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Original Article

Grid Integrated Renewable Energy Based EV-Charging Station

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Abstract: This paper presents a comprehensive energy management approach for a hybrid DC microgrid integrating solar, wind, and battery storage systems. The primary objective is to develop an advanced control strategy for electric vehicle (EV) charging stations, ensuring robust and resilient grid-connected operation. The proposed methodology addresses key aspects such as power balancing, DC bus voltage regulation, and battery state-of-charge (SoC) optimization. To meet these objectives, a hierarchical control architecture is implemented, structured into primary, secondary, and tertiary levels. The primary control ensures real-time power matching between renewable sources and load demand, while the secondary control manages battery operations to smooth fluctuations and improve system stability. A bi-directional DC-DC converter with a dual-switch topology is designed specifically for efficient battery charging and discharging control.

Keywords— Power Management Controller, AC/DC Hybrid Microgrid, Battery Energy Storage System (BESS), Solar Photovoltaic (PV) System, and Doubly-Fed Induction Generator (DFIG) Wind Turbine.

I. INTRODUCTION

The growing global demand for energy, coupled with mounting concerns over climate change and environmental sustainability, has driven significant interest in incorporating renewable energy sources into modern power systems [1]. Microgrids—defined by their localized generation, distribution, and consumption of energy—have emerged as a promising solution to meet these challenges. Among various microgrid configurations, the hybrid integration of solar and wind energy, complemented by advanced energy storage systems, offers a transformative approach to sustainable energy generation, storage, and management.

Solar photovoltaic (PV) systems convert sunlight into electricity, while wind turbines harness kinetic energy from the wind to produce power—both are renewable, sustainable, and environmentally friendly, emitting little to no greenhouse gases during operation [2, 3]. The installation of these renewable sources has seen exponential growth globally, with over 1 TW of installed solar PV capacity and more than 900 GW of wind energy capacity as of 2024. However, their inherent intermittency and variability—due to fluctuating weather conditions—pose significant challenges in maintaining a consistent and reliable power supply in microgrid environments [4].

To address these reliability issues, energy storage technologies—particularly battery energy storage systems (BESS)—are critical. Batteries store surplus energy generated during peak periods and discharge it during periods of low generation or high demand, thus stabilizing voltage and frequency within the microgrid. Lithium-ion batteries dominate the market due to their high energy density, fast response times, and decreasing costs. Alternative technologies such as flow batteries, super capacitors, and flywheels are also gaining attention for specific use cases. Integrating these storage solutions not only enhances grid reliability but also enables real-time energy optimization and load balancing, especially crucial for energy-intensive applications like electric vehicle (EV) charging [5].

The primary objective of this work is to develop a novel hybrid EV charging station capable of providing fast and efficient charging while placing minimal load on the utility grid. Presently, most EV charging stations source power directly from the utility grid, which remains largely dependent on fossil fuel-based power generation. This undermines the environmental benefits of EVs, which are otherwise promoted as sustainable alternatives to internal combustion engine vehicles. Therefore, transitioning to renewable energy-based hybrid DC microgrids is imperative for realizing the full ecological potential of EV adoption [6].

In this proposed system, a DC microgrid architecture is developed, consisting of a PV-battery array interconnected through a bi-directional DC-DC converter and interfaced with the AC utility grid. The AC grid is supported by a doubly-fed induction generator (DFIG), which allows for variable speed operation and increased efficiency in harnessing wind energy. The bi-directional converter plays a pivotal role in regulating power flow within the DC grid and the battery storage technology (BST), which together form the foundation of the EV charging infrastructure. During surplus generation, excess energy is stored in the battery, while in cases of high load or renewable unavailability, stored energy or AC grid power can be utilized. A schematic representation is provided in Figure 1.

Furthermore, intelligent energy management systems (EMS) and real-time control algorithms are integrated to monitor generation patterns, storage states, and demand profiles. The EMS ensures optimal scheduling and switching between energy sources, enhancing system efficiency, longevity of battery life, and minimizing energy wastage. Integration with IoT-based sensors and cloud data platforms allows predictive maintenance, user analytics, and dynamic pricing models for EV users.

