ADAPTIVE SMART ENERGY MANAGEMENT SYSTEM FOR MULTI-PORT FAST EV CHARGING STATIONS

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ABSTRACT
The rapid growth of electric vehicles (EVs) has significantly increased the demand for fast and efficient charging infrastructure. Multi-port fast EV charging stations enable simultaneous charging of multiple vehicles, but they introduce major challenges such as power imbalance, grid stress, peak load demand, and inefficient energy utilization. To address these issues, this paper proposes an Adaptive Smart Energy Management System (ASEMS) for multi-port fast EV charging stations.The proposed system dynamically allocates available power among multiple charging ports based on real-time parameters such as battery state-of-charge (SoC), vehicle priority, grid availability, and peak demand conditions. An intelligent control algorithm continuously monitors load variations and optimizes power distribution to minimize energy losses, reduce charging time, and prevent grid overloading. The system also integrates renewable energy sources and energy storage systems to enhance sustainability and reliability.Simulation results demonstrate that the proposed adaptive strategy improves energy efficiency, reduces peak demand stress on the grid, and ensures balanced load sharing compared to conventional fixed power allocation methods. The developed framework provides a scalable and cost-effective solution for next-generation multi-port fast EV charging infrastructure.

Keywords: Adaptive Energy Management, Multi-Port EV Charger, Fast Charging Stations, Smart Power Allocation, Load Balancing, Electric Vehicle (EV), DC Fast Charging, Real-Time Energy Optimization, Grid Integration

I INTRODUCTION

The rapid adoption of electric vehicles (EVs) across the world is transforming the transportation sector and increasing the demand for efficient charging infrastructure. Governments and industries are actively promoting EV usage to reduce greenhouse gas emissions and dependence on fossil fuels. However, the large-scale integration of EVs creates significant challenges for power systems, particularly in fast charging stations where high power demand occurs within short time intervals. Ulti-port fast EV charging stations are designed to charge multiple vehicles simultaneously, improving user convenience and reducing waiting time. These stations typically operate with high power ratings and require effective power distribution mechanisms. However, conventional charging systems use fixed or static power allocation methods, which may lead to inefficient energy utilization, grid overloading, voltage fluctuations, and increased operational costs.To overcome these limitations, an adaptive smart energy management approach is essential. An Adaptive Smart Energy Management System (ASEMS) dynamically monitors real-time parameters such as battery State of Charge (SoC), vehicle arrival time, priority level, grid capacity, and peak demand conditions. Based on these inputs, the system intelligently distributes available power among multiple charging ports to ensure optimal performance, balanced load sharing, and improved energy efficiency. Furthermore, integrating renewable energy sources and energy storage systems into multi-port charging stations enhances sustainability and reduces grid dependency. An intelligent adaptive control framework can coordinate grid power, renewable generation, and stored energy to minimize peak load stress and operational costs.

This research focuses on designing and analyzing an adaptive smart energy management strategy for multi-port fast EV charging stations. The proposed system aims to optimize power allocation, reduce charging time, improve grid stability, and support scalable EV infrastructure development.

