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Modelling and Control of a Grid-Connected Hybrid PV–Wind Energy System with EV Battery Backup Storage for Continuous Power Supply and Energy Management

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ABSTRACT: This paper presents the modelling, simulation, and performance analysis of a grid-connected hybrid renewable energy system integrating photovoltaic (PV) and wind energy sources with electric vehicle (EV) battery backup storage for reliable power management. The proposed system employs a PV array coupled with a boost converter and Maximum Power Point Tracking (MPPT) algorithm to maximize solar energy extraction under varying irradiance conditions. A wind energy conversion system acts as an alternate renewable source to ensure continuous power availability when solar generation is reduced or unavailable. The EV battery storage system, rated at 240 V and 60 Ah, is interfaced through a bidirectional buck–boost converter that enables controlled charging and discharging based on power availability and load demand. During surplus renewable generation, the battery operates in buck mode for charging, while during renewable source interruption or low generation, it functions in boost mode to supply backup power to the load. A grid-connected inverter facilitates power injection to the utility grid and supports load continuity during grid disconnection events. Simulation results under dynamic solar irradiance, wind speed variations, and temporary grid outage conditions demonstrate effective energy management, seamless source transition, stable DC-link voltage regulation, and uninterrupted power supply to EV loads. The hybrid system significantly reduces dependence on battery-only backup by optimally utilizing complementary renewable sources, thereby enhancing system reliability, grid interaction, and overall energy efficiency. This study validates the effectiveness of hybrid renewable integration for sustainable EV charging infrastructure and smart grid applications.

KEYWORDS: Hybrid Renewable Energy System, Photovoltaic (PV), Wind Energy, Electric Vehicle (EV) Charging, Battery Energy Storage System (BESS), Maximum Power Point Tracking (MPPT), Bidirectional Buck–Boost Converter, Grid-Connected Inverter, DC-Link Voltage Control, Energy Management System, Smart Grid, Renewable Energy Integration, Backup Power System, Simulink Modelling, Power Flow Control.

I. INTRODUCTION

The increasing global demand for clean, sustainable, and reliable energy has accelerated the integration of renewable energy sources into modern power systems. Among the various renewable technologies, photovoltaic (PV) and wind energy systems have emerged as the most promising solutions due to their environmental benefits, wide availability, and decreasing installation costs. However, the intermittent nature of solar irradiance and wind speed creates significant challenges in maintaining continuous and stable power supply, particularly for critical applications such as electric vehicle (EV) charging and grid support systems.

Electric vehicles are becoming an essential component of sustainable transportation, leading to increased demand for efficient charging infrastructure powered by renewable sources. Integrating EV charging systems with renewable energy not only reduces dependence on conventional fossil-fuel-based electricity but also enhances overall energy sustainability. Nevertheless, fluctuations in renewable power generation can affect charging reliability, necessitating the inclusion of energy storage systems as backup sources. Battery Energy Storage Systems (BESS) play a crucial role in

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balancing energy generation and consumption by storing surplus renewable power and supplying energy during periods of insufficient generation. In this context, hybrid renewable energy systems combining PV, wind, and battery storage offer an effective solution for improving system reliability and ensuring uninterrupted power delivery. PV systems equipped with Maximum Power Point Tracking (MPPT) controllers can optimize solar energy extraction under varying irradiance conditions, while wind energy systems provide complementary generation during low solar availability. A bidirectional buck–boost converter enables efficient battery charging and discharging, allowing seamless energy exchange between the DC link and battery storage based on system operating conditions. Additionally, grid-connected inverters facilitate power transfer to utility networks and maintain load continuity during temporary grid outages.

This paper focuses on the modeling and simulation of a grid-connected hybrid PV–wind renewable energy system integrated with EV battery backup storage. The system is designed to manage dynamic variations in solar irradiance, wind speed, and grid availability while ensuring stable power supply to EV loads and enabling excess power injection into the grid. Through intelligent control of MPPT, bidirectional converters, and inverter operation, the proposed system enhances renewable energy utilization, minimizes battery stress, and improves overall energy management efficiency.

