.

Furthermore, the paper titled “Investigating Cyber attacks Against Off-Grid Solar-Powered Electric Vehicle Charging Stations” by S. Yazdanipour, F. M. Arani, and A. A. Jahromi (2024) explores the cyber security challenges associated with off-grid solar EV charging infrastructure. The authors identify potential cyber threats such as data manipulation, unauthorized access, denial-of-service attacks, and sensor spoofing, which can significantly affect system performance and safety. The study proposes a cyber security assessment framework focusing on communication networks, control systems, and power electronic interfaces. Real-time anomaly detection techniques are discussed for identifying malicious activities using system parameters like voltage and current signals. Mitigation strategies, including encryption, secure communication protocols, and intrusion detection systems, are also presented. The research highlights the importance of incorporating cyber security measures in renewable energy systems to ensure reliable and safe operation. This work provides valuable insights into designing resilient and secure EV charging infrastructures.

3. Methodology:

3.1 Existing System:

Existing electric vehicle (EV) charging systems primarily rely on conventional grid connected infrastructure, where the majority of charging stations draw their power directly from the electrical grid without incorporating renewable energy sources. These systems often operate with fixed charging characteristics and lack the adaptability required to respond to fluctuations in energy demand, grid stability, or variable renewable generation. As a result, grid-dependent charging contributes significantly to peak load stress, voltage instability, and increased operational costs, especially during times of high EV usage. Additionally, conventional charging stations do not typically include mechanisms for storing excess energy or balancing power flow, leading to inefficiencies and limited system resilience. Solar-assisted EV charging systems have been introduced in some regions; however, most existing solar-based solutions still operate with minimal intelligence and limited integration. These systems usually rely on direct solar input combined with basic charge controllers, which are insufficient for maintaining consistent charging performance during variations in solar irradiance. Many of these setups lack bidirectional energy flow capabilities, preventing efficient storage of surplus solar energy or the controlled delivery of stored energy to EVs. As a result, energy utilization remains suboptimal, and renewable generation is often wasted during periods of excess solar output. Furthermore, most current systems lack meaningful interaction with the electrical grid beyond simple energy consumption. They typically do not support exporting excess solar energy, nor do they provide grid balancing or power quality.

3.2 Existing System Block Diagram:

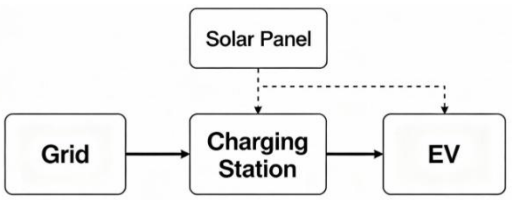


Figure 3: Existing System Black Diagram

3.3 Disadvantages:

- High dependence on the electrical grid for continuous EV charging.
- Inability to store surplus solar energy for later use.
- Lack of adaptive control for managing variable solar output.

- No bidirectional power flow capability between storage and EV.
- Absence of grid balancing or excess energy export functionality.

3.4 Proposed System:

The proposed system introduces an intelligent, renewable-driven charging architecture designed to overcome the limitations of traditional EV charging infrastructures. This Smart Solar EV Charging Station integrates solar energy generation, adaptive control mechanisms, energy storage management, and grid interaction into a unified and highly efficient platform. The system begins with solar panels that serve as the primary energy source, delivering DC power that is continuously monitored through voltage sensors to ensure stable and safe charging conditions for electric vehicles. Real-time monitoring enables immediate adjustments in power flow, allowing the system to respond effectively to fluctuations in solar irradiance and varying load demands. A bidirectional DC-DC converter serves as the core energy management component, facilitating controlled energy transfer between the solar panels, the energy storage unit, and the EV charging port. When solar power exceeds immediate charging requirements, the converter directs surplus energy into the battery storage system, ensuring optimal utilization of available renewable energy. During periods of reduced solar generation, the stored energy can be efficiently supplied to the EV, thus enhancing system reliability and reducing reliance on grid power. This dynamic energy flow not only maximizes renewable utilization but also contributes to consistent and stable charging performance. 10 The system further incorporates a voltage source inverter that enables effective interaction with the electrical grid. In situations where solar energy production exceeds both storage capacity and charging demand, the inverter exports excess energy to the grid, supporting grid stability and promoting sustainable energy distribution. Additionally, the grid can supply supplementary power when solar output is insufficient, ensuring uninterrupted charging functionality. Through its integrated adaptive control algorithms, the proposed system maintains stable voltage levels, balances power flow, and optimizes the operation of all interconnected components. This comprehensive design enhances efficiency, improves energy reliability, and supports the broader transition toward environmentally sustainable electric mobility.