Looking ahead, the deployment of such hybrid renewable-powered EV charging stations can significantly decarbonize transportation infrastructure, especially in urban areas and highways. By enabling vehicle-to-grid (V2G) capabilities, EVs themselves can act as mobile storage units, feeding power back into the grid during peak hours. Additionally, with advancements in power electronics and AI-based control systems, future micro grids are expected to become even more autonomous, adaptive, and economically viable.

The major contributions of this paper are outlined as follows:

1. Adaptive Power Management in Hybrid Micro grids: A novel Power Management Controller (PMC) is proposed to address the frequent and unpredictable fluctuations in both power generation and load demand within a hybrid microgrid environment. The PMC dynamically monitors real-time parameters and intelligently coordinates energy flow between renewable sources (solar and wind), battery storage, and the utility grid. This ensures grid stability, reduces energy losses, and prevents system imbalance under variable generation conditions.

2. Enhanced Solar Energy Utilization in DC Microgrid Architecture: In the DC microgrid configuration, solar photovoltaic (PV) output variability—caused by diurnal patterns and weather fluctuations—is mitigated using a dedicated Battery Energy Storage System (BESS). The battery is charged during periods of excess solar generation and discharged during low solar output or peak load periods. This facilitates reliable and continuous power delivery, enabling the DC microgrid to operate independently or in conjunction with the main grid.

3. Seamless Bi-Directional Energy Flow Through Intelligent Converter Control: The integration of bi-directional DC-DC converters enables two-way energy exchange between the battery and the DC bus. This feature is crucial for both grid-connected and islanded modes of operation. The control strategy implemented ensures efficient charging and discharging cycles, maximizing battery lifespan and optimizing energy dispatch during high-demand periods, such as EV fast charging.

4. Integration with Doubly-Fed Induction Generator (DFIG) for Wind Power Support: The hybrid system incorporates a DFIG-based wind energy conversion system connected to the AC grid. The DFIG offers variable-speed operation and improved efficiency over traditional fixed-speed generators, providing an additional renewable source that enhances grid resilience and reduces dependency on solar alone.

II. HYBRID MICROGRID SYSTEM MODELING

A. Modeling of PV Array System

Individual photovoltaic (PV) cells are interconnected in both series and parallel configurations to achieve the desired voltage and current output levels in a photovoltaic (PV) array [7]. This arrangement enables the array to generate the required electrical power based on system design and load demand. To analyze and simulate the behavior of a solar cell, an equivalent electrical model is commonly used. This model typically consists of a current source representing the photocurrent, a diode to account for the p-n junction behavior, a series resistance to model internal losses, and a load connected externally. Figure 2 illustrates the equivalent circuit of solar cells connected in parallel, highlighting the combined electrical behavior of the PV system under such configuration.

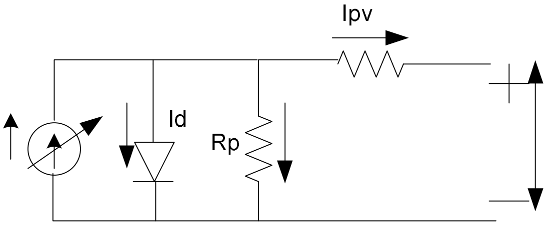

Figure 2 Equivalent circuit of PV system.

$$I_S = \left(\frac{\gamma}{\gamma_{ref}}\right) I_{Sref} + \alpha_{Isc}(T_a - T_{ref}) \qquad (1)$$

Where, γ represent irradiance level in w/m2, Ta is temperature in kelvin, α_{ISC} is short circuit current coefficient and I_{Sref}, T_{ref} and γ_{ref} are standard value under test conditions.

B. *Modeling of Battery Storage*

A battery, which serves as a source of electrical power, typically comprises multiple electrochemical cells connected in series or parallel to achieve the required voltage and capacity levels. Each electrochemical cell generates electrical energy through chemical reactions, and when combined, they form a complete battery system capable of storing and delivering power as needed.

