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Enhancing EV Charging Performance with ANN-Controlled Solar/Wind Hybrid Systems

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Abstract*:* *Electric vehicles (EVs) are pivotal for sustainable transportation, yet their integration into the energy grid presents challenges in ensuring efficient and eco-friendly charging solutions. This study introduces an Artificial Neural Network (ANN)-controlled solar/wind hybrid power system to enhance EV charging performance. The proposed system integrates photovoltaic panels and wind turbines to harness renewable energy efficiently under varying environmental conditions. The ANN controller optimizes energy distribution between solar, wind, and storage systems, ensuring maximum power extraction and grid stability during peak demand. MATLAB simulations demonstrate significant improvements in charging efficiency and energy utilization compared to conventional methods. Results reveal that the hybrid system reduces dependency on the grid, minimizes carbon emissions, and enhances reliability for highway-based EV charging stations. This research establishes ANN-based control as a robust solution for scaling renewable energy integration in EV infrastructures, contributing to cleaner and more sustainable transportation networks.*

Keywords: Electric vehicle charging station, Buck converter, Boost converter, Solar, Wind

I. INTRODUCTION

The increasing adoption of EVs as a sustainable alternative to traditional internal combustion engine vehicles has necessitated advancements in charging infrastructure [1, 2]. As the global emphasis on reducing greenhouse gas emissions intensifies, renewable energy sources (RES), such as solar and wind, have emerged as promising solutions to meet the energy demands of EVs while minimizing environmental impact [3-6]. However, the inherent intermittency and variability of solar and wind energy pose significant challenges in ensuring stable and reliable power for EV charging stations, particularly along highways and remote areas [7, 8].

To address these challenges, hybrid RES combining solar photovoltaic (PV) and wind turbines have gained traction for their ability to provide a balanced energy output under varying weather conditions [9-11]. Such systems utilize solar energy during the daytime and wind energy during both day and night, thereby enhancing reliability [12, 13]. Additionally, energy storage systems play a crucial role in storing excess energy and supplying power during periods of low renewable energy generation [14-16].

Despite their potential, the performance of solar/wind hybrid systems largely depends on effective control strategies for energy management. Traditional control methods often fail to optimize the utilization of renewable resources, leading to inefficiencies in energy distribution and higher operational costs [17-19]. Recent advancements in artificial intelligence, particularly Artificial Neural Networks (ANNs), have demonstrated remarkable capabilities in optimizing nonlinear and complex systems. ANNs, with their ability to learn and adapt to dynamic scenarios, can effectively manage energy flow in hybrid systems, maximizing power output while maintaining grid stability [20-22].

This paper proposes an ANN-controlled solar/wind hybrid power system aimed at enhancing EV charging performance. By leveraging the predictive and adaptive capabilities of ANN, the system ensures efficient energy distribution between renewable sources, storage units, and the grid. MATLAB simulations validate the proposed system's performance,

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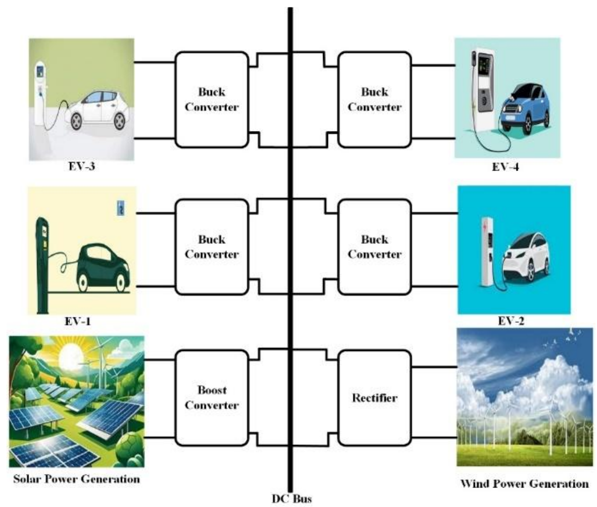
showcasing its superiority in terms of energy efficiency and charging reliability over conventional methods. This research contributes to the development of sustainable EV charging infrastructure by integrating intelligent control mechanisms into renewable energy systems, thus promoting a cleaner and greener transportation future.

