Integration of Wind Energy into a Grid-Connected PV-BES Electric Vehicle Charging Station for Enhanced Renewable Energy Utilization

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Abstract: This paper presents a hybrid PV-wind-battery electric vehicle charging station designed to increase renewable-energy utilization and reduce dependence on the utility grid. The new system builds on an existing setup where solar panels and batteries are connected to the same DC bus, and it adds a Wind Energy Conversion System to this shared bus. A Battery Energy Storage System (BESS), bidirectional converter, grid-connected voltage source converter, and Energy Management System (EMS) coordinate source sharing and charging continuity. A MATLAB/Simulink model verifies the system under renewable variation, grid disconnection, and grid reconnection. The revised paper uses compact conference-style discussion with PV, wind, battery, DC-link, and EV charging equations to present the technical model clearly.

Index Terms: EV charging, photovoltaic system, wind energy conversion, BESS, DC bus, EMS, grid-connected inverter.

I. INTRODUCTION

The quick rise in electric vehicles (EVs) is a major push for sustainable transportation around the world. As governments and businesses encourage people to switch from traditional gas-powered cars to electric ones, there's a growing need for efficient, dependable, and eco-friendly charging setups. Even though a lot of electricity still comes from fossil fuel power plants, using renewable energy at EV charging stations is now a big focus for cutting down harmful emissions and making energy use more sustainable.

Solar panels are a common choice for charging electric vehicles because they create clean energy, don't cost much to use, and are simple to install. Charging stations that are connected to the power grid can use solar energy during the day and switch to the grid when the sun isn't shining. To keep charging going even when the sun isn't out, Battery Energy Storage Systems (BESS) are used to store extra solar energy and release it when needed. Even though solar plus battery systems are better for using renewable energy, they still have limits during long cloudy periods or at night, making them rely more on the grid.

Wind energy is a good backup because it often works when solar energy is low. Adding a Wind Energy Conversion System (WECS) to an existing solar plus battery charging station can make renewable energy more available, make charging more reliable, and lower dependence on the grid without changing much of the existing setup. Plus, smart Energy Management Systems (EMS) can help manage power flow between solar, wind, batteries, and the grid to keep everything running smoothly under different weather conditions.

This paper suggests adding wind energy to an existing solar plus battery EV charging station that's connected to the grid. The new setup keeps the same power converter design and control methods but adds a wind system to help use more renewable energy. MATLAB/Simulink is used to test how well the system works under different renewable energy conditions. The results show that renewable energy is used more effectively, charging is more dependable, voltage control is more consistent, and there's less reliance on the grid for power.

The main points of this study are:

- Putting a wind energy system into an existing setup that already has solar panels and a battery for charging electric vehicles.
- Creating a smart Energy Management System to better manage how electricity is used.
- Using MATLAB and Simulink to design and test the new hybrid charging station.
- Testing how the system performs under changing renewable energy conditions.
- Showing better use of renewable energy and less reliance on the grid compared to the usual solar plus battery setup.

II. RELATED WORK AND RESEARCH GAP

Existing studies on EV charging stations cover rooftop PV charging, battery-assisted fast charging, grid synchronization, vehicle-to-grid operation, and smart energy management. These works show that renewable energy and BESS support can improve charging reliability and power quality.

The key limitation is that many PV-battery charging systems still depend mainly on solar irradiance. During low-sun conditions, the battery and grid carry most of the demand. This paper addresses that gap by adding wind generation and presenting a compact model with power-flow equations.

TABLE 1: Existing and Proposed Charging Architectures

Aspect	PV-Battery Station	Proposed PV-Wind-Battery Station
Renewable source	PV only	PV + wind
Low-sun support	BESS and grid	Wind + BESS + grid
Grid dependency	Higher during low irradiance	Reduced by hybrid renewable input
Control	Existing EMS	EMS retained with wind branch
Scalability	Moderate	Higher due to DC-bus modularity

III. PROPOSED SYSTEM ARCHITECTURE

A. System Architecture

The proposed station consists of a PV array, WECS, BESS, bidirectional DC-DC converter, voltage source converter, common DC bus, utility grid, EMS, and EV charging load. The PV and WECS branches inject renewable power into the DC bus. The BESS charges during surplus generation and discharges during deficit.