Figure 3 illustrates the equivalent electrical circuit model of a storage battery unit. This model is widely used in energy system simulations to represent the dynamic behavior of batteries under various charging and discharging conditions. The circuit effectively smooths out erratic fluctuations in power output, particularly those arising from intermittent renewable energy sources such as solar and wind.

The relationship governing the terminal voltage of the battery is expressed by equation (2), which considers both the open-circuit voltage and the voltage drop across the internal resistance of the battery [8–10]:

$$V_B = V_{OC} + R_1 . I_b + V_1 \qquad (2)$$

Where: V_{oc}= open circuit voltage of the storage battery, I_b = battery current, V_B = battery terminal voltage.

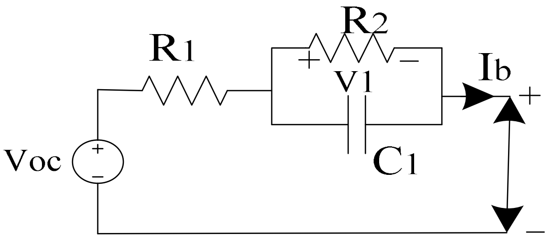

Figure 3 Equivalent circuit of storage battery.

C. *Modeling of Wind*

The Doubly-Fed Induction Generator (DFIG) is a widely used type of electrical generator in modern wind turbine systems, designed to convert the mechanical energy generated by the rotating turbine blades into electrical energy [11]. In the context of wind turbine modeling, this generator is commonly referred to by its acronym, DFIG.

The DFIG architecture allows the stator to be directly connected to the grid, while the rotor is connected via a back-to-back power electronic converter. This configuration provides variable-speed operation and enables independent control of both active and reactive power, significantly improving the overall efficiency and stability of the wind energy conversion system.

DFIGs are especially advantageous because they can efficiently harvest wind energy over a broad range of wind speeds, allowing wind turbines to operate closer to their optimal power point under varying atmospheric conditions. This feature makes DFIG-based systems more effective than fixed-speed generators, particularly in large-scale wind farms where grid compliance, power quality, and dynamic control are critical.

Furthermore, the power output of a wind turbine equipped with a DFIG can be expressed as a function of wind speed using a piecewise-defined mathematical model, which captures the nonlinear relationship between wind speed and electrical output. This modeling approach accounts for different operating regions of the wind turbine, including cut-in, rated, and cut-out wind speeds, providing a more accurate and realistic simulation of system performance.

$$\mathrm{P}(v) = \begin{cases} \frac{P_r(v - v_{ci})}{(v_r - v_{ci})} & v_{ci} \le v \le v_r \\ P_r & v_r \le v \le v_{co} \\ 0 & v < v_{ci} \ or \ v > v_{co} \end{cases} \qquad (3)$$

Where $P_W(v)$ is wind turbine generator output with ambient wind speed v, P_r is power of wind turbine at rated speed and v_{ci} **is cut in wind speed** , v_{co} is the cut-out wind speed and vr is rated wind speed.

III. EV-CHARGING STATION

The widespread adoption of electric vehicles (EVs) within society is closely linked to the availability and accessibility of reliable charging infrastructure [12]. However, EV charging stations typically require a substantial amount of electrical energy, which, in many regions, is still predominantly sourced from fossil fuel-based power plants. Consequently, while EVs are often promoted as environmentally friendly alternatives to conventional vehicles, their true potential for reducing carbon emissions can only be realized when renewable energy sources—such as solar and wind power—are utilized for charging purposes [13, 14].

The primary objective of this research is to design and implement a renewable energy-integrated subsystem aimed at minimizing dependency on the conventional utility grid. This is achieved through the development of an optimized charging station infrastructure that supports large-scale EV charging while maximizing the use of clean, renewable energy sources [15].

In the proposed system, EV charging is facilitated via renewable energy input using a bi-directional DC-DC converter. This converter plays a critical role in maintaining the required battery voltage and managing the state of charge (SOC) of the EV battery. On one side of the converter, DC power is supplied by a PV-Wind hybrid system, while on the other side, the EV battery system is connected, enabling efficient power transfer between the two [16, 17].