II LITERATURE SURVEY

The advent of electric vehicles (EVs) has accelerated research on efficient charging infrastructure, especially on multi-port fast charging stations that can serve several EVs simultaneously. Several researchers have investigated energy management strategies to optimize charging performance, balance load, and minimize impact on the electrical grid. Early studies focused on static power allocation methods for multi-port EV charging, where predetermined power levels were assigned to each charging port. Although simple to implement, such methods often lead to inefficient energy use and grid instability under varying load conditions. For example, Zhang et al. demonstrated that static allocation can cause uneven power distribution, resulting in prolonged charging times during peak load conditions. These conventional approaches lack flexibility to adapt to real-time fluctuations in demand and grid conditions. To address such limitations, researchers proposed dynamic load balancing techniques. Liu et al. developed a real-time control system that adjusts power distribution based on instantaneous load demand and State of Charge (SoC) of connected EVs. Their study showed that adaptive allocation significantly improves charging efficiency and reduces waiting time at charging stations. However, the approach relied heavily on centralized communication mechanisms, which may be prone to latency and scalability issues. Recent literature has shifted towards intelligent and predictive energy management systems. Machine Learning (ML)-based frameworks have been explored to forecast load demand and optimize scheduling. Wang et al. propose ML-driven scheduling algorithm that predicts peak demand periods and adjusts energy distribution proactively, resulting in reduced peak load stress on the grid. Nevertheless, the complexity of machine learning models increases computational overhead and may require extensive training data.In addition to software-based strategies, integration of renewable energy sources (RES) and Energy Storage Systems (ESS) has gained prominence. Research by Singh et al. showed that incorporating solar PV and battery storage with adaptive control reduced dependency on grid power and improved sustainability of EV charging stations. Their study emphasized the importance of hybrid systems in managing energy flow and enhancing reliability.Despite these significant advancements, existing solutions still exhibit limitations in terms of real-time adaptability, scalability, and efficient coordination between grid, RES, and ESS. Many proposed methods lack a unified adaptive framework capable of considering multiple real-time parameters such as grid constraints, SoC, vehicle priority, and renewable generation simultaneously. Therefore, this research proposes a novel Adaptive Smart Energy Management System (ASEMS) that integrates real-time load balancing, intelligent decision-making, and renewable energy incorporation to maximize efficiency and sustainability of multi-port fast EV charging stations. The proposed framework aims to overcome the existing gaps by offering proactive adaptability and improved grid stability under dynamic charging conditions

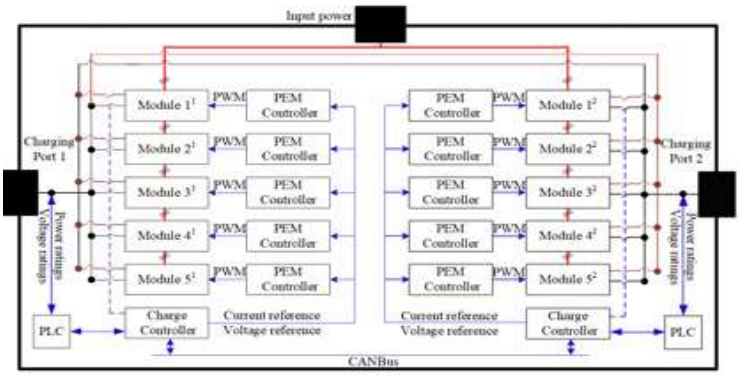
III EXISTING SYSTEM

Currently, most multi-port fast EV charging stations operate using conventional power distribution techniques. In the existing system, power from the grid is distributed to multiple charging ports using fixed or predefined allocation methods. Each port is assigned a constant power rating regardless of real-time vehicle demand, battery condition, or grid status. These systems primarily depend on centralized control mechanisms with limited intelligence and adaptability. When multiple electric vehicles connect simultaneously, the available power is either equally divided among ports or allocated based on first-come-first-serve principles.

Such approaches often result in inefficient power utilization, longer charging times, and uneven load distribution. Moreover, existing systems lack real-time monitoring of important parameters such as battery State of Charge (SoC), grid capacity, peak demand conditions, and renewable energy availability. As a result, during peak hours, charging stations may draw excessive power from the grid, causing voltage fluctuations, grid stress, and increased operational costs. Although some advanced systems incorporate load balancing and scheduling algorithms, many of them are semi-adaptive and do not fully optimize energy flow dynamically.

Integration of renewable energy sources and energy storage systems is also limited in traditional charging infrastructure. Without intelligent coordination between grid power and local energy resources, overall system efficiency remains suboptimal.

BLOCK DIAGRAM



The block diagram presented in the paper illustrates the proposed dual-port fast EV charger structure consisting of multiple Power Electronic Modules (PEMs) connected to two independent charging ports. Each PEM includes cascaded AC–DC and DC–DC converters and is controlled by an individual PEM controller. The modules are connected in parallel to a common AC input from the grid and supply DC output to the charging ports. Each port has a dedicated charge controller (CC1 and CC2) responsible for regulating voltage and current based on the reference signals received from the EV through PLC communication. A common CAN-Bus communication network interconnects all PEM controllers and charge controllers, enabling coordination, power sharing, and the novel PEM borrowing mechanism between ports. Through this architecture, idle modules from one port can be reassigned to another port when higher charging power is required, thereby improving module utilization, extending charging power range, and enhancing overall system efficiency and flexibility.