The organization of the following paper contains: Section II provides a comprehensive system description. Section III introduces the proposed method, focusing on the implementation of the ANN controller for enhanced voltage regulation. In Section IV, the simulation results and discussions are presented, demonstrating a performance of proposed method. Finally, Section V concludes the paper with key findings and suggests avenues for future research.

II. SYSTEM DESCRIPTION



The proposed hybrid system integrates solar and wind energy sources to support EV charging, ensuring uninterrupted power availability and maximizing renewable energy utilization as shown in the fig.1. This system leverages the unique characteristics of each energy source, combining their strengths to meet the dynamic energy demands of EVs [23]. Solar energy is harvested through photovoltaic (PV) panels, and wind energy is generated using wind turbines, with both sources connected to a centralized DC bus through power converters. The system is designed to optimize extraction and conversion of energy from these sources, ensuring high efficiency and reliability [24]. By integrating these renewable energy technologies, the system minimizes grid dependency, reduces carbon emissions, and enhances the sustainability of EV charging stations.

A) Solar Power Generation

The solar power generation subsystem relies on photovoltaic (PV) panels to convert sunlight into electrical energy [25]. These panels operate under varying irradiance and temperature conditions, resulting in non-linear power output characteristics. To ensure maximum energy extraction, the system employs a boost converter controlled by a Perturb and Observe (P&O) Maximum Power Point Tracking (MPPT) algorithm [26]. The P&O MPPT continuously monitors voltage and current of PV panels to identify MPP, adjusting the boost converter's duty cycle accordingly. This mechanism compensates for variations in solar irradiance, such as those caused by shading, cloud cover, or time of day, thereby maintaining optimal power output. The boost converter interfaces the PV panels with the DC bus, stepping up the voltage as required for efficient integration with the hybrid system.

B) Wind Power Generation

The wind energy subsystem employs wind turbines to harness kinetic energy from moving air and convert it into electrical energy. The output of the wind turbine varies depending on wind speed and turbine characteristics. To achieve stable DC power suitable for EV charging, the alternating current (AC) output from the wind turbine is rectified using a diode bridge rectifier. The rectifier smooths fluctuating AC into a steady DC voltage, which is then fed into the

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DC bus. This design allows the wind energy subsystem to complement the solar PV system, particularly during periods of low solar irradiance. For instance, wind energy production typically increases during night-time or cloudy conditions, ensuring continuous power generation. This synergy between the two renewable sources enhances system reliability and performance.

C) Power Conversion and Integration

The DC bus acts as the central power hub, combining energy from the solar PV and wind subsystems. A series of buck converters are employed to step downs voltage from DC bus to required levels for EV charging. Each EV charging port is equipped with a dedicated buck converter, enabling independent control and operation. This modular design allows the system to accommodate multiple EVs simultaneously, ensuring flexibility and scalability. The buck converters are regulated by an Artificial Neural Network (ANN)-based control strategy, which generates gate pulses to maintain optimal voltage and current levels at each charging port. The ANN controller enhances system's adaptability to dynamic load conditions, ensuring efficient and reliable charging for all connected EVs.

By combining solar and wind energy with intelligent power management and control, the proposed system provides a high-performance, eco-friendly solution for EV charging. The integration of advanced converters and ANN control ensures maximum utilization of RES, contributing to the sustainability of modern transportation infrastructure.

III. PROPOSED METHOD

The proposed method integrates an ANN-based control strategy into hybrid solar/wind EV charging system, significantly enhancing system performance. This integration ensures efficient power management, adaptive control, and robust performance under dynamic load and environmental conditions. The ANN controller is designed to regulate the gate pulses for the buck converters connected to each EV charging port, optimizing the charging process for multiple electric vehicles. Additionally, the boost converter employed in the solar power generation subsystem operates using a P&O MPPT algorithm to extract maximum possible energy from PV panels. Together, the ANN and MPPT algorithms create a cohesive control architecture that balances energy supply and demand while ensuring maximum renewable energy utilization.