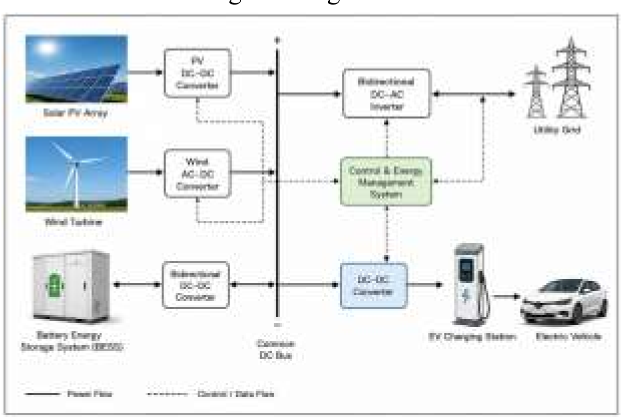

Fig. 1. Overall architecture of the hybrid PV-wind-battery EV charging station.

B. Operating Principle

The Energy Management System follows a renewable energy priority strategy to ensure efficient utilization of available power sources.

TABLE 2: Operating Modes of the Proposed System

Operating Condition	Power Source	Battery	Grid
High PV & Wind	PV + Wind	Charging	OFF
Moderate Renewable Power	PV + Wind	Idle	OFF
Low Renewable Power	PV + Wind + Battery	Discharging	OFF
Battery SOC Low	PV + Wind + Grid	Idle	ON
Night / Low Wind	Grid + Battery	Discharging	ON

The hybrid charging station works by keeping things in balance between the solar panels, the wind system, the battery, and the main power grid, all controlled by the Energy Management System. When everything is working normally, the solar panels and the wind turbine together send electricity to a shared DC bus to charge electric vehicles. If there's more electricity being produced than needed for charging, the extra power is sent to the battery using a special converter so it can be used later when needed.

When there's not enough sunlight, less wind, or more vehicles needing to charge, the system uses the stored energy in the battery to keep charging going without stopping. If the solar panels, wind generator, and batteries don't produce enough power on their own, the main power grid provides the extra electricity needed through a voltage converter. This way of managing everything helps maintain a steady voltage, uses renewable energy more effectively, relies less on the main power supply, and makes the whole charging station more reliable and effective.

TABLE 3: Main Functional Blocks

Block	Role
PV array	Supplies solar DC power through converter control.
WECS	Adds wind-generated power to improve renewable availability.
BESS	Buffers surplus/deficit power and supports grid outages.
VSC	Interfaces the DC bus with the utility grid.
EMS	Selects operating mode based on PV, wind, SOC, demand, and grid status.

IV. MATHEMATICAL MODEL

A. PV Array

PV output is approximated from rated PV power, irradiance, and cell-temperature correction.

$$P_{PV}=P_{rated}(G/G_{ref})[1+\alpha_T(T_c-T_{ref})] \qquad (1)$$

where P_{PV} is the output power of the PV array, G is Solar irradiance, G_{ref} is Reference irradiance, T_c is PV cell temperature, T_{ref} is Reference temperature, and α_T is the temperature coefficient.

B. Wind Energy Conversion

Wind-turbine output follows the standard aerodynamic power relation, where wind speed has a cubic influence on available power.

The mechanical power extracted from the wind turbine is given by

$$P_W = \frac{1}{2}\rho A C_p(\lambda,\beta) v_w^3 \qquad (2)$$

The tip-speed ratio is

$$\lambda = \frac{\omega_r R}{v_w} \qquad (3)$$

Here P_W is Wind turbine output power, ρ is air density, A is swept area, C_P is the power coefficient, β is pitch angle, λ is tip-speed ratio, and V_W is wind speed, ωr is Rotor angular speed (rad/s) and R is Turbine blade radius.

C. BESS and DC-Link

The Battery State of Charge (SOC) is updated using the charging and discharging currents as

$$SOC(k+1) = SOC(k) - \frac{(\eta_d I_{dis} - \eta_c I_{ch})\Delta t}{Q_B} \qquad (4)$$

Here SOC is Battery State of Charge, I_{dis} is Battery discharge current (A), I_{ch} is Battery charging current (A), η_d is Discharging efficiency, η_c is Charging efficiency, Δt is Sampling interval (s), Q_B is Battery capacity.

D. DC-Link Power Balance

The Energy Management System maintains power balance at the common DC bus as

$$P_{PV} + P_W + P_{BESS} + P_{Grid} = P_{EV} + P_{Loss