II. LITERATURE SURVEY

Recent research in hybrid renewable energy systems has increasingly focused on integrating photovoltaic (PV), wind energy, battery energy storage systems (BESS), and electric vehicle (EV) charging to improve power reliability, energy efficiency, and grid interaction. Early reviews emphasized that hybrid PV–wind systems significantly enhance renewable penetration by compensating for the intermittent behavior of individual energy sources while reducing voltage instability and harmonic distortion in grid-connected and standalone applications [1]. Comprehensive studies further highlighted that combining solar and wind generation with modern power electronic converters provides a sustainable solution for distributed energy systems, particularly when supported by intelligent control and optimization frameworks [2], [3]. The integration of battery energy storage has become essential for overcoming renewable intermittency and ensuring continuous load support. Advanced hybrid energy storage reviews demonstrated that battery systems improve renewable utilization, stabilize DC-link voltages, and support uninterrupted operation during source fluctuations or grid outages [4]. Studies on EV charging infrastructures with integrated PV and storage systems reported that energy storage can effectively manage peak demand, enhance charging station self-sufficiency, and reduce grid dependency [5], [6]. Moreover, recent investigations into renewable-powered EV charging stations confirmed that hybrid architectures combining PV, wind, and battery systems are economically viable and technically effective for sustainable transportation applications [7], [8].

Maximum Power Point Tracking (MPPT) and converter technologies remain critical in improving system efficiency. Several studies have proposed advanced MPPT strategies, including fuzzy logic, ANFIS, and hybrid optimization methods, which substantially increase solar and wind power extraction under rapidly changing environmental conditions [9], [10]. These control strategies ensure that renewable sources operate near their optimal efficiency, particularly in dynamic irradiance and wind speed scenarios. Parallel research on bidirectional buck–boost converters and vehicle-to-grid (V2G) charger topologies emphasized their role in efficient battery charging/discharging, enabling EV batteries to function as both storage devices and auxiliary power sources [11]. Grid-connected inverter technologies have also evolved considerably, with recent literature demonstrating that multifunctional inverters can provide not only DC/AC conversion but also grid support services such as reactive power compensation, harmonic mitigation, and power injection during surplus generation [12]. Such capabilities are especially valuable in smart microgrids where renewable sources, storage devices, and EV loads must be coordinated in real time. Reviews on unified power quality conditioners and advanced inverter controls have shown that these technologies improve overall system stability while ensuring compliance with grid standards [13]. In recent years, hybrid PV–wind–battery systems specifically designed for EV charging and smart grid applications have gained significant research attention. Techno-economic analyses have demonstrated that these systems can reduce operational costs, maximize renewable energy utilization, and maintain reliable charging performance even during renewable source variability [14]. Additionally, simulation-based studies have confirmed that coordinated operation of PV, wind, battery storage, and grid interfaces can effectively reduce battery stress by distributing load demand among multiple renewable sources [15].

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

1. To design and develop a grid-connected hybrid PV–wind renewable energy system integrated with EV battery backup storage for continuous power supply.
2. To implement efficient Maximum Power Point Tracking (MPPT) and bidirectional buck–boost converter control for optimal renewable power extraction and battery charging/discharging.
3. To ensure reliable energy management and uninterrupted EV charging during varying solar irradiance, wind speed fluctuations, and grid outage conditions.

Problem Statement: The intermittent nature of photovoltaic (PV) and wind energy sources creates significant challenges in ensuring reliable and continuous power supply for electric vehicle (EV) charging and grid-connected applications. Variations in solar irradiance, wind speed, and temporary grid outages can lead to unstable power generation, reduced efficiency, and increased dependence on battery storage. Conventional systems often fail to provide effective coordination between renewable sources, battery backup, and grid interaction. Therefore, there is a need for an intelligent hybrid renewable energy system that integrates PV, wind, battery storage, and bidirectional power control to ensure uninterrupted EV charging, efficient energy management, and stable grid support under dynamic operating conditions.

III. METHODOLOGY

The proposed hybrid renewable energy system (Fig.1) is designed to provide continuous and efficient power supply for electric vehicle (EV) charging and grid-connected applications by integrating photovoltaic (PV) energy, wind energy, battery energy storage, and intelligent power management strategies. The complete system is modeled in MATLAB/Simulink, where PV and wind sources act as primary renewable energy generators, while the battery energy storage system functions as a backup source to maintain uninterrupted power during renewable fluctuations or grid outages. This integrated architecture ensures stable operation, efficient renewable utilization, and reliable power delivery under varying environmental conditions. The photovoltaic system serves as the primary energy source and is connected to a DC–DC boost converter controlled through a Maximum Power Point Tracking (MPPT) algorithm. The MPPT controller continuously monitors the PV output and adjusts the converter duty cycle to extract maximum available power under changing irradiance conditions. In the simulation, solar irradiance varies dynamically, starting at 600 W/m², increasing to 1000 W/m², dropping to zero during a temporary outage, and later recovering. The boost converter regulates the PV voltage and maintains a stable DC-link voltage, enabling efficient energy transfer to the inverter, battery system, and connected load.