Structure of ANN:

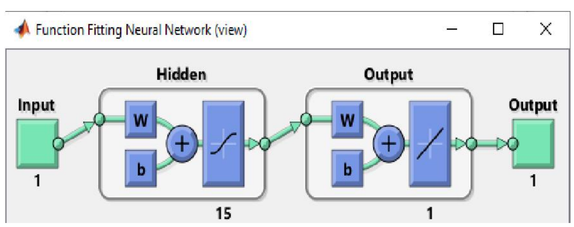

Fig. 2 Schematic diagram of NN controller

The ANN controller plays a crucial role in this hybrid system by replacing conventional control methods that rely on fixed algorithms or linear systems. Traditional control methods often struggle with non-linear, time-varying inputs, such as fluctuating renewable energy outputs and varying EV charging demands. ANN, however, excels in handling such complexities due to its ability to learn, adapt, and generalize from data. The ANN in this system is trained to generate precise gate pulses for the buck converters, ensuring stable voltage and current delivery to the EVs. This intelligent control mechanism minimizes voltage ripples and energy losses, ensuring that each EV is charged efficiently without overloading the system. The ANN's ability to adapt to real-time changes in load conditions significantly improves the reliability and robustness of the charging process.

The ANN's integration enhances the hybrid system's performance by ensuring faster response times and superior control accuracy compared to conventional controllers. For instance, when multiple EVs are connected for charging simultaneously, the ANN dynamically adjusts the duty cycles of the buck converters, balancing the load across all charging ports. This feature prevents overloading and ensures fair power distribution among the connected vehicles. Additionally, the ANN's predictive capabilities enable it to anticipate potential fluctuations in energy supply from the

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solar and wind subsystems, allowing the system to adjust proactively. This level of adaptability ensures uninterrupted EV charging, even under rapidly changing environmental or load conditions.

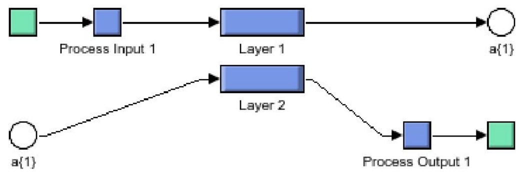

Fig.3 Internal Structure of NN Controller

The importance of ANN in this project lies in its ability to transform the EV charging process into a smarter, more efficient, and highly adaptive system. Unlike conventional controllers that rely on fixed parameters, the ANN leverages its learning capability to optimize the system for diverse and unpredictable scenarios. This is particularly crucial in hybrid systems where renewable energy sources introduce variability in power generation. By integrating ANN, the proposed method ensures that the hybrid system operates at peak efficiency while maintaining the flexibility to adapt to real-world challenges. The ANN integration elevates the performance of the hybrid solar/wind EV charging system. By ensuring precise control, faster adaptability, and superior efficiency, the ANN-based controller addresses the limitations of traditional control strategies and creates a robust, future-ready solution for EV charging infrastructure. This innovative approach not only optimizes the energy delivery process but also contributes to the broader goal of sustainable and intelligent transportation systems.

IV. SIMULATION RESULTS AND DISCUSSION

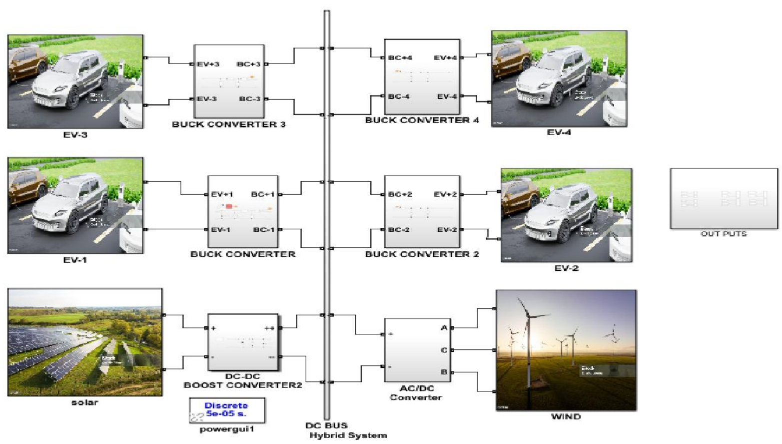

Fig 4 Simulink model

The above fig. 4 shows the simulation diagram of proposed system, which integrates a hybrid power generation system comprising both solar and wind energy sources for charging electric vehicles.