This study introduces a bi-directional DC-DC converter with a dual-switch topology, as illustrated in Figure 4. The proposed converter is capable of simultaneous buck and boost operations, allowing both charging and discharging of the battery depending on the system's real-time power flow requirements [18–20]. This flexible and intelligent control mechanism ensures stable, efficient, and grid-independent operation of EV charging infrastructure while aligning with sustainability goals.

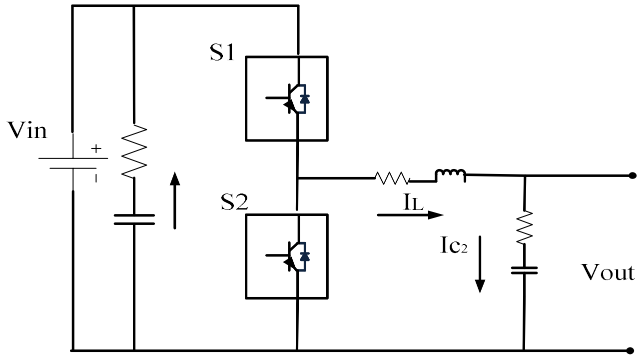

Figure 4. The single line diagram of proposed DC-DC converter

IV. SIMULATION MODEL AND RESULT DISCUSSION

The simulation setup includes a main utility grid rated at 154 MW and 34.5 kV, representing a realistic medium-voltage distribution network. A step-down transformer is employed to reduce the grid voltage to 0.4 kV, making it suitable for interfacing with the low-voltage microgrid components.

The hybrid generation system consists of a Doubly-Fed Induction Generator (DFIG)-based wind turbine system and a dual-stage photovoltaic (PV) array, enabling efficient energy harvesting from both wind and solar resources. A Voltage Source Inverter (VSI) is used to facilitate the conversion of DC power from the hybrid sources into synchronized AC power compatible with the grid.

To support EV charging, a dual-switch bidirectional DC-DC converter is integrated into the system. This converter performs bidirectional energy transfer, converting AC power into regulated DC power for charging the EV battery pack, and vice versa if needed for vehicle-to-grid (V2G) operation.

The detailed specifications of the system components—including PV capacity, wind turbine ratings, battery configuration, converter parameters, and grid connection details—are provided in Table 1, serving as a reference for the simulation environment and validation results.

Table-1

Solar PV array	
Parallel - Series	10, 5
Voltage generated	33.18 V
Current generated	78.35 A
Values of resistance and capacitor across solar PV array	R = 1e-3 (ohm) and C = 1000e-6 (F)

PV-Boost converter	
RL Branch	R = 0.1 ohm, L = 1e-3 (H)
RC Branch	R = 0.1 ohm, C = 100e-6 (F)
Boosted voltage	48.06 V
Unit delay	sample time = 1e-4 s
Duty cycle	$D_{max} = 0.48$, $D_{init} = 0.05$
PI controller/ upper	P = 1, I = 30,/

saturation limit	0.95
Bidirectional converter	
sample time	5e-6 s
switching frequency	10e3
PI controller gains	P = 0.005, I = 10
RC branch	R = 0.1, C = 1e-6 F
RL branch	R = 0.1, L = 1e-3 H
Battery Parameters	
Voltage	24V
Rated capacity	40Ah
Initial state of charge (SOC)	45 %
Battery response time	1 s

During the operation of the hybrid microgrid system, the primary sources contributing to electrical power generation are the Solar Photovoltaic (PV) system, the Doubly-Fed Induction Generator (DFIG)-based Wind Turbine (WT), and the battery energy storage system (BESS). These components work in coordination to ensure a stable and continuous power supply to meet the load demand and support EV charging infrastructure.

The solar PV output is inherently variable and follows a nonlinear, stochastic pattern, influenced by factors such as solar irradiance, temperature, and time of day.

