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Modelling and Optimization of a PV–Wind–BESS Hybrid DC Microgrid for Fast EV Charging Infrastructure

Nagananda R, Dr.Gopiya Naik S

Research Scholar, P.E.T. Research Foundation, P.E.S. College of Engineering, Mandya, Karnataka, India

Professor, Dept. of EEE, P.E.S. College of Engineering, Mandya, Karnataka, India

ABSTRACT: This paper presents the modelling and optimization of a PV–Wind–Battery Energy Storage System (BESS) hybrid DC microgrid designed to address the challenges created by fast electric vehicle (EV) charging. Fast charging of multiple EVs imposes sudden and highly dynamic load variations, which can lead to voltage instability, reduced efficiency, and stress on power electronic components. To overcome these issues, a comprehensive simulation model is developed to coordinate renewable sources and storage for supplying reliable high-power charging. MPPT (Maximum Power Point Tracking) algorithms are implemented for both PV and wind systems to extract maximum available energy under varying environmental conditions, while the combined control strategy maintains a stable and desired DC voltage level. The study evaluates power flow, dynamic response, and efficiency enhancements achieved through optimized energy management and converter control. Stability implications arising from rapid EV charging demand are analysed, and practical system-level remedies are proposed to mitigate voltage fluctuations and improve microgrid resilience. Results demonstrate that the optimized PV–Wind–BESS hybrid system significantly enhances reliability, efficiency, and stability for next-generation fast EV charging infrastructure.

KEYWORDS: PV–Wind–BESS Hybrid System, DC Microgrid, Fast EV Charging, MPPT, Renewable Energy Integration, Energy Management Strategy, DC Voltage Regulation, Power Flow Optimization, Stability Analysis

I. INTRODUCTION

The rapid global adoption of electric vehicles (EVs) has created a strong demand for reliable, efficient, and sustainable charging infrastructure. Among various charging technologies, fast and ultra-fast DC charging stations have become essential for reducing vehicle downtime and improving user convenience. However, these high-power charging systems introduce substantial challenges to conventional distribution grids, including sudden load surges, voltage instability, increased stress on power electronic converters, and reduced overall system efficiency. As the grid continues to evolve toward decentralized generation and smart energy management, hybrid renewable energy–based DC microgrids have emerged as a promising solution to support high-demand EV charging requirements.

DC microgrids powered by renewable sources such as photovoltaic (PV) arrays and wind turbines offer several advantages, including reduced carbon footprint, improved power quality, and independence from weak or congested utility networks. Integrating a Battery Energy Storage System (BESS) further enhances system flexibility by compensating for intermittency in renewable generation and meeting peak power demands during fast EV charging events. When properly coordinated, a PV–Wind–BESS hybrid system can deliver stable, high-power energy, minimizing reliance on the conventional grid and ensuring smooth operation under dynamically changing load conditions.

Despite these benefits, optimal control and coordination of multiple energy sources remain a major research challenge. Renewable energy outputs fluctuate due to weather variations, while fast EV charging creates unpredictable and rapidly changing load profiles. These factors can degrade power quality, destabilize DC bus voltage, and lower overall system efficiency if not managed properly. Therefore, advanced modelling, simulation, and optimization techniques are essential to evaluate system behaviour and design intelligent control strategies. Incorporating Maximum Power Point Tracking (MPPT) algorithms for both PV and wind systems ensures maximum extraction of available renewable energy, while coordinated converter control is required to maintain voltage stability and balance power flow in the microgrid.

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This study focuses on the detailed modelling and optimization of a PV–Wind–BESS hybrid DC microgrid specifically designed to support fast EV charging stations. A comprehensive simulation framework is developed to analyze the dynamic interactions among renewable sources, storage components, and high-demand EV charging loads. The work emphasizes system-level stability analysis, efficiency improvement, and resilience enhancement through optimized energy management. Furthermore, the research proposes practical remedies to mitigate voltage fluctuations and reduce the adverse impacts of rapid load variations, ensuring that the microgrid operates reliably even under extreme charging scenarios.

By evaluating power flow characteristics, transient response, and overall system performance, the proposed hybrid system demonstrates significant improvements in efficiency, voltage stability, and operational reliability. The findings contribute toward the development of next-generation sustainable, smart, and robust EV charging infrastructure, capable of supporting widespread electric mobility without compromising grid stability.

