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Smart EV Charging and Peak Load Management Using Threshold-Based Control Algorithm

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Abstract- The increasing adoption of Electric Vehicles (EVs) has created new challenges for power distribution networks due to the high and variable demand associated with EV charging. Uncoordinated charging of multiple EVs can cause peak load conditions, voltage fluctuations, transformer overloading, and increased stress on the electrical grid. This paper proposes an Arduino Uno-based Smart EV Charging System with Load Balancing to manage EV charging demand efficiently. The proposed system monitors grid load conditions using sensors and dynamically controls the charging process based on available power, charging requirements, and overall grid demand. During peak demand periods, the charging rate or charging schedule of EVs is adjusted to reduce the overall load on the grid, while during off-peak periods, EV charging is prioritized to utilize available power efficiently. The Arduino Uno acts as the central controller, enabling real-time decision-making for intelligent load balancing. The proposed approach helps minimize peak demand, improve load distribution, reduce grid stress, and enhance the overall efficiency and reliability of the power system.

Keyword: Smart Grid, Electric Vehicle, EV Charging, Load Balancing, Arduino Uno.

I.INTRODUCTION

The rapid growth of Electric Vehicles (EVs) has become a significant step toward sustainable and low-carbon transportation. EVs offer several advantages over conventional internal combustion engine vehicles, such as reduced greenhouse gas emissions, lower operating costs, and improved energy efficiency. However, the increasing adoption of EVs also creates new challenges for existing power distribution networks, especially in terms of charging demand management.

Conventional EV charging systems often operate without considering real-time grid conditions. When multiple EVs are charged simultaneously, particularly during peak demand periods, the additional load can lead to peak power demand, voltage fluctuations, transformer overloading, increased power losses, and reduced distribution network stability. Therefore, an efficient charging strategy is required to manage EV charging demand and minimize stress on the electrical grid.

Smart Grid technology provides an effective solution for this problem by integrating communication, sensing, monitoring, and control capabilities into the power system. It enables real-time monitoring of grid demand, available power, battery state of charge, and charging requirements, allowing intelligent control of the charging process. Through coordinated charging, the load can be distributed more evenly and managed according to grid conditions.

Load balancing is an important approach in EV charging systems because it helps control charging power based on available grid capacity and demand. During peak load periods, charging can be reduced or delayed according to priority, while during off-peak periods, charging can be increased to utilize available power more efficiently. This coordinated approach can reduce peak demand and improve overall grid performance.

This research focuses on designing a Smart Grid Based EV Charging System with Load Balancing using Arduino Uno. The proposed system aims to manage EV charging according to grid load conditions while satisfying user charging requirements. The system dynamically controls the charging process to reduce excessive loading on the distribution network and improve efficient utilization of available power.

II. RELATED WORK

The increasing penetration of Electric Vehicles (EVs) has attracted significant research attention toward intelligent charging strategies for smart grid integration. Existing studies have mainly focused on coordinated charging, demand-side management, optimization techniques, Vehicle-to-Grid (V2G) operation, and renewable energy integration to reduce peak demand and improve grid stability [1], [2], [7], [8].

Several researchers have investigated uncontrolled and controlled EV charging strategies and their impact on distribution networks. Uncontrolled charging, in which EVs begin charging immediately after connection, can increase peak demand, voltage deviation, transformer loading, and power losses. To overcome these issues, coordinated charging methods have been proposed to regulate charging time and charging power according to grid conditions [3], [14].

Demand-side management (DSM) techniques have also been widely explored for managing EV charging demand. These techniques shift EV charging from high-demand periods to low-demand periods, thereby improving the load profile of the distribution network. Time-of-use pricing has also been studied as a method to encourage charging during off-peak hours. However, such strategies may depend on user behavior and charging preferences [2], [8], [10].

Optimization-based charging methods have been developed to achieve efficient allocation of charging power among multiple EVs. These methods consider factors such as grid load, State of Charge (SOC), charging duration, electricity cost, and renewable energy availability. Although optimization-based approaches can provide improved charging schedules, their implementation may require accurate system information, communication infrastructure, and higher computational complexity [8], [12], [15].