To improve system reliability and compensate for PV intermittency, wind energy is incorporated as an alternate renewable source. The wind system contributes power based on varying wind speed conditions, thereby ensuring continuous renewable support when solar energy is unavailable or reduced. During periods of low solar irradiance, wind power supplements the system, reducing the dependency on battery storage. This complementary behavior between PV and wind sources enhances overall renewable penetration and stabilizes power generation across different operating conditions. The battery energy storage system, rated at 240 V and 60 Ah with an initial state of charge of 20%, is connected through a bidirectional buck–boost converter. This converter enables both charging and discharging operations depending on power availability. When renewable power generation exceeds load demand, the converter operates in buck mode, allowing excess energy to charge the battery efficiently. Conversely, during periods of low renewable generation or source interruption, the converter switches to boost mode, enabling the battery to discharge and supply backup power to the system. The bidirectional converter control circuit generates switching pulses for MOSFETs to ensure smooth transitions between charging and discharging modes while maintaining battery health and DC-link stability. A grid-connected voltage source inverter (VSI) is employed to convert the DC power from renewable sources and battery storage into AC power suitable for grid injection and EV charging. Under normal conditions, the inverter delivers power to both the load and the utility grid when excess renewable energy is available. During grid outage periods, simulated between 0.5 and 0.7 seconds, the inverter isolates grid interaction while battery and renewable sources continue supplying the EV load. Once the grid is restored, surplus power from the hybrid system is reinserted into the grid, ensuring effective utilization of generated renewable energy. An intelligent energy management system coordinates power flow among PV, wind, battery storage, EV load, and grid connection based on real-time operating conditions. This control strategy continuously monitors source generation, battery state of charge, load demand, and grid status to determine optimal operating modes.

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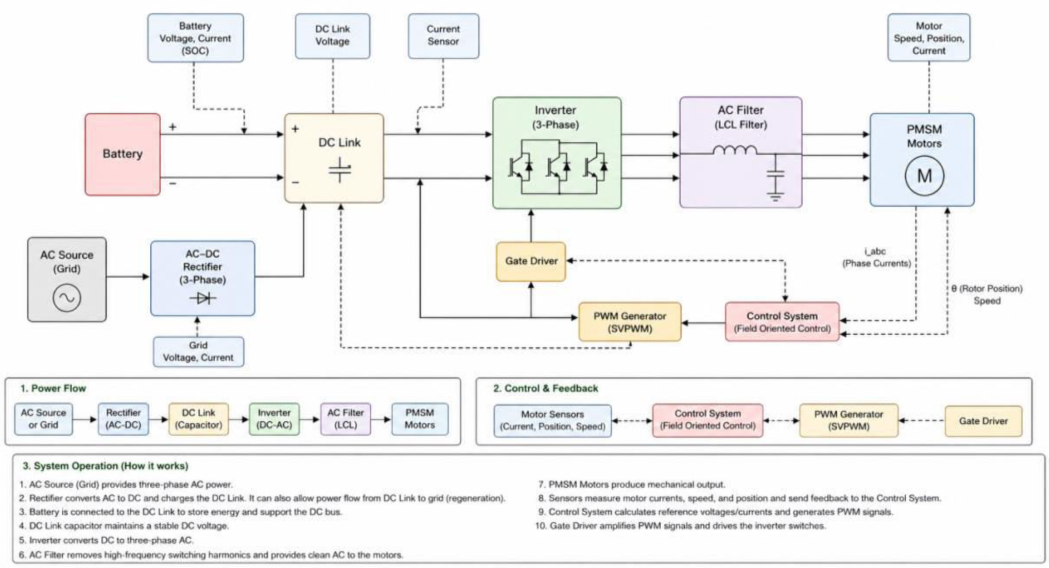

Fig. 1 Block Diagram of Hybrid PV–Wind Energy System with EV Battery Backup and Grid Integration