3.5 Proposed Block Diagram:

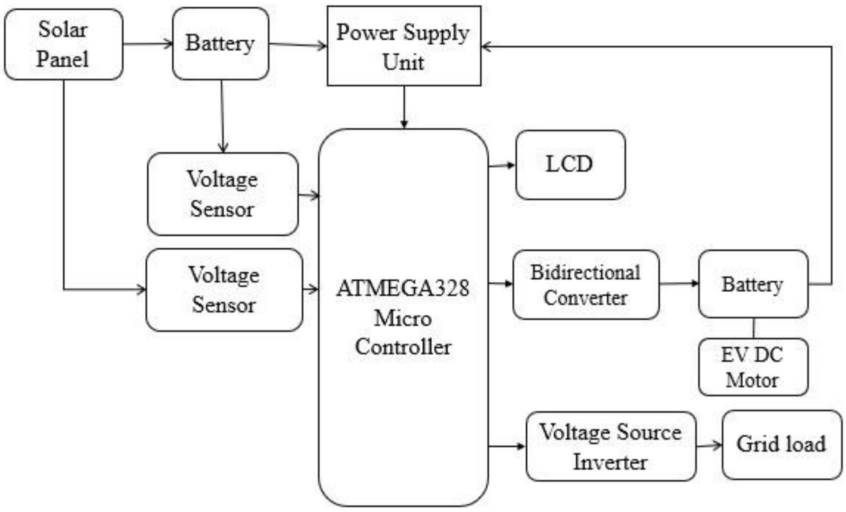


Figure 2: Proposed Block Diagram

4. System Implementation:

4.1 Arduino Ide:

The Arduino integrated development environment (IDE) is a cross-platform application (for Windows, macOS, Linux) that is written in the programming language Java. It is used to write and upload programs to Arduino board. The source code for the IDE is released under the GNU General Public License, version 2.

The Arduino IDE supports the languages C and C++ using special rules of code structuring.[4] The Arduino IDE supplies a software library from the Wiring project, which provides many common input and output procedures. User-written code only requires two basic functions, for starting the sketch and the main program loop, that are compiled and linked with a program stub main() into an executable cyclic executive program with the GNU tool chain, also included with the IDE distribution. The Arduino IDE employs the program argued to convert the executable code into a text file in hexadecimal encoding that is loaded into the Arduino board by a loader program in the board's firmware.

Arduino is an open-source electronics platform based on easy-to-use hardware and software. Arduino boards are able to read inputs - light on a sensor, a finger on a button, or a Twitter message - and turn it into an output - activating a motor, turning on an LED, publishing something online. You can tell your board what to do by sending a set of instructions to the microcontroller on the board

The Arduino IDE:

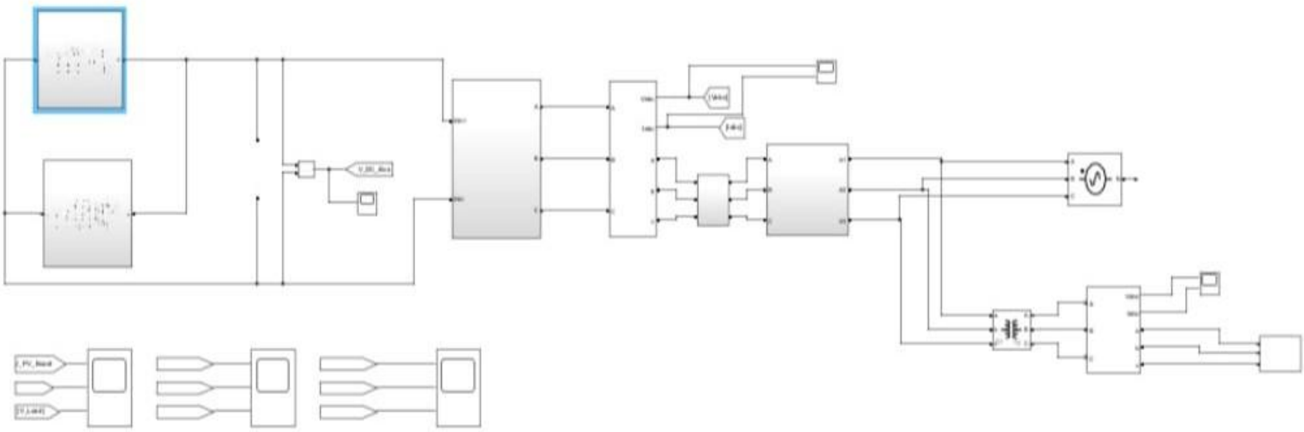
The Arduino IDE is incredibly minimalistic, yet it provides a near-complete environment for most Arduino-based projects. The top menu bar has the standard options, including “File” (new, load save, etc.), “Edit” (font, copy, paste, etc.), “Sketch” (for compiling and programming), “Tools” (useful options for testing projects), and “Help”. The middle section of the IDE is a simple text editor that where you can enter the program code. The bottom section of the IDE is dedicated to an output window that is used to see the status of the compilation, how much memory has been used, any errors that were found in the program, and various other useful messages.

Projects made using the Arduino are called sketches, and such sketches are usually written in a cut-down version of C++ (a number of C++ features are not included). Because programming a microcontroller is somewhat different from programming a computer, there are a number of devicespecific libraries (e.g., changing pin modes, output data on pins, reading analog values, and timers).

This sometimes confuses users who think Arduino is programmed in an "Arduino language." However, the Arduino is, in fact, programmed in C++. It just uses unique libraries for the device. The Arduino Integrated Development Environment - or Arduino Software (IDE) - contains a text editor for writing code, a message area, a text console, a toolbar with buttons for common functions and a series of menus. It connects to the Arduino and Genuine hardware to upload programs and communicate with them.

Programs written using Arduino Software (IDE) are called sketches. These sketches are written in the text editor and are saved with the file extension .ino. The editor has features for cutting/pasting and for searching/replacing text. The message area gives feedback while saving and exporting and also displays errors. The console displays text output by the Arduino Software (IDE), including complete error messages and other information. The bottom right hand corner of the window displays the configured board and serial port. The toolbar buttons allow you to verify and upload programs, create, open, and save sketches, And Open The Serial Monitor

Simulation Diagram:



Simulation Output:

Figure: DC Link voltage

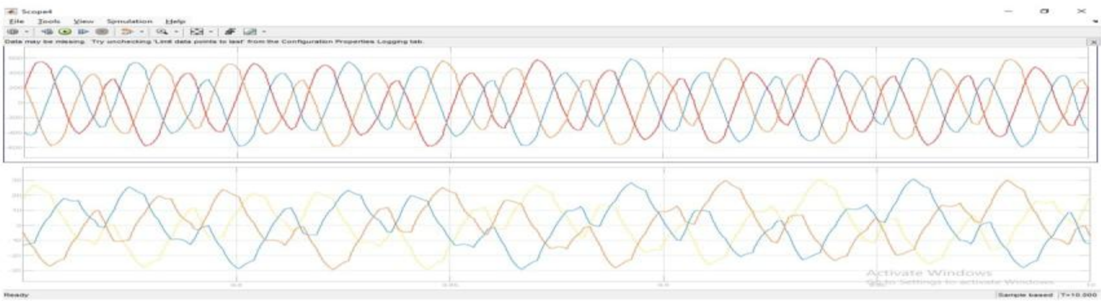
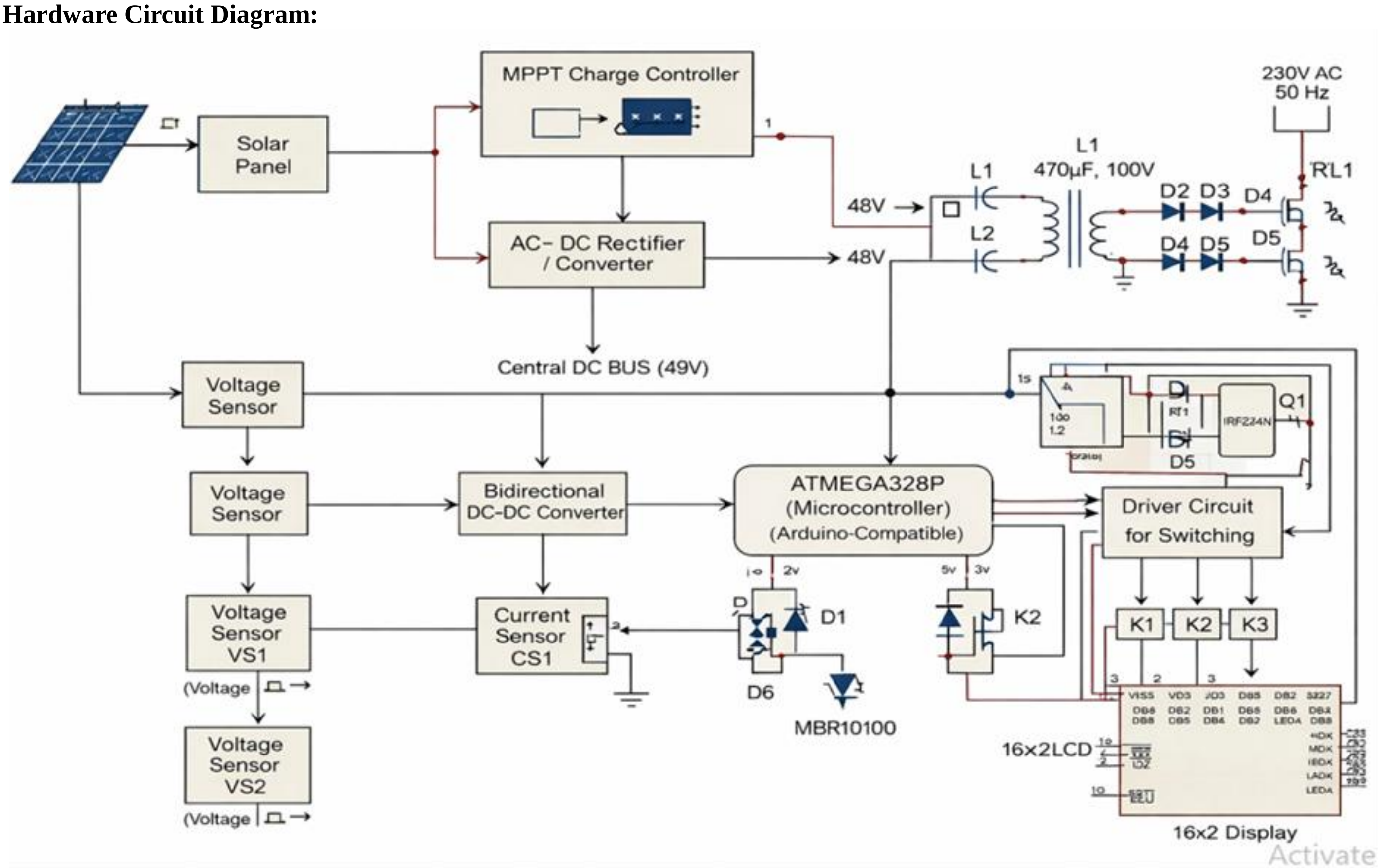