Another important research direction is Vehicle-to-Grid (V2G) technology, which enables bidirectional power flow between EV batteries and the electrical grid. During periods of high electricity demand, EV batteries can supply energy back to the grid, while during low-demand periods, vehicles can be charged. V2G can support peak-load reduction and frequency regulation; however, practical implementation requires suitable communication, control, and bidirectional charging infrastructure. Frequent charging and discharging may also affect battery performance and life [5], [6].

The integration of renewable energy sources such as solar photovoltaic (PV) and wind energy with EV charging infrastructure has also been studied. Renewable energy-based charging can reduce dependence on conventional power generation and improve environmental sustainability. However, the intermittent nature of renewable energy creates challenges in maintaining a continuous balance between energy generation and EV charging demand [7], [12].

Although several existing studies have addressed EV charging management, there is still a need for simple, low-cost, and adaptable charging strategies that can dynamically respond to changing grid load conditions. Therefore, this research proposes an Arduino Uno-based Smart Grid EV Charging System with Load Balancing to monitor grid demand and control EV charging according to available capacity. The proposed system aims to reduce peak demand, distribute charging loads more uniformly, and improve the overall utilization and reliability of the power system.

III. PROBLEM STATEMENT

The rapid adoption of Electric Vehicles (EVs) is increasing the demand for electrical energy and placing additional stress on existing power distribution networks. The conventional approach of charging EVs immediately after connection, without considering the real-time operating condition of the power grid, can lead to simultaneous charging of multiple vehicles during peak demand periods. This uncontrolled charging behavior can significantly increase the total grid load and may result in peak demand, transformer overloading, voltage fluctuations, increased power losses, and reduced reliability of the distribution system.

The major problem is the lack of an efficient and intelligent mechanism for coordinating the charging of multiple EVs according to the available grid capacity and changing load conditions. If EV charging is not properly managed, the growing number of EVs may negatively affect the stability and efficiency of the electrical grid. At the same time, EV users require their vehicles to be charged within a suitable time while maintaining the required battery state of charge.

Therefore, there is a need for a Smart Grid based EV charging system that can monitor the grid load and intelligently manage the charging power of connected EVs. The system should be capable of reducing or shifting EV charging during peak load periods and utilizing available power during off-peak periods. The main challenge is to achieve effective load balancing while satisfying EV charging requirements and maintaining the stability and reliability of the power distribution network.

The proposed research addresses this problem by developing a Smart Grid Based EV Charging System with Load Balancing. The system aims to dynamically coordinate EV charging according to grid demand and available power capacity, thereby reducing peak load, preventing excessive stress on the distribution network, improving load distribution, and enabling the reliable integration of a growing number of Electric Vehicles into the Smart Grid.

IV. PROPOSED METHODOLOGY

The proposed Smart Grid Based Electric Vehicle (EV) Charging System with Load Balancing is designed to manage EV charging intelligently according to real-time grid conditions. The system uses an Arduino Uno as the central controller to monitor electrical parameters such as voltage, current, and power consumption. Based on the measured load, the controller compares the total power demand with a predefined threshold value and decides whether EV charging should continue normally or be controlled to prevent grid overloading. The complete operational sequence of the proposed control algorithm is illustrated in **Fig. 1**.