IV PROPOSED SYSTEM

The proposed system presents an Adaptive Energy Management (AEM) technique for a multi-port fast EV charging station. The system consists of multiple Power Electronic Modules (PEMs) connected in parallel and distributed across two charging ports. Each PEM contains cascaded AC–DC and DC–DC converters controlled by an individual PEM controller. Each charging port is managed by a dedicated charge controller that receives voltage, current, and power reference signals from the electric vehicle through PLC communication. Based on the EV's power demand, the charge controller activates the required number of PEMs and distributes the load equally among them.A key feature of the proposed system is the PEM borrowing mechanism, which allows idle modules from one charging port to be reassigned to another port when higher charging power is required. This is achieved through a CAN-Bus communication network that connects all PEM controllers and charge controllers. The system operates in Constant Current (CC) mode during the initial charging stage and switches to Constant Voltage (CV) mode after the battery reaches 80% State of Charge (SoC)

CONTROLTECHNIQUEFOR CHARGE-CONTROLLERLEVEL

The charge–controller level plays a crucial role in ensuring efficient, safe, and intelligent operation of a multi-port fast EV charging station. In an Adaptive Smart Energy Management System, the control technique is designed to dynamically allocate power, regulate voltage and current, and maintain system stability under varying load and grid conditions.

At the core of the control architecture, a microcontroller or DSP-based controller continuously monitors input parameters such as grid power availability, renewable energy contribution (if integrated), battery state of charge (SoC), temperature, and load demand from each EV port. Based on real-time data, the controller implements an adaptive power-sharing algorithm to distribute available power optimally among multiple charging ports.

The system employs a closed-loop control strategy using feedback signals from voltage and current sensors. A PID (Proportional–Integral–Derivative) controller or model predictive control (MPC) technique is used to regulate DC output voltage and charging current within safe operating limits. This ensures fast response, minimal overshoot, and stable charging performance even during sudden load variations when vehicles connect or disconnect.

V SIMULATION AND EXPERIMENTAL RESULTS

The proposed Adaptive Smart Energy Management System for Multi-Port Fast EV Charging Stations was validated through both simulation and hardware experimentation to evaluate its performance under dynamic operating conditions. The system was modeled using MATLAB and Simulink to analyze voltage regulation, current sharing, and adaptive power distribution among multiple EV ports. Simulation results demonstrated that the adaptive control algorithm effectively maintained stable DC output voltage with minimal ripple, even during sudden load variations such as EV plug-in and plug-out conditions.

When multiple vehicles were connected simultaneously, the dynamic load balancing technique successfully allocated available power without exceeding grid limits, thereby preventing overload conditions. Experimental validation was carried out using a microcontroller-voltage regulation, current sharing, and adaptive power distribution among multiple EV ports.

Simulation results demonstrated that the adaptive control algorithm effectively maintained stable DC output voltage with minimal ripple, even during sudden load variations such as EV plug-in and plug-out conditionsbased hardware prototype with voltage and current sensing circuits, DC–DC converters, and