II. LITERATURE SURVEY

Hybrid PV–Wind–Battery microgrids have gained significant attention as a solution for reliable and efficient integration of renewable energy sources into modern power systems. Effective energy management strategies and advanced control mechanisms are essential to ensure system stability, optimal power sharing, and reliable operation under variable environmental conditions and dynamic load demands such as electric vehicle (EV) charging. Elkazaz, Sumner, and Thomas [1] demonstrated that a convex programming–based energy management system combined with model predictive control can optimize power dispatch in PV–Wind–Battery microgrids, enhancing voltage regulation and reducing operational costs. Similarly, Qi, Liu, Lin, Zhong, and Chen [2] proposed a distributed hybrid energy storage control strategy incorporating MPPT algorithms and equilibrium control, which improves the stability of microgrid outputs under fluctuating generation conditions.

MPPT techniques play a critical role in extracting maximum available energy from PV and wind sources. Li, Shi, Zhu, and Gan [3] analysed energy management in direct current (DC) microgrids, highlighting that coordinated MPPT and control strategies significantly reduce power fluctuations and maintain DC bus voltage stability. Dayananda and Deshpande [4] applied super-twisting sliding mode controllers for battery energy management in standalone PV–Wind–Battery microgrids, demonstrating improved handling of intermittent renewable inputs. Li, Chen, Wu, Cheng, and Yang [5] introduced a decentralized control strategy for hybrid energy storage systems, further stabilizing DC microgrid voltage under sudden load changes.

Integration of EV loads introduces additional challenges due to high power demand and rapid load variations. Xing, Qin, Zhu, Liu, and Zhou [6] examined photovoltaic–flywheel–EV microgrid systems, emphasizing the importance of coordinated energy management to satisfy dynamic charging requirements. Hassan, Jaszczur, Hafedh, Abbas, and Abdulateef [7] optimized PV–fuel cell hybrid systems with high renewable penetration, showing that careful energy storage sizing and control ensure reliability during peak loads. Yuan, Ye, Chen, and Deng [8] studied optimal configuration of PV and battery storage in rural microgrids, demonstrating that proper sizing and management enhance stability and power quality.

Artificial intelligence and advanced control techniques have been explored to improve microgrid performance. Vani, Balakrishnan, Singaram, and Senthil Kumar [9] implemented neural network–based MPPT for PV–Wind–Battery microgrids, achieving maximum power extraction and enhanced system stability. Cheng, Li, Huang, and Zhou [10] developed an energy-coordinated control strategy for DC microgrids integrating PV, storage, and EV charging, demonstrating improved voltage regulation and load sharing. Mahjoub, Chrifi-Alaoui, Drid, and Derbel [11] proposed an intelligent prediction-based energy management system, which improves the microgrid's ability to meet dynamic load demands with minimal fluctuations.

Robust control and ANN-based techniques have also been studied for hybrid systems. Bana, D’Arco, and Amin [12] applied ANN-based current control with embedded MPPT to grid-connected PV systems, enhancing power quality and transient response. Al-Jaboury, Hamodat, and Daoud [13] designed neural network–based controllers for PV hybrid energy storage systems, enabling stable voltage and reliable operation. Mol and Linda [14] combined genetic algorithms with neural networks for PV–Wind integration, improving maximum power tracking and energy efficiency. Sharma, Chauhan, and Saxena [15] employed ANN-based MPPT techniques for hybrid PV–Wind–Battery systems, demonstrating improved energy utilization and system resilience.

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Overall, the reviewed literature indicates that hybrid PV–Wind–Battery microgrids with intelligent energy management, advanced MPPT techniques, and optimized storage control significantly enhance stability, efficiency, and reliability. Such systems are especially effective for dynamic and high-power EV charging applications, and AI-based controllers, coordinated DC microgrid management, and predictive strategies are critical enablers for resilient, efficient, and sustainable operation [16].

Here are three clear objectives based on our provided study description:

1. To model and simulate a PV–Wind–BESS hybrid DC microgrid for fast EV charging stations, capturing the dynamic interactions among renewable energy sources, battery storage, and high-demand EV loads.
2. To optimize energy management and control strategies for the hybrid system, ensuring voltage stability, power quality, and efficient utilization of renewable energy through coordinated converter control and MPPT algorithms.
3. To enhance system resilience and operational reliability by analysing transient responses and proposing practical solutions to mitigate voltage fluctuations and rapid load variations during fast EV charging events.