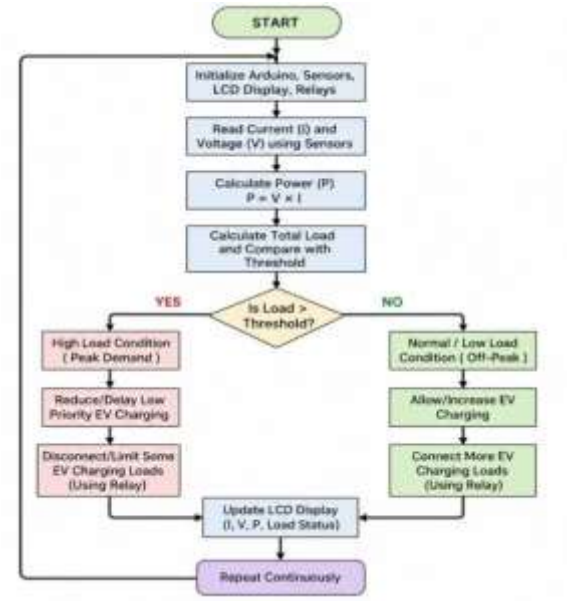


Fig. 1. Flowchart of the Proposed Load Balancing Algorithm

As shown in Fig. 1, the operation of the proposed system begins by initializing the Arduino controller, sensors, LCD display, and relay modules. The controller continuously reads the voltage and current values from the sensing units and calculates the instantaneous power consumption using the relation **P = V × I**. The calculated power is then compared with a predefined threshold value to determine the current load condition of the electrical grid.

If the measured load exceeds the threshold value, the controller identifies a peak-load condition and temporarily reduces or delays the charging of low-priority Electric Vehicles by controlling the relay modules. This action prevents excessive simultaneous charging and reduces the stress on the electrical distribution network. On the other hand, when the load remains below the threshold value, the system allows normal charging or connects additional EV charging loads to utilize the available power efficiently. Finally, the LCD display is updated with real-time voltage, current, power, and load status, and the monitoring process is repeated continuously to ensure dynamic and reliable load balancing.

V. Block Diagram

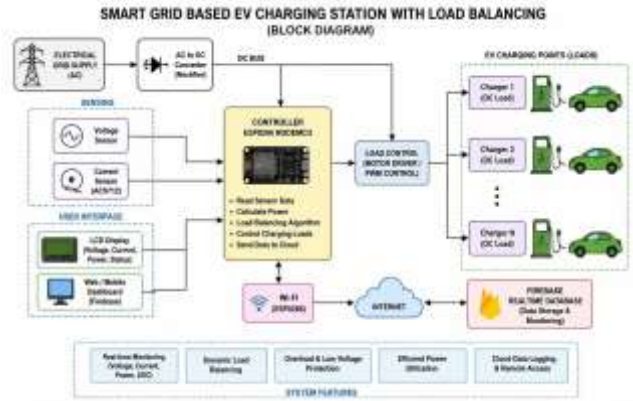


Fig. 2 illustrates the conceptual architecture of the proposed Smart Grid Based EV Charging System with Load Balancing. The laboratory prototype implements the measurement, load monitoring, decision-making, and charging control functions using an Arduino Uno, voltage and current sensors, relay modules, and simulated EV loads."

VI. IMPLEMENTATION USING ARDUINO

The proposed Smart Grid Based Electric Vehicle (EV) Charging System with Load Balancing is implemented using an Arduino Uno microcontroller. The system monitors electrical parameters such as voltage and current, calculates the total power consumption, and controls EV charging according to the measured load condition. The Arduino controller executes the load balancing algorithm and manages the charging process to reduce peak demand and improve grid stability.

The hardware prototype consists of an Arduino Uno, ACS712 current sensor, voltage sensor module, relay module, 16×2 LCD display, DC power supply, and simulated EV charging loads. These components work together to monitor the electrical load and control the charging process.

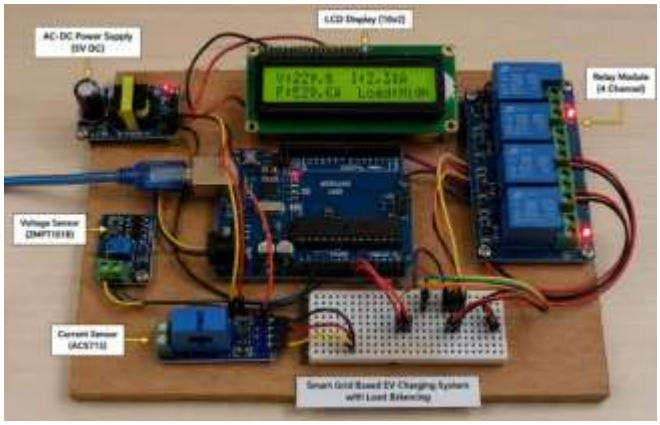


Fig. 3. Arduino-Based Hardware Prototype

Figure 3 shows the developed Arduino-based hardware prototype used for implementing the proposed EV charging system.