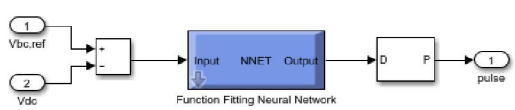

Fig 5 Buck converter Controller with ANN Control

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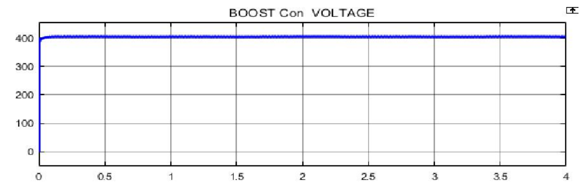
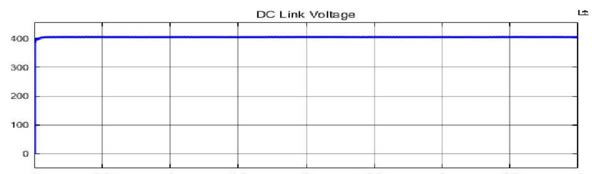
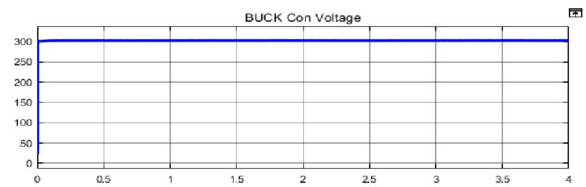


Fig. 6. The employed boost converter voltage

Figure 6 shows that the utilized boost converter increases voltage from 100V to 400V in proposed DC fast charging station.



7(a) DC link Voltage



7(b) Buck Converter Voltage

Fig. 7. The employed buck converter voltage and the DC link voltage.

Figure 7 illustrates output voltage of buck converter, which must match a required voltage of EV batteries.