The hybrid micro grid system incorporates a DC load of 15.5 kW along with two AC loads rated at 17.5 kW and 12.5 kW, respectively. These loads collectively simulate realistic energy demand scenarios within a distributed energy system. As the solar irradiance varies over time, the output from the PV system also fluctuates accordingly. To ensure consistent power delivery, the battery storage unit dynamically adjusts its output to complement the PV generation, thereby maintaining system stability.

It is evident that the grid power flow becomes negative, indicating that the hybrid microgrid is not only self-sufficient but also feeding excess power back into the grid, thus contributing positively to the overall energy infrastructure. The battery system plays a crucial role in balancing the power mismatch caused by the variable nature of solar generation. It charges during periods of excess PV output and discharges when solar power declines, effectively smoothing the fluctuations.

Despite continuous variations in both solar and wind power generation, the system maintains a stable DC output at the DC bus, ensuring uninterrupted operation of the connected DC load. During periods of reduced solar output, the battery discharges to uphold the DC bus voltage. Conversely, when solar generation increases, the battery enters charging mode. This bidirectional power exchange enables the system to maintain a constant DC voltage across the DC bus, ensuring reliable operation of the load and supporting power quality requirements.

V. CONCLUSIONS.

The energy management of a hybrid solar–wind–battery-based DC microgrid offers a transformative approach to addressing the challenges of renewable energy integration, grid reliability, and clean transportation infrastructure. As the global energy landscape shifts toward decentralized and decarbonized systems, hybrid micro grids are emerging as a key enabler in achieving both energy security and environmental sustainability.

This study has demonstrated the technical feasibility and operational effectiveness of a hierarchical, multi-level energy management system (EMS) tailored for a hybrid microgrid intended to support EV charging applications. The proposed control framework successfully coordinates energy flows among solar PV, wind turbines (DFIG-based), and battery energy storage systems, ensuring real-time power balancing, voltage stability, and efficient power dispatch. This coordination is particularly critical in DC microgrids, where consistent DC-bus voltage must be maintained for proper functioning of EV charging stations and power electronic converters.

By intelligently leveraging the complementary nature of solar and wind resources, the microgrid increases its operational flexibility and energy harvesting efficiency. Solar PV typically performs best during daylight hours, while wind power may be available intermittently across day and night. This complementary generation profile reduces the burden on storage systems and utility grids, enhancing overall system reliability.

The bi-directional DC-DC converter with dual-switch topology plays a pivotal role in enabling bidirectional energy transfer, supporting both charging and discharging cycles. This capability allows not only charging of EVs but also potential Vehicle-to-Grid (V2G) interaction in future deployments, turning EVs into mobile energy storage units.

Simulation results validate the system’s robustness under varying solar irradiance, wind speed, and load profiles. The system is shown to sustain constant DC output, preserve battery health by managing the state of charge (SOC) within safe limits, and maintain grid stability in both on-grid and islanded modes. These results confirm the practical applicability of the proposed model in a wide range of scenarios, from urban grid-connected EV charging networks to remote rural electrification projects where grid access is limited or unreliable.

Additionally, this study addresses the growing concern of indirect emissions associated with EV adoption. While EVs are often labeled as zero-emission vehicles, their environmental benefits are only fully realized when the electricity used for charging is generated from clean energy sources. The integration of renewables into EV charging infrastructure through micro grids provides a true green mobility solution, aligning with global climate goals and net-zero emission targets.

From an economic perspective, the optimized use of renewable energy reduces dependency on expensive grid power and peak-time tariffs, offering cost savings for both operators and end-users. Moreover, intelligent energy dispatch and load prioritization can lead to demand-side optimization, reducing operational costs while improving power quality and user satisfaction.

Future Scope

To further enhance the system, future work could explore:

- Integration of Machine learning algorithms for predictive energy management and fault detection.
- Use of real-time weather forecasting and adaptive MPPT algorithms to maximize renewable energy capture.
- Deployment of block chain-based energy trading within microgrid communities.
- Expansion of the model to accommodate multi-point EV charging, demand response features, and peer-to-peer energy sharing.

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