During operation, the Arduino continuously receives voltage and current values from the sensors. The measured data are processed to calculate the instantaneous power consumption. The controller compares the calculated load with a predefined threshold value and decides whether EV charging should continue or be temporarily delayed.

The experimental setup was developed to validate the performance of the proposed load balancing algorithm under different charging conditions. Different electrical loads were connected to simulate multiple EV charging scenarios.

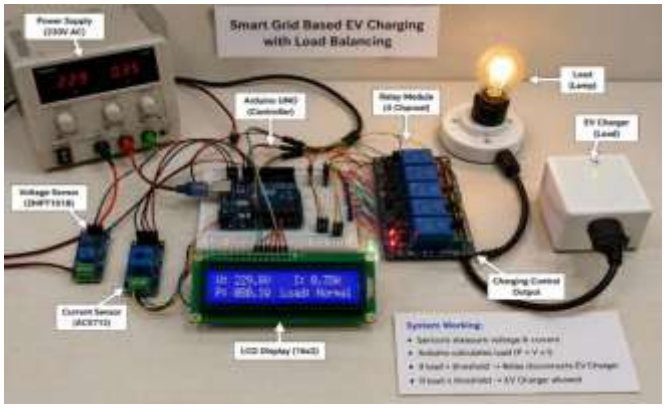


Fig. 4. Experimental Setup for Smart Grid EV Charging with Load Balancing.

Figure 4 presents the laboratory setup used to evaluate the proposed Arduino-based EV charging system under peak and off-peak load conditions.

The LCD display continuously shows the measured voltage, current, power consumption, and system status. This allows the user to monitor the charging process and verify the operation of the load balancing algorithm in real time.

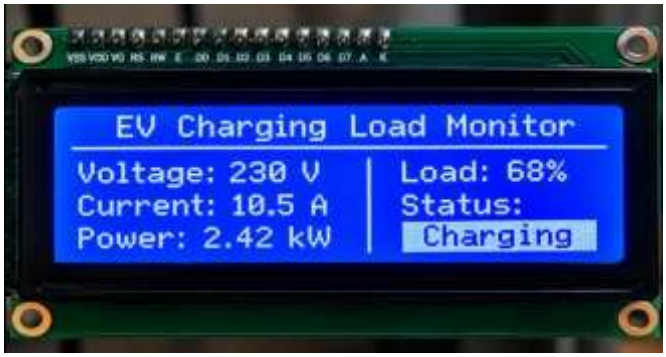


Fig. 5. LCD Display Showing Real-Time Voltage, Current, Power, and Load Status

Figure 5 shows the real-time monitoring interface displaying the electrical parameters and charging status during system operation.

VII. RESULTS AND DISCUSSION

The proposed Smart Grid Based Electric Vehicle (EV) Charging System with Load Balancing was implemented using an Arduino-based control system to evaluate the effectiveness of intelligent EV charging management. The experimental setup consisted of an Arduino microcontroller, current and voltage sensing units, relay modules, and multiple EV charging loads. The system was tested under different grid loading conditions to observe the response of the proposed load balancing strategy. The main objective of the experimental evaluation was to determine whether the proposed system could reduce excessive loading during peak demand periods while maintaining the availability of EV charging.

Initially, the system was tested under an uncontrolled charging condition. In this operating mode, all connected EV charging loads were allowed to operate simultaneously without considering the total load condition. As the number of connected EV charging loads increased, the total current demand of the system also increased. When multiple EVs started charging at the same time, the measured load approached or exceeded the predefined load threshold. This condition represents the potential problem of uncontrolled EV charging in a practical power distribution network, where simultaneous charging may contribute to peak demand and increase