IV. DEVELOPMENT OF SIMULINK MODEL

The development of the MATLAB/Simulink model (Fig.2) for the proposed hybrid renewable energy system begins with designing the photovoltaic (PV) subsystem as the primary energy source. A PV array block is selected from the Simulink renewable energy library and configured according to the required voltage and power ratings. Solar irradiance and temperature inputs are applied through signal builder blocks to simulate real-time environmental variations. In this model, irradiance is programmed to vary from 600 W/m² initially, increase to 1000 W/m² after 0.2 seconds, drop to zero between 0.55 and 0.66 seconds, and then recover to 1000 W/m². The PV output is connected to measurement blocks for monitoring voltage and current parameters throughout the simulation. The next stage involves implementing the Maximum Power Point Tracking (MPPT) controller to ensure maximum power extraction from the PV source. A Perturb and Observe (P&O) or Incremental Conductance MPPT algorithm is developed using Simulink logic blocks, mathematical operators, and pulse generation units. The MPPT controller continuously compares voltage and current variations to determine the optimal duty cycle required for maximum power operation. This duty cycle is then supplied to a PWM generator that controls the switching of the DC–DC boost converter MOSFET. Following MPPT integration, a boost converter is designed using an inductor, capacitor, MOSFET switch, and diode. The converter steps up the PV voltage to the required DC-link voltage for inverter and battery integration. Proper values of inductance and capacitance are selected based on voltage ripple and switching frequency requirements. The converter output is connected to a DC-link capacitor, which stabilizes voltage and provides smooth DC power to the subsequent stages. Voltage sensors are added to monitor converter performance and DC-link regulation.

To enhance system reliability, the wind energy subsystem is incorporated as an alternate renewable source. A wind turbine model with generator and rectifier components is developed to simulate variable wind speed conditions. Wind speed is programmed to fluctuate over time, representing practical operating scenarios where wind complements solar generation. The rectified wind output is connected to the common DC-link bus, allowing it to contribute directly to system power when available. This integration ensures that renewable generation remains available even when PV output decreases. The battery energy storage system is then modeled using a rechargeable battery block configured at 240 V, 60 Ah, with an initial state of charge (SOC) of 20%. The battery is interfaced with the DC-link through a bidirectional buck–boost converter. This converter is designed using dual MOSFET switches, inductors, and capacitors to enable both charging and discharging modes. Control logic is implemented to determine converter operation based on DC-link voltage, renewable power availability, battery SOC, and load demand. When renewable generation exceeds demand, the converter operates in buck mode to charge the battery, while during renewable shortages, it switches to boost mode to discharge battery power back into the system. A voltage source inverter (VSI) is developed to convert DC-link power into AC power suitable for EV load supply and grid connection. The inverter is built using IGBT or MOSFET bridge circuits controlled through sinusoidal pulse width modulation (SPWM). A control subsystem synchronizes inverter output with grid voltage and frequency parameters. The inverter is connected to a transmission

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line model and utility grid source, enabling both grid support and power injection. Circuit breakers are incorporated to simulate grid disconnection between 0.5 and 0.7 seconds, allowing analysis of backup operation during outages.

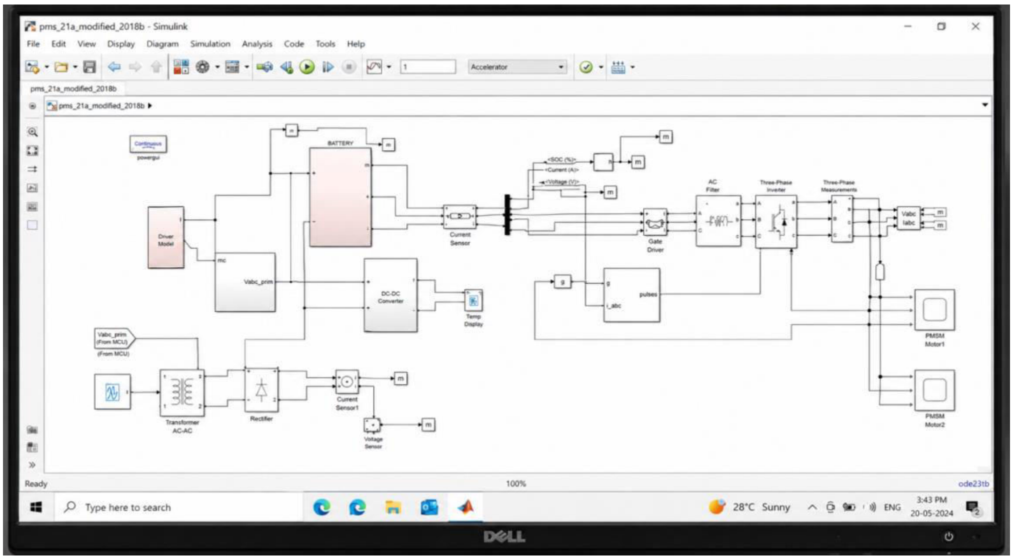

Fig.2 Simulation of Hybrid PV–Wind Energy System with EV Battery Backup and Grid Integration