Problem Statement:

Fast charging of electric vehicles (EVs) puts a heavy load on conventional power grids, causing voltage instability and reduced efficiency. Renewable energy–based DC microgrids using solar (PV) and wind, combined with battery storage (BESS), can provide a sustainable solution. However, fluctuating renewable output and unpredictable EV charging loads make it challenging to maintain stable voltage and reliable power supply. This study focuses on designing and optimizing a PV–Wind–BESS hybrid DC microgrid to ensure efficient, stable, and reliable fast EV charging.

III. METHODOLOGY

The proposed PV–Wind–BESS hybrid DC microgrid (Fig. 1) is designed to supply reliable, high-power charging to multiple EVs while integrating renewable energy sources and energy storage. The methodology is structured into system modelling, control strategy, simulation scenarios, performance analysis, and system-level remedies.

The **system modelling** phase involves representing the four main subsystems: PV energy conversion, wind energy conversion, battery energy storage, and EV loads. The PV array is connected to a boost converter that steps up the variable DC output to the desired DC voltage of the bus. Maximum Power Point Tracking (MPPT) is implemented to ensure maximum energy extraction under varying irradiance. Similarly, the wind turbine drives a permanent magnet synchronous generator (PMSG), with its AC output converted to DC via a three-phase AC–DC converter, also regulated using MPPT to maximize energy capture under fluctuating wind speeds. The BESS connects to the DC bus through a bidirectional DC–DC converter, supplying power during high EV demand or absorbing excess renewable energy to maintain stable DC voltage. Multiple fast-charging EVs are interfaced with DC–DC converters to ensure regulated charging current and voltage.

The **control and coordination** strategy employs a hierarchical approach. At the local level, MPPT controllers for PV and wind systems maximize renewable power generation, while DC–DC converters for the BESS and EV loads regulate voltage and current to maintain the desired DC bus voltage. At the supervisory level, an Energy Management System (EMS) coordinates power flow among PV, wind, and BESS to optimize efficiency, manage battery charge/discharge cycles, and reduce system stress during rapid load changes.

Simulation scenarios are designed to evaluate system performance under various conditions. Normal operation scenarios consider varying solar irradiance and wind speeds while charging multiple EVs. High-demand scenarios test the system’s response to multiple EVs charging simultaneously, analysing DC voltage stability, converter response, and battery support. Transient scenarios simulate sudden drops in renewable generation or abrupt changes in EV load to assess system dynamics and stability. All simulations are implemented in MATLAB/Simulink using Sandscape Electrical models.

Performance analysis focuses on efficiency and stability. Efficiency is evaluated by comparing energy delivered to EVs with total generated energy, accounting for converter and storage losses. Stability analysis examines DC voltage deviations, current spikes, and converter stress during high-demand and transient conditions. Optimization of battery sizing, converter ratings, and EMS strategies is performed to enhance efficiency, maintain the desired DC voltage, and ensure reliable operation during simultaneous fast charging.

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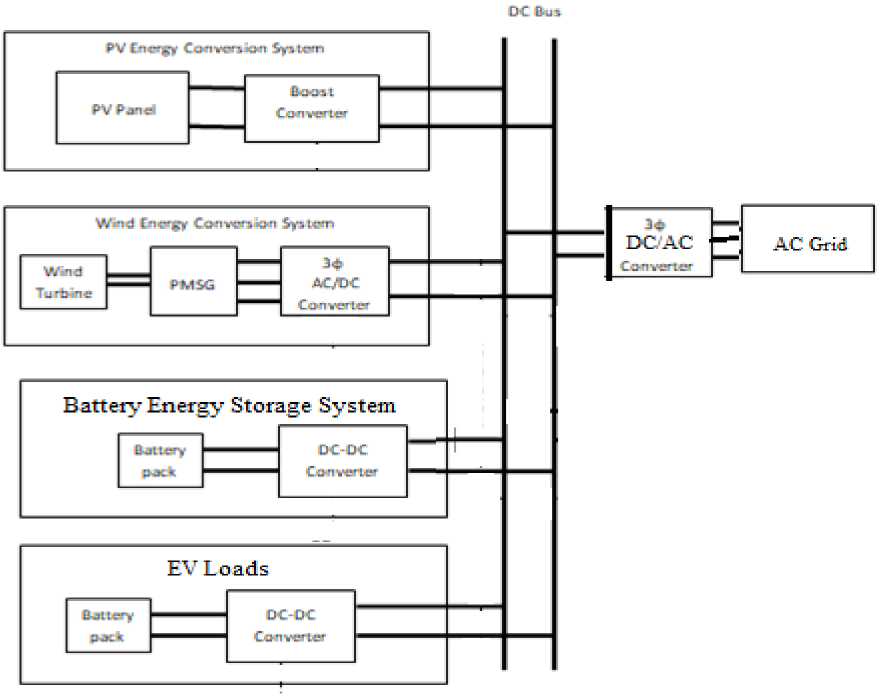