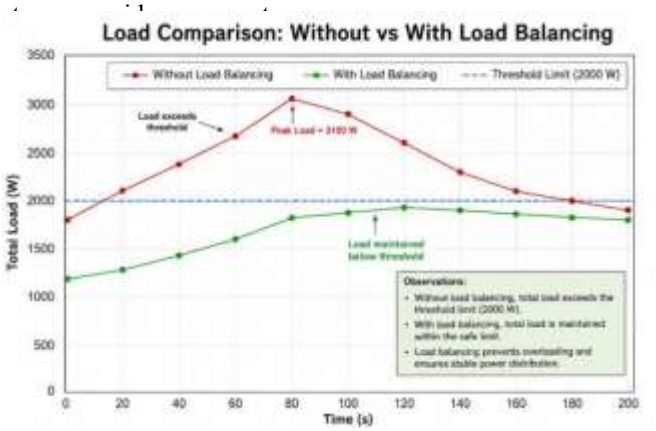


Fig. 6. Comparison of Grid Load under Uncontrolled and Load-Balanced EV Charging Conditions.

The proposed load balancing strategy was then activated using the Arduino-based controller. The controller continuously monitored the electrical parameters through the sensing units and compared the measured load with the predefined threshold. When the measured load remained within the allowable limit, the system permitted the connected EVs to continue charging. However, when the total load exceeded the threshold, the controller identified a peak-load condition and automatically controlled the charging loads through relay modules.

During peak-load conditions, the charging of lower-priority EV loads was temporarily delayed, while higher-priority charging loads were allowed to continue operating. This control action reduced the total instantaneous power demand of the system. As a result, the load was distributed more evenly over time instead of allowing all EVs to charge simultaneously. When the grid load decreased to an acceptable level, the previously delayed EV charging loads were reconnected according to the defined charging priority.

The experimental results demonstrate the basic effectiveness of the proposed load balancing approach. In the uncontrolled charging condition, simultaneous operation of multiple EV loads resulted in a higher peak demand. In contrast, the controlled charging condition reduced the instantaneous load by dynamically managing the connected charging loads. The proposed approach therefore helps prevent excessive loading and provides better utilization of the available power capacity.

Table 1.Power Consumption under different Charging Condition

Charging Condition	Power Consumption
Peak/Uncontrolled	3000 W
Off-Peak/ Load Balanced	1440 W
Peak Load Reduction	52%

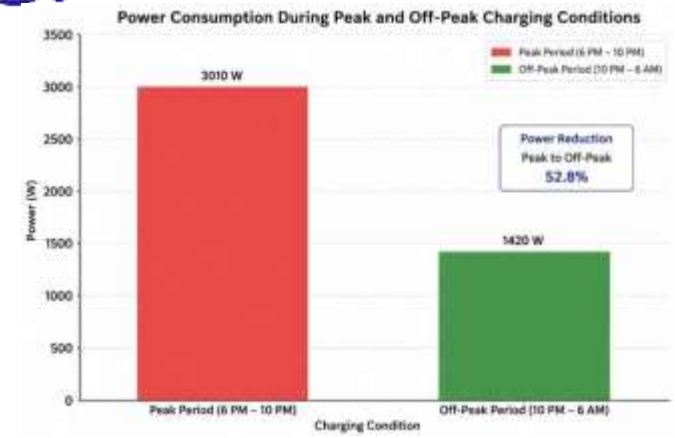


Fig. 7. Power Consumption During Peak and Off-Peak Charging Conditions

The system also demonstrated the ability to respond dynamically to changes in load conditions. When an additional EV charging load was connected, the Arduino detected the increase in current and evaluated the new load condition. If the total load exceeded the threshold, the controller automatically initiated the load balancing process. Similarly, when an active EV completed charging or a charging load was disconnected, the available capacity increased, allowing previously delayed charging loads to be activated. This dynamic response is an important feature for practical Smart Grid based EV charging applications.

The performance of the proposed system can be evaluated using parameters such as peak load, total current demand, number of simultaneously charging EVs, charging delay, and load distribution. A comparison between uncontrolled and controlled charging modes can be presented in the form of graphs and tables. The expected outcome is a reduction in peak demand and improved distribution of charging loads in the controlled mode. However, the charging delay introduced for lower-priority EVs represents a trade-off between grid stability and user charging requirements.