An EV load or charging load model is integrated into the system to represent practical power consumption. The load remains active throughout the simulation, requiring continuous supply regardless of renewable or grid conditions. Measurement blocks are used to monitor load voltage, current, and power. During renewable interruptions, the battery system ensures uninterrupted EV charging by supplying backup power through the inverter. To coordinate all components effectively, a centralized energy management control system is developed using Simulink logic gates, comparators, and switching controls. This system continuously monitors PV output, wind power, battery SOC, grid status, and load requirements. Based on these parameters, it generates switching commands for the bidirectional converter, inverter, and grid breaker to ensure optimal power flow.

Finally, scopes, display blocks, and data logging systems are connected throughout the model to observe system parameters such as PV power, wind power, battery power, SOC, grid power, inverter output, and EV load response. The simulation is executed over the defined time period to evaluate system behavior under dynamic irradiance, wind variability, and grid outage conditions. The resulting performance verifies the successful operation of the hybrid PV–wind renewable energy system with intelligent battery backup, continuous EV charging capability, and effective grid integration.

V. RESULT AND DISCUSSION

The simulation results (Fig. 3) demonstrate the effective performance of the proposed hybrid renewable energy system under varying solar irradiance, wind conditions, battery operation, and grid availability. The photovoltaic (PV) source initially operates under reduced irradiance conditions of 600 W/m² from 0 to 0.2 seconds, resulting in comparatively lower power generation. During this period, the PV output is limited, and the battery energy storage system operates in discharging mode to supplement the power deficit and ensure continuous supply to the EV load. This confirms the importance of the battery as an immediate backup source during low renewable generation conditions.

At 0.2 seconds, the solar irradiance increases to 1000 W/m², leading to a significant improvement in PV power generation. The MPPT controller successfully tracks the new maximum operating point, allowing the boost converter to extract higher power from the PV array efficiently. As a result, the system generates sufficient renewable energy to meet load demand while also charging the battery through the bidirectional converter operating in buck mode. During this period, excess power is available for grid injection, demonstrating efficient renewable utilization and effective power management. Between 0.55 and 0.66 seconds, solar irradiance drops to zero, representing a temporary loss of PV generation. Under this condition, the PV source becomes unavailable, and the battery immediately transitions into boost mode to provide backup power. Simultaneously, the wind energy subsystem contributes available power

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depending on wind speed conditions, thereby reducing the total burden on the battery. The battery discharge profile during this interval confirms that the system can maintain uninterrupted EV charging and load support even during complete solar power interruptions.