Fig. 1 PV Wind BESS based Hybrid DC Microgrid for EV fast charging Infrastructure

Finally, **system-level remedies** are proposed based on simulation results. These include EMS scheduling adjustments, optimized BESS utilization, tuning of converter control loops to minimize DC voltage oscillations, and coordination between PV and wind MPPT algorithms to prevent instability during rapid load changes. The methodology ensures that the hybrid DC microgrid efficiently supports fast EV charging, maximizes renewable energy use, and maintains stable operation under varying conditions.

IV. DEVELOPMENT OF SIMULINK MODEL

The proposed Simulink model (Fig. 2) represents a hybrid PV–Wind–BESS based DC microgrid designed to support fast electric vehicle (EV) charging infrastructure with enhanced reliability and efficiency. In this model, the photovoltaic (PV) array and wind energy conversion system (Fig. 3) are integrated through dedicated DC–DC converters to a common DC bus, enabling effective utilization of intermittent renewable sources. A battery energy storage system (BESS) is interfaced via a bidirectional DC–DC converter to regulate the DC bus voltage, mitigate power fluctuations, and support peak EV charging demand. The fast EV charger is modeled as a variable DC load to reflect real-time charging scenarios. An energy management and control strategy is implemented to optimally coordinate power sharing among PV, wind, and BESS, ensuring maximum renewable penetration, reduced battery stress, and stable DC bus operation under varying generation and load conditions. The Simulink-based modelling framework facilitates performance evaluation in terms of voltage stability, power balance, and system efficiency, demonstrating the suitability of the proposed hybrid DC microgrid for sustainable and high-power EV charging applications.

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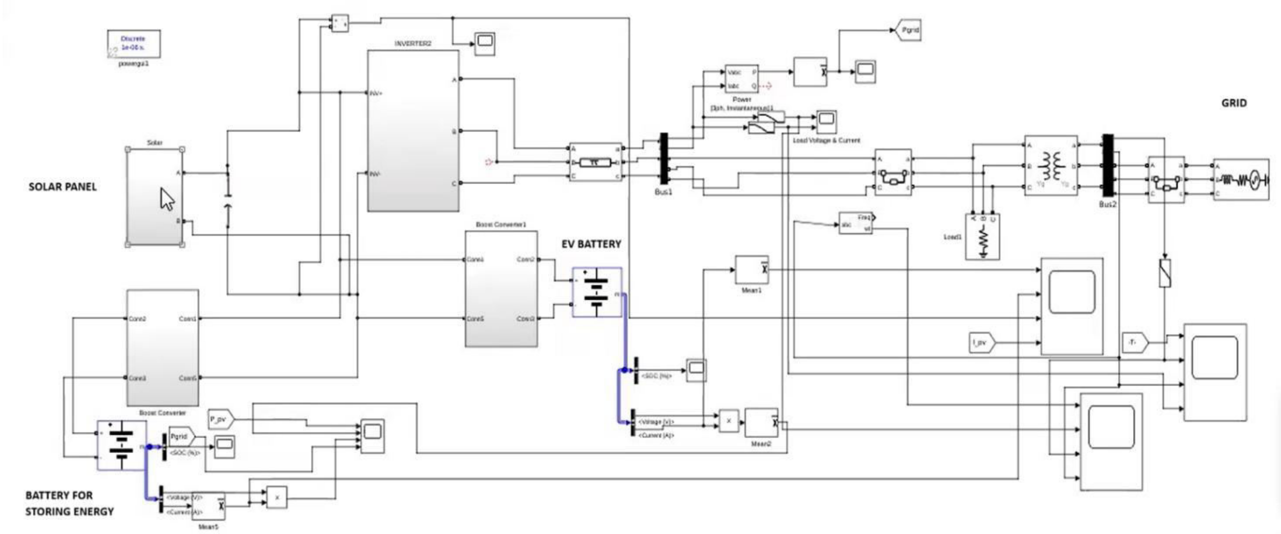

Fig. 2 PV Wind BESS Hybrid DC Microgrid for EV fast Charging infrastructure

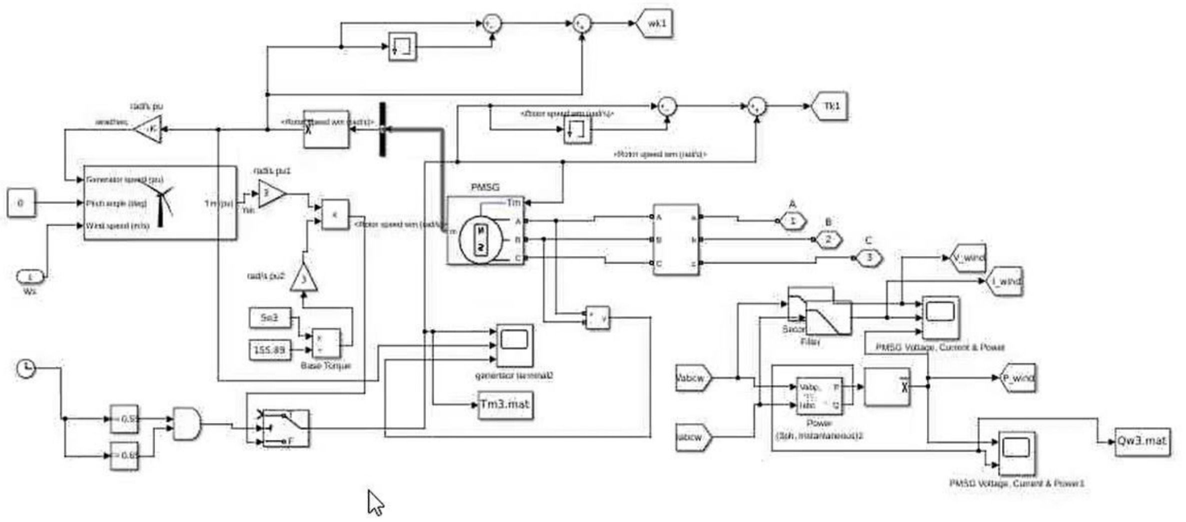

Fig. 3 Wind Power Generation for simulation block diagram

V. RESULT AND DISCUSSION

Initially, the PV power (Fig. 4) is low and does not contribute significantly to the system, while the EV load is supported by the grid and the battery. At **t = 0.2 s**, the PV source is turned ON, leading to an increase in PV power output, and the generated energy is used to charge the PV-connected battery; as a result, the **state of charge (SOC)** of the battery begins to increase. At **t = 0.5 s**, the grid is disconnected, and the system operates solely on renewable sources and battery storage, causing the battery charging rate to increase in order to maintain system power balance and support the EV load. At **t = 0.55 s**, the PV source is turned OFF, which reduces the available renewable power. Subsequently, at **t = 0.6 s**, the battery shifts from charging to discharging mode and starts supplying power to the EV battery to meet fast charging demand. At **t = 0.65 s**, the PV source is turned ON again, restoring renewable generation and enabling the PV-connected battery to resume charging. Finally, at **t = 0.7 s**, the grid is reconnected, resulting in an increase in grid power contribution, reduced battery loading, and improved power sharing within the system. These results demonstrate effective source coordination and uninterrupted EV charging (Fig. 5- Fig. 7) under varying operating conditions.

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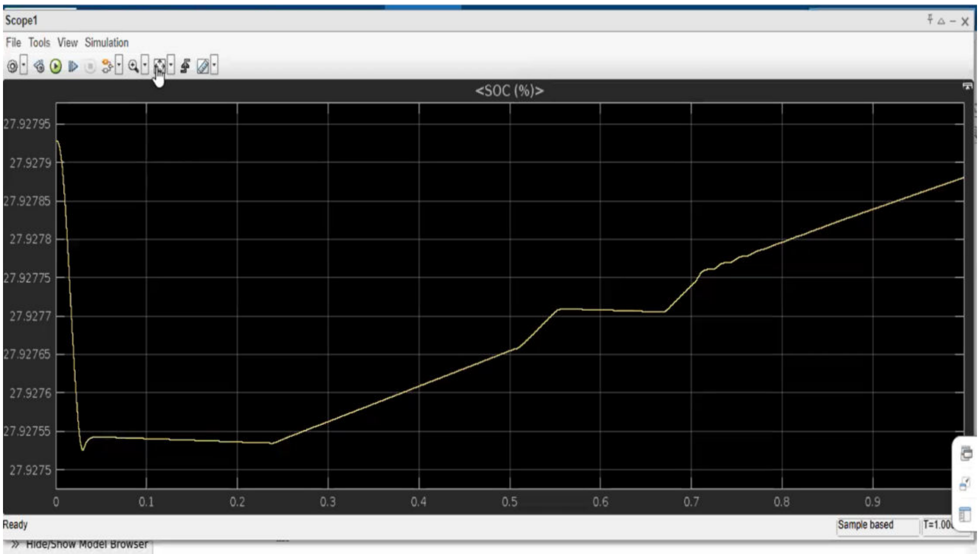

Fig. 4 Battery State of Charging which is Connected to PV, Wind and DC Grid

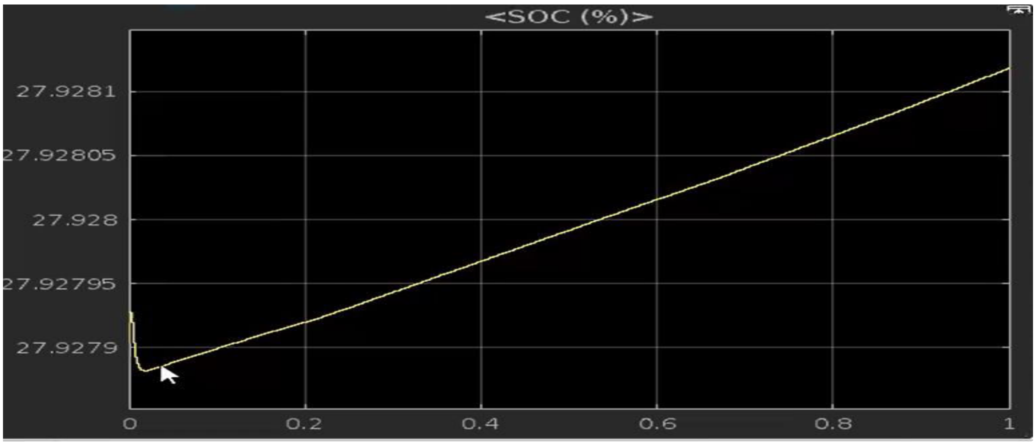

Fig. 5 EV Battery charges continuously irrespective of variation in PV system, Wind energy and Grid Connection

From t = 0.55 s to t = 0.66 s, the wind speed is zero; therefore, the wind power output is zero and the PMSG is disconnected from the generator during this interval. During the remaining time, wind power supplies energy to the battery, which is connected to the PV, wind, and grid sources.

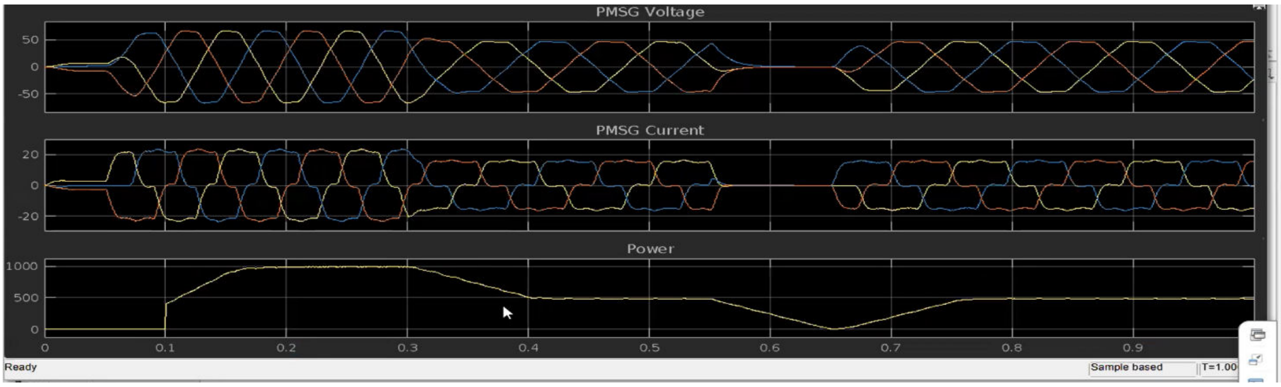

Fig. 6 Variation of PMSG voltage and current with respect to Wind Power

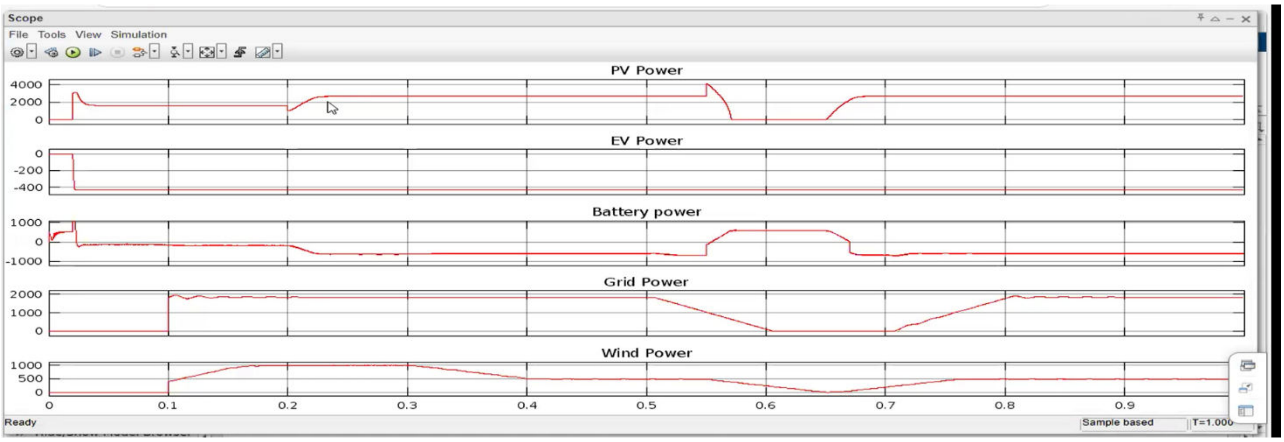

Fig .7 Irrespective of variation in PV power, Grid power and Wind power, EV power remains constant

VI. CONCLUSION AND FUTURE SCOPE

This work demonstrates that a PV–Wind–BESS hybrid DC microgrid can effectively support fast EV charging stations while maintaining voltage stability, improving efficiency, and enhancing operational reliability. By integrating renewable energy sources with battery storage and implementing optimized control strategies, the system can handle fluctuating renewable output and rapidly changing loads. The proposed model and simulation framework provide valuable insights into energy management, transient response, and power flow optimization, contributing to the development of sustainable, resilient, and smart EV charging infrastructure for widespread adoption of electric mobility.

Future Scope:

The future development of PV–Wind–BESS hybrid DC microgrids can focus on the implementation of real-time control and predictive algorithms to achieve better coordination among PV, wind, and battery storage systems under highly variable load conditions. Such advanced control strategies will enhance system stability and efficiency, particularly during rapid fluctuations in EV charging demand.Further improvements can be made by integrating additional renewable energy sources, such as fuel cells or small hydro systems, which would increase the reliability and sustainability of the microgrid. By diversifying the energy mix, the system can ensure continuous power supply even during periods of low solar or wind generation.

The adoption of advanced EV charging strategies, including vehicle-to-grid (V2G) systems, represents another promising direction. V2G technology allows bidirectional energy flow between vehicles and the grid, providing additional grid support and enabling more efficient energy management. To validate theoretical models and simulations, experimental testing of the hybrid microgrid in a real-world EV charging station is essential. This will provide practical insights into system performance, transient response, and operational challenges under actual conditions. Finally, the economic and environmental optimization of hybrid microgrids presents an important future scope. Efforts can be directed toward reducing costs, minimizing carbon footprint, and enabling large-scale deployment, thereby supporting sustainable and resilient EV charging infrastructure worldwide.

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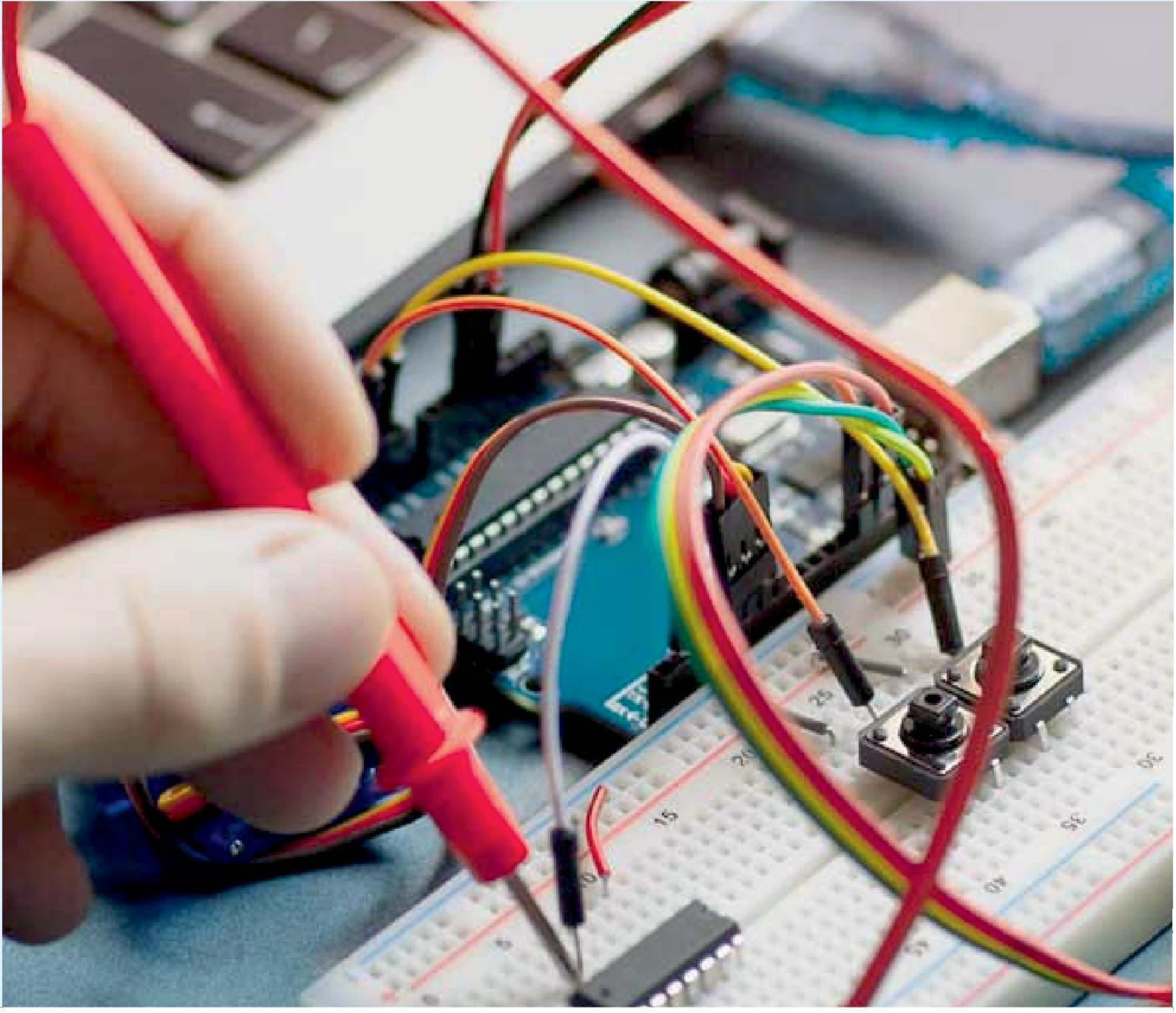

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