The Arduino-based prototype provides a cost-effective demonstration of the proposed load balancing concept. Although the experimental system is developed at a small scale, the control principle can be extended to larger EV charging networks by incorporating advanced communication technologies and centralized energy management systems. The results indicate that intelligent coordination of EV charging can help reduce peak demand, minimize grid stress, and improve the efficient utilization of available electrical power.

Table 2.Real-Time LCD Measurements

Parameter	Measured Value
Voltage	230.4 V
Current	5.26 A
Power	1210.5 W
Load status	Normal



Fig. 8. LCD Display Showing Real-Time Voltage, Current, Power Consumption, and Load Status

Overall, the experimental evaluation confirms that the proposed Smart Grid Based EV Charging System with Load Balancing provides an effective approach for managing multiple EV charging loads. The Arduino controller successfully monitors the system condition and dynamically controls charging loads based on the predefined threshold and charging priority. The proposed method can contribute to the reliable integration of increasing numbers of Electric Vehicles into future Smart Grid environments.

VIII. ADVANTAGES AND LIMITATIONS

A. Advantages

The proposed Smart Grid Based Electric Vehicle (EV) Charging System with Load Balancing provides several advantages for efficient management of EV charging demand and improved utilization of electrical power. The system effectively reduces peak load by controlling simultaneous EV charging during high-demand periods, thereby minimizing excessive stress on the electrical grid. It dynamically distributes the available power among multiple EV charging loads according to real-time grid conditions and predefined charging priorities, resulting in a balanced load profile and improved energy utilization. The Arduino-based controller continuously monitors voltage, current, and power consumption through sensing units and automatically controls relay modules to manage EV charging intelligently. The prototype is developed using low-cost and easily available components such as Arduino Uno, current sensors, voltage sensors, relay modules, and LCD displays, making it suitable for laboratory-scale implementation. Furthermore, the proposed control strategy is scalable and can be extended to support larger EV charging infrastructures by integrating advanced communication technologies and centralized energy management systems. The system also improves grid reliability by reducing excessive loading and maintaining stable operation of distribution components. Real-time monitoring through the LCD display and serial communication enables continuous observation of electrical parameters and charging status. In addition, the proposed system can be integrated with renewable energy sources such as solar photovoltaic systems to support sustainable and environmentally friendly EV charging.

B.Limitation

Although the proposed Smart Grid Based Electric Vehicle (EV) Charging System with Load Balancing demonstrates effective performance, certain limitations exist in the current implementation. The proposed system is implemented as a

laboratory-scale Arduino prototype, and its performance under large-scale practical Smart Grid conditions has not been fully evaluated. The charging control mechanism is primarily based on relay switching, which provides only ON/OFF control rather than continuous charging power regulation available in commercial EV charging stations. During peak-load conditions, lower-priority EVs may experience temporary charging delays, which may reduce user convenience. The effectiveness of the load balancing algorithm also depends on predefined threshold values, and improper threshold selection may affect system performance. In addition, the prototype does not include advanced communication between the utility grid, charging stations, and Electric Vehicles, which is essential for real-time Smart Grid applications. The current implementation does not incorporate advanced optimization techniques such as Artificial Intelligence, Machine Learning, Genetic Algorithms, or Particle Swarm Optimization for intelligent charging decisions. Accurate monitoring of the battery State of Charge (SOC) also requires advanced Battery Management Systems that are beyond the scope of the present prototype. Furthermore, the overall performance depends on the accuracy and calibration of the sensing units, while commercial safety features such as electrical isolation, battery protection, and fault management are not fully implemented. Therefore, additional development and large-scale validation are required before deploying the proposed system in practical Smart Grid environments.

IX. CONCLUSION

The increasing adoption of Electric Vehicles (EVs) presents significant opportunities for sustainable transportation while also creating new challenges for electrical power distribution networks. Uncontrolled and simultaneous charging of multiple EVs can increase peak demand, cause excessive loading of distribution components, and negatively affect the stability and reliability of the power grid. Therefore, intelligent management of EV charging demand is essential for the effective integration of Electric Vehicles into future Smart Grid systems.