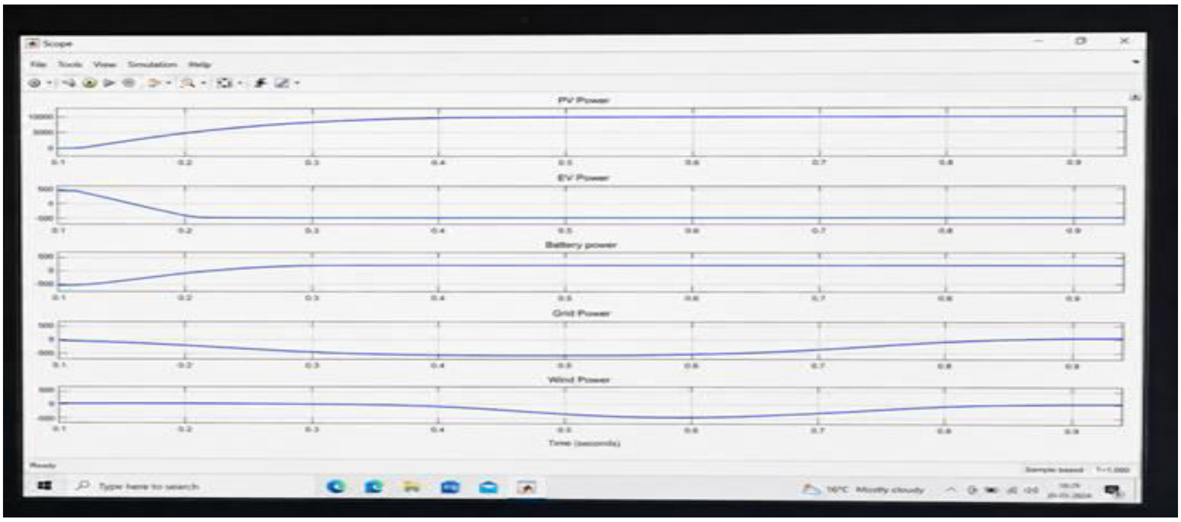

Fig. 3 Simulation Results of Hybrid PV–Wind Energy System Showing Solar Irradiance Variation, PV Power Output, Wind Power Contribution, Battery Charging/Discharging Performance, Grid Power Flow, and Continuous EV Load Supply

The wind energy source plays a complementary role throughout the simulation by providing alternate renewable power when PV generation is insufficient. Initially, high wind speed contributes substantial power generation, but after 0.3 seconds, wind speed decreases, reducing power contribution. During the interval from 0.55 to 0.7 seconds, wind power remains relatively low; however, it still supports system stability by partially assisting the battery. After 0.75 seconds, wind generation increases again, restoring additional renewable contribution. This behavior demonstrates that integrating wind energy enhances system reliability and reduces sole dependency on battery storage. The battery charging and discharging characteristics clearly reflect intelligent bidirectional converter operation. Initially, due to limited PV generation, the battery discharges to support load requirements. After the increase in solar irradiance at 0.2 seconds, surplus renewable power charges the battery, increasing its state of charge. During renewable unavailability or reduced generation periods, the battery discharges again to maintain load continuity. Once renewable generation recovers, the battery returns to charging mode. This dynamic charging-discharging cycle confirms the effectiveness of the energy management system in optimizing battery utilization while preserving operational continuity.

Grid power behavior also validates proper system coordination. Under normal operating conditions, the inverter supports both load and grid interaction, allowing surplus renewable power injection into the utility grid. However, during the simulated grid outage from 0.5 to 0.7 seconds, grid power becomes unavailable, and no power injection occurs. Despite this disconnection, the combined operation of battery backup and renewable sources ensures uninterrupted power supply to the EV load. After 0.7 seconds, grid connectivity is restored, and the inverter resumes grid power injection using available renewable surplus. This confirms the system's ability to maintain stable operation during grid disturbances. Overall, the results confirm that the proposed hybrid PV–wind renewable energy system with battery backup provides reliable and continuous power supply for EV charging applications. The system effectively manages dynamic solar irradiance, wind variability, battery charging/discharging, and temporary grid outages while maximizing renewable energy utilization. The integration of complementary renewable sources significantly reduces battery stress, enhances energy efficiency, and improves overall system reliability. These findings validate the suitability of the proposed architecture for sustainable smart grid applications, renewable EV charging infrastructure, and advanced distributed energy systems.

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VI. CONCLUSION AND FUTURE SCOPE

The proposed hybrid renewable energy system successfully integrates photovoltaic (PV), wind energy, battery energy storage, and grid connectivity to provide reliable and continuous power supply for electric vehicle (EV) charging and smart grid applications. The MATLAB/Simulink-based model demonstrates effective coordination of multiple renewable sources under dynamic operating conditions, including varying solar irradiance, fluctuating wind speed, and temporary grid outages. The implementation of Maximum Power Point Tracking (MPPT) ensures optimal power extraction from the PV source, while the bidirectional buck–boost converter enables efficient battery charging and discharging based on real-time power availability and load demand.

Simulation results confirm that the system maintains uninterrupted EV load supply even during periods of reduced or zero PV generation by utilizing battery backup and alternate wind energy support. The integrated control strategy effectively manages source transitions, stabilizes DC-link voltage, and optimizes power flow between renewable sources, battery storage, EV load, and the utility grid. During surplus generation, excess renewable power is successfully utilized for battery charging and grid injection, thereby enhancing energy efficiency and reducing renewable wastage. The inclusion of wind energy as a supplementary source significantly reduces dependency on battery storage alone, thereby minimizing battery stress and improving system reliability.