Figure: inverter voltage and current

5. Hardware Implementation:

Hardware Circuit Diagram:



- Solar Photovoltaic (PV) Panel: The solar photovoltaic panel is the primary renewable energy source used in the EV charging station. It converts solar radiation into DC electrical energy and supplies power to the charging system. The PV panel reduces dependency on conventional grid power and supports sustainable energy utilization.
- DC-DC Boost Converter: The DC-DC boost converter is used to increase and regulate the output voltage obtained from the solar PV panel. It maintains a constant DC bus voltage required for efficient EV charging and improves overall power conversion efficiency.
- Battery Energy Storage System (BESS): The battery storage system stores excess energy generated by the solar PV system and provides backup power during low solar irradiance conditions. It enhances system reliability and supports continuous charging operation.
- Adaptive Control Unit: The adaptive control unit acts as the main controller of the system. It continuously monitors solar power generation, battery condition, EV load demand, and grid power availability. Based on operating conditions, the controller manages power flow and maintains DC voltage stability.
- Voltage and Current Sensors: Voltage and current sensors are used for real-time measurement of system parameters. These sensors provide feedback signals to the controller for monitoring, protection, and adaptive power management operations.
- Grid Interface Unit: The grid interface unit connects the charging station to the utility grid. It supplies additional power during insufficient solar generation and supports grid power balancing to maintain stable operation.
- EV Charging Module: The EV charging module delivers regulated DC power to charge electric vehicles safely and efficiently. It includes charging control and protection mechanisms to prevent overcharging and electrical faults.
- Protection Circuit: The protection circuit safeguards the system against overvoltage, overcurrent, short circuits, and abnormal operating conditions. It improves system safety and reliability.
- Display and Monitoring System: The display unit provides real-time information such as PV voltage, battery status, charging current, and grid power usage. IoT-based monitoring can also be integrated for remote supervision and control.
- Power Management System: The power management system controls energy distribution between the solar PV panel, battery storage, utility grid, and EV charging load. It ensures efficient energy utilization and maintains DC voltage stability under varying load conditions.

6. Conclusion:

The conclusion of the Smart Solar EV Charging Station with Adaptive Control and Grid Power Balancing highlights the significance of integrating renewable energy, intelligent control mechanisms, and advanced power electronics to support future-ready electric mobility. The proposed concept demonstrates how solar generation, energy storage, bidirectional conversion, and grid interaction can function synergistically to provide a stable, efficient, and sustainable charging environment. By leveraging adaptive control strategies, the system ensures consistent voltage levels, optimized power flow, and real-time coordination among all subsystems, thereby enhancing overall performance and reliability. A key achievement of the system is its ability to maximize the use of renewable solar energy while reducing dependence on conventional grid electricity. Through the bidirectional DC-DC converter, surplus solar power is stored effectively for later use, ensuring continuous charging during periods of low irradiance. The voltage source inverter further strengthens the system by enabling export of excess energy to the grid, thus supporting grid stability and promoting efficient renewable integration.

7. Future Scope:

- Solar Photovoltaic (PV) Panel: The solar photovoltaic panel is the primary renewable energy source used in the EV charging station. It converts solar radiation into DC electrical energy and supplies power to the charging system. The PV panel reduces dependency on conventional grid power and supports sustainable energy utilization.
- DC-DC Boost Converter: The DC-DC boost converter is used to increase and regulate the output voltage obtained from the solar PV panel. It maintains a constant DC bus voltage required for efficient EV charging and improves overall power conversion efficiency.
- Battery Energy Storage System (BESS): The battery storage system stores excess energy generated by the solar PV system and provides backup power during low solar irradiance conditions. It enhances system reliability and supports continuous charging operation.
- Adaptive Control Unit: The adaptive control unit acts as the main controller of the system. It continuously monitors solar power generation, battery condition, EV load demand, and grid power availability. Based on operating conditions, the controller manages power flow and maintains DC voltage stability.

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