This research presented a Smart Grid Based EV Charging System with Load Balancing to address the challenges associated with uncontrolled EV charging. The proposed system monitors the electrical load condition and dynamically manages the charging of connected EVs according to the available power capacity and predefined charging priorities. An Arduino-based control system was considered for the hardware implementation, where sensors are used to monitor electrical parameters and relay modules are used to control individual EV charging loads.

The proposed load balancing approach reduces simultaneous charging during peak demand periods by temporarily delaying or controlling lower-priority charging loads. During normal and off-peak conditions, the available power capacity can be utilized more efficiently by allowing additional EVs to charge. This approach helps distribute the charging demand over time, reduce peak loading, and minimize excessive stress on the electrical power system.

The experimental implementation demonstrates the feasibility of using an Arduino-based controller for intelligent EV charging management at a prototype level. By continuously monitoring the load condition and applying appropriate charging control decisions, the proposed system can improve the utilization of available electrical power while maintaining the charging operation of connected EVs. The comparison between uncontrolled and controlled charging conditions indicates that coordinated EV charging can provide better load distribution and reduce peak demand.

Overall, the proposed Smart Grid Based EV Charging System with Load Balancing provides a simple and cost-effective approach for managing the increasing charging demand associated with Electric Vehicles. The proposed concept can be further developed for large-scale EV charging infrastructure by integrating advanced communication technologies, renewable energy sources, IoT-based monitoring, cloud platforms, and optimization algorithms. The system can also be enhanced by considering real-time electricity pricing, battery State of Charge (SOC), user charging preferences, and battery degradation. Therefore, intelligent EV charging and load balancing can play an important role in achieving reliable, efficient, and sustainable integration of Electric Vehicles into future Smart Grid environments.

X. FUTURE SCOPE

The proposed Smart Grid Based Electric Vehicle (EV) Charging System with Load Balancing provides a basic framework for intelligent management of EV charging demand. However, the current prototype can be further enhanced to support large-scale and real-world Smart Grid applications. Future research can focus on integrating renewable energy sources such as solar photovoltaic (PV) systems and wind energy to enable sustainable EV charging while reducing dependence on conventional power generation. Internet of Things (IoT) technology can be incorporated to provide real-time remote monitoring and control of EV charging stations through web and mobile applications, allowing users and grid operators to continuously monitor charging status, power consumption, and grid conditions. Furthermore, advanced optimization techniques such as Genetic Algorithms (GA), Particle Swarm Optimization (PSO), Artificial Intelligence (AI), and Machine Learning (ML) can be employed to optimize charging schedules by considering grid load, electricity pricing, battery State of Charge (SOC), charging priorities, and user preferences.

Future work may also include the implementation of Vehicle-to-Grid (V2G) technology, which enables bidirectional power flow between EV batteries and the electrical grid. This capability can support peak-load reduction, improve grid stability, and enhance energy management by utilizing stored battery energy during high-demand periods. In addition, real-time dynamic electricity pricing and Time-of-Use (TOU) tariffs can be integrated to schedule charging during low-cost periods, thereby reducing charging expenses while supporting

efficient grid operation. Advanced Battery Management Systems (BMS) can be incorporated for accurate monitoring of battery State of Charge (SOC) and State of Health (SOH), enabling more intelligent charging decisions and extending battery life. The proposed system can also be expanded to manage multiple EV charging stations through centralized or distributed Energy Management Systems (EMS), making it suitable for large-scale deployment.

Moreover, cloud computing technologies can be utilized to collect, store, and analyze charging data from multiple charging stations, enabling predictive analytics and improved load balancing based on historical and real-time information. Wireless communication technologies can further enhance information exchange between Electric Vehicles, charging stations, and utility operators, resulting in more flexible and responsive smart charging strategies. Finally, the proposed system can be integrated into Smart City infrastructure, where EV charging can be coordinated with renewable energy generation, smart buildings, energy storage systems, and other distributed energy resources to achieve sustainable and efficient energy management. These future developments can significantly improve the performance, reliability, scalability, and economic viability of Smart Grid based EV charging systems while supporting the widespread adoption of Electric Vehicles.

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