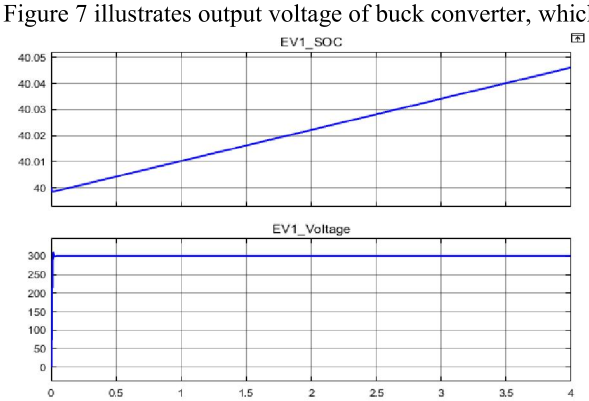


Fig.8 EV1 Outputs

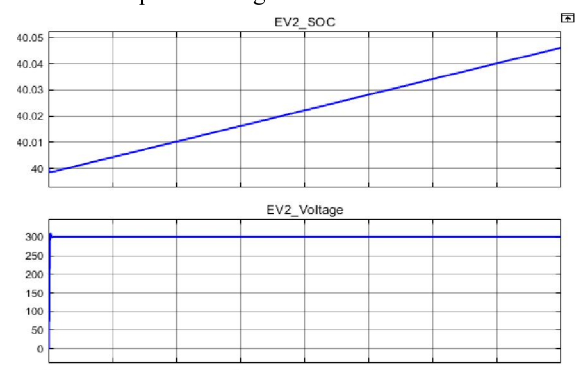


Fig.9 EV2 Outputs

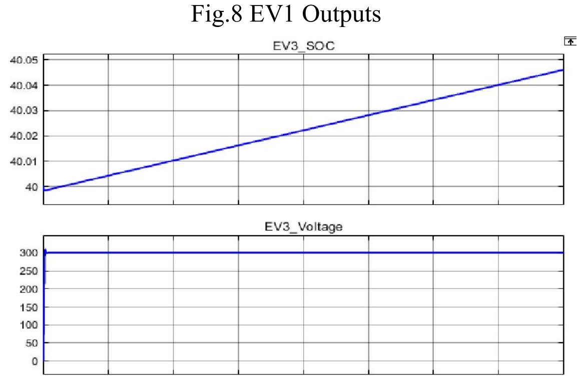


Fig.10 EV3 Outputs

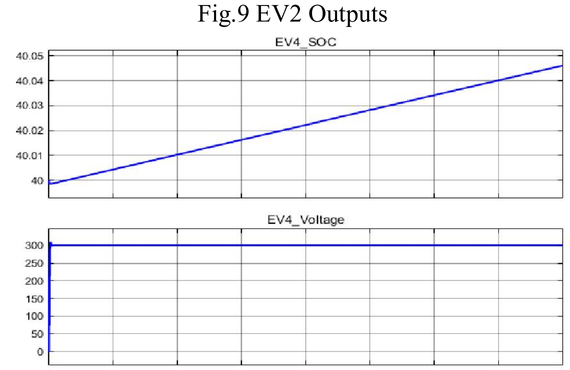


Fig 11 EV4 Outputs

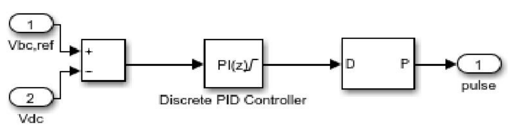


Fig 12 Buck converter Controller with PI Control.

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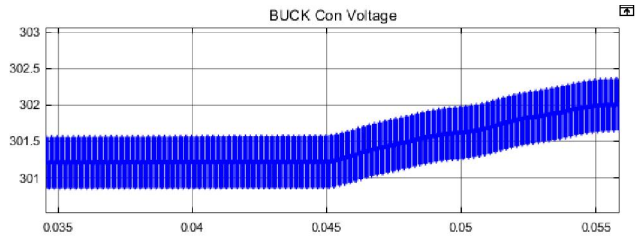

Fig 13 Zoomed results of Electrical Vehicle Battery Voltage with Buck converter Controlled by PI Controller

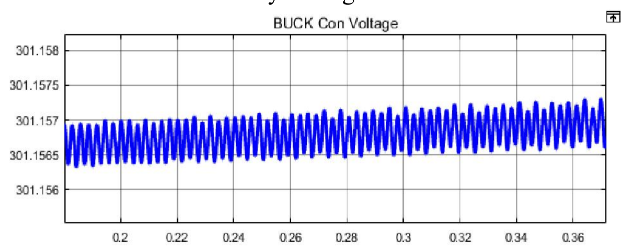

Fig 14 Zoomed results of Electrical Vehicle Battery Voltage with Buck converter Controlled by ANN Controller

Figures 13 and 14 illustrate the zoomed-in results of an Electric Vehicle (EV) battery voltage controlled by a Buck converter using both a PI Controller and an ANN Controller. Observations indicate that when the Buck converter is controlled by PI Controller, output voltage of EV exhibits significant ripple content and more disturbed outputs. In contrast, utilizing the ANN Controller for the Buck converter results in a much smoother output voltage with minimal ripple. The reduced ripple content and smoother voltage levels achieved with the ANN Controller enhance battery performance and longevity. Excessive ripple and disturbed voltage outputs can lead to rapid battery degradation. Thus, the ANN Controller provides superior performance compared to the PI Controller, ensuring a more stable and reliable power supply for EV batteries.

V. CONCLUSION

This paper presents an innovative approach to enhancing EV charging performance by integrating an ANN controller into a hybrid solar/wind energy system. The proposed system effectively addresses the challenges associated with fluctuating renewable energy sources and varying EV charging demands. By utilizing the ANN controller, the system adapts to real-time changes, optimizing power distribution to multiple EVs and ensuring efficient energy usage. The integration of the P&O MPPT algorithm in the solar subsystem further improves energy extraction, maximizing the utilization of renewable resources. The ANN's ability to learn and adapt provides superior control accuracy, faster response times, and enhanced system reliability compared to traditional control methods. Overall, the proposed method offers a sustainable and efficient solution for future EV charging infrastructure, contributing to the development of smart, renewable-powered transportation systems.

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