Hardware implementation and real-time prototype development can be pursued to validate simulation outcomes under practical operating conditions. Future systems may also explore vehicle-to-grid (V2G) functionality, allowing EV batteries to actively support grid services during peak demand periods. Expanding the system to include additional renewable sources such as fuel cells or hydrogen storage can further improve energy security and sustainability. Moreover, techno-economic analysis and large-scale deployment studies can help assess the commercial viability of the proposed system for smart cities, renewable charging stations, and distributed micro grid applications.

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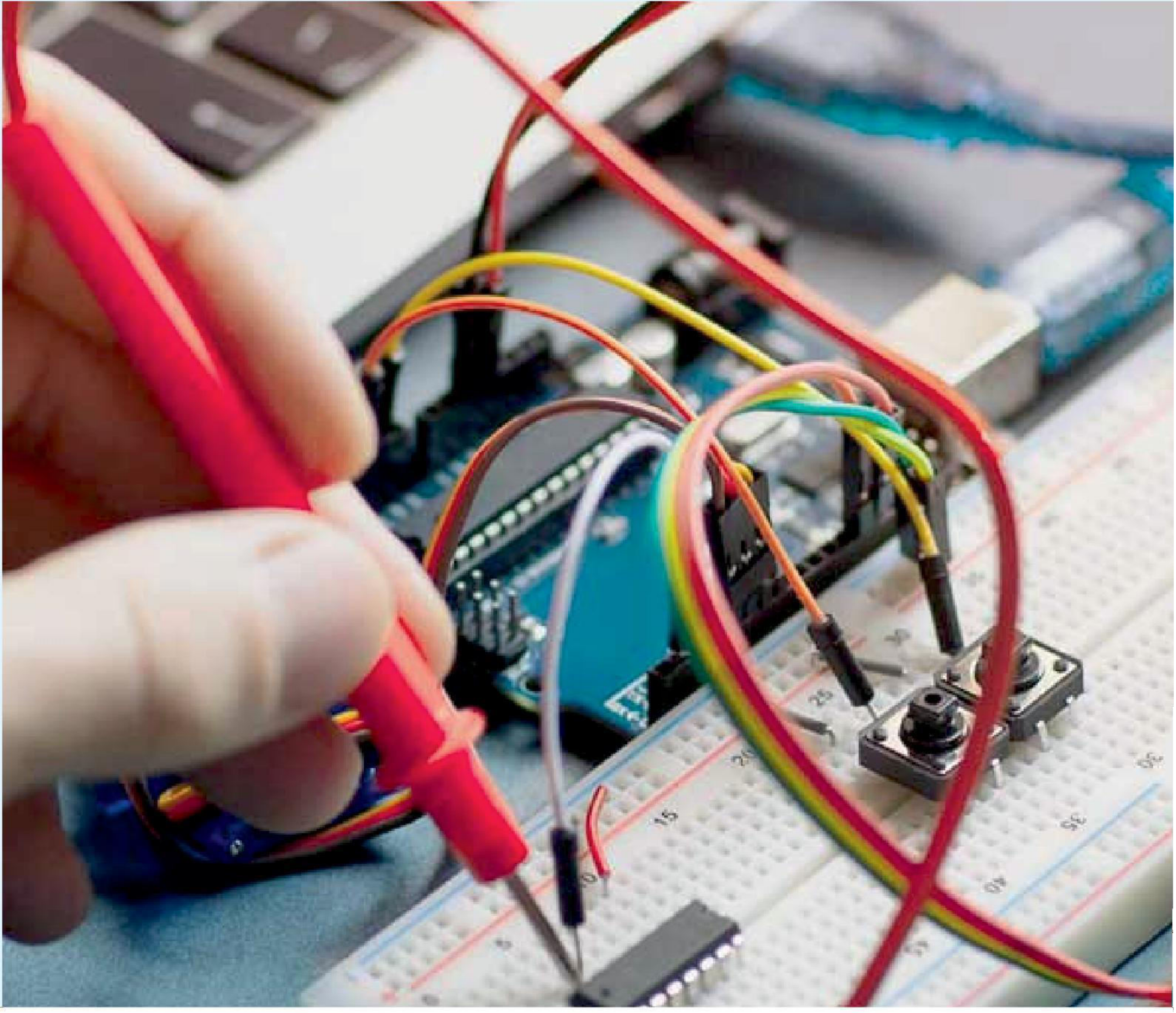

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