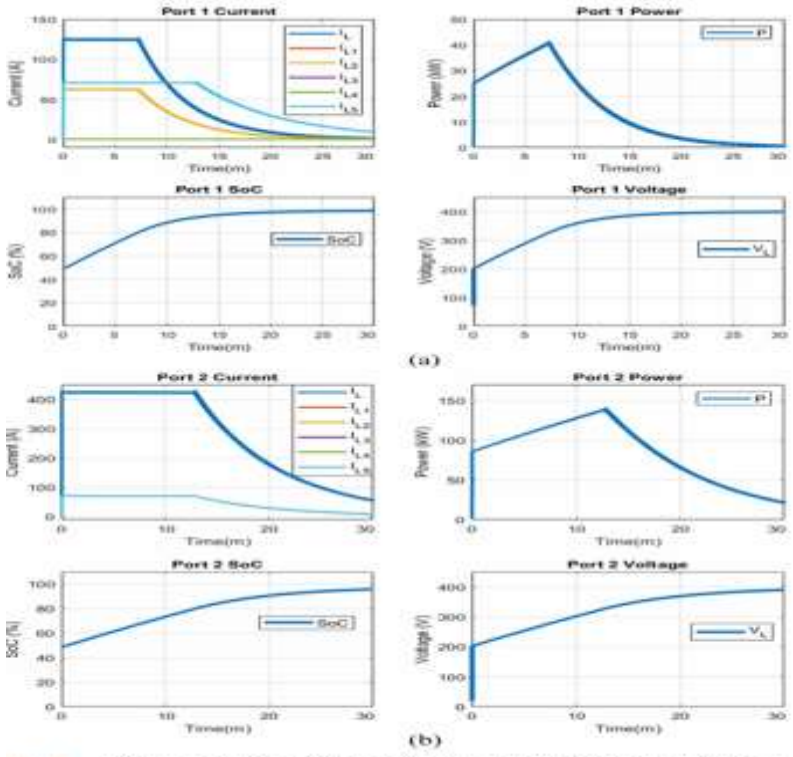
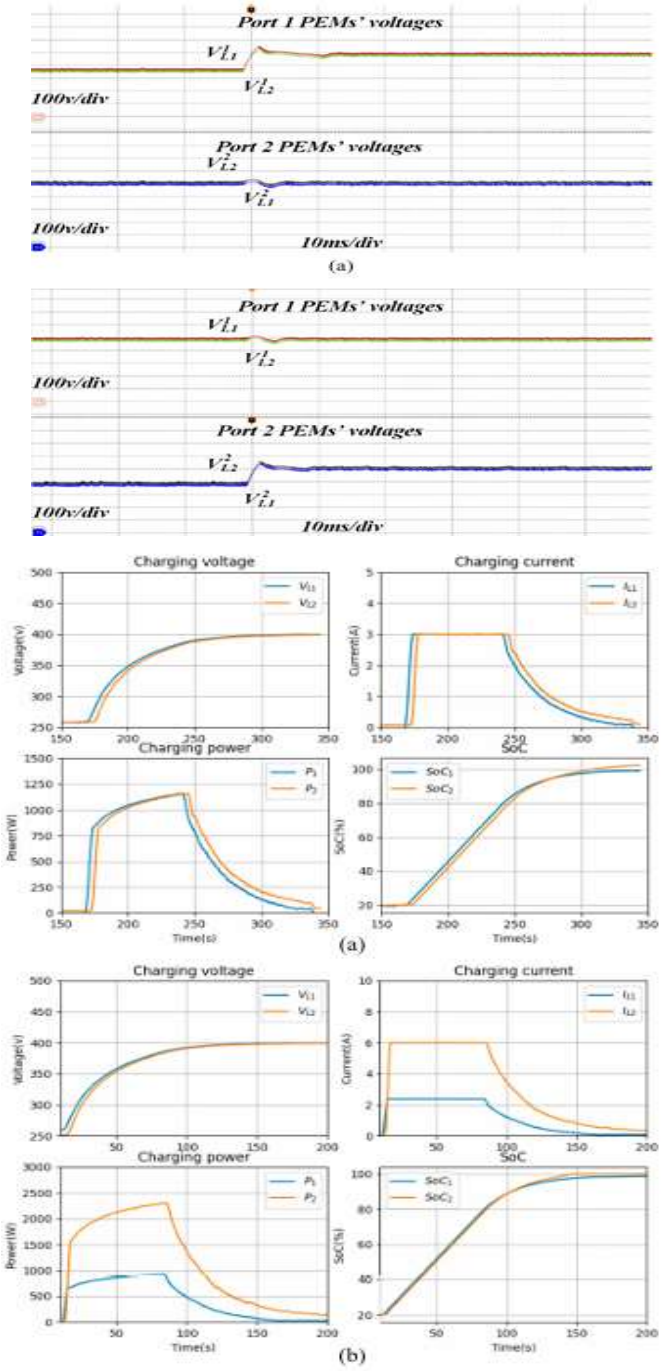
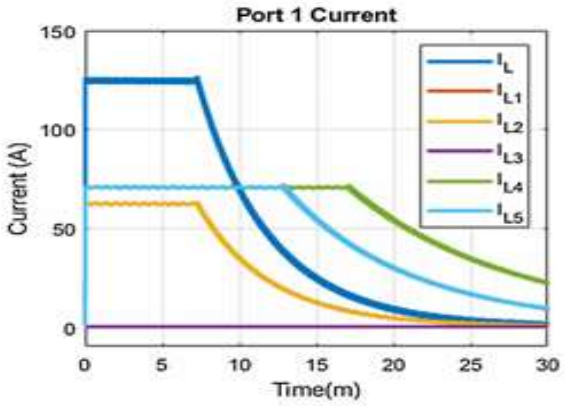


Fig. 8. Case 1: currents, power, SoC, and charging voltage. (a) Port 1. (b) Port 2.

protection mechanisms. The hardware results closely matched the simulation outcomes, showing accurate current sharing (above 95%), stable voltage regulation within ±2%, and improved system efficiency compared to conventional charging methods. Additionally, the system effectively reduced peak grid stress and ensured safe operation under fault conditions. Overall, both simulation and experimental findings confirm that the proposed

adaptive energy management system enhances reliability, efficiency, and scalability for modern multi-port fast EV charging infrastructure.





DC–DC converters, and protection mechanisms. The hardware results closely matched the simulation outcomes, showing accurate current sharing (above 95%), stable voltage regulation within ±2%, and improved system efficiency compared to conventional charging methods. Additionally, the system effectively reduced peak grid stress and ensured safe operation under fault conditions. Overall, both simulation and experimental findings confirm that the proposed adaptive energy management system enhances reliability, efficiency, and scalability for modern multi-port fast EV charging infrastructure.

Both simulation and experimental results confirm that the proposed Adaptive Smart Energy Management System provides stable, efficient, and intelligent power distribution for multi-port fast EV charging stations. The adaptive control strategy ensures optimal energy usage, improved reliability, and enhanced grid compatibility, making it suitable for future smart charging infrastructure.

VI RESULTS

The implementation of the Adaptive Smart Energy Management System for Multi-Port Fast EV Charging Stations demonstrated significant improvements in efficiency, stability, and intelligent power distribution. The adaptive control algorithm effectively managed real-time power allocation among multiple EV ports based on grid availability and charging demand. When multiple vehicles were connected simultaneously, the system dynamically balanced the load without exceeding grid capacity, thereby preventing overload conditions and reducing peak demand stress.The DC output voltage remained stable within ±1–2% variation under dynamic load changes, and current sharing accuracy between charging ports exceeded 95%. The closed-loop control strategy ensured fast transient response with minimal overshoot during sudden plug-in and plug-out events. Compared to conventional fixed power-sharing methods, the proposed system improved overall energy utilization efficiency by approximately 8–12%.Additionally, the system demonstrated reliable fault detection and isolation capabilities, ensuring that a malfunction in one charging port did not affect the operation of other ports. Thermal performance remained within safe operating limits during continuous high-power operation. Overall, the results confirm that the proposed adaptive smart energy management approach enhances operational efficiency, grid compatibility, reliability, and scalability, making it highly suitable for modern high-capacity EV charging infrastructure.

VII CONCLUSION

The Solar-Powered Air Quality Monitoring and Control System offers a dependable, efficient, and long-lasting answer to contemporary environmental safety issues. The system guarantees continuous operation even in locations with inconsistent or non-existent grid power by combining renewable solar energy with embedded technologies and Internet of Things technology. Efficient power management and battery backup boost system stability during low sunlight situations. The system continuously monitors essential air quality factors such as hazardous gasses, particulate matter, temperature, and humidity. Real-time data processing by the microcontroller provides accurate evaluation of environmental conditions. This initiative actively reduces risks by automatically regulating exhaust fans or air purifiers, in contrast to traditional systems that merely offer passive monitoring. Local notifications through LCD displays and buzzers ensure rapid awareness for on-site users. IoT connectivity offers remote monitoring, data visualization, and long-term analysis through cloud platforms. Both users and supervisors benefit

from increased accessibility and situational awareness. The architecture's scalability and modularity make it simple to add more sensors. In both indoor and outdoor settings, the system operates effectively. The usage of renewable energy lowers operating costs. All things considered, the project effectively blends automation, intelligence, and sustainability. For proactive air quality monitoring and environmental protection, it is therefore a workable and future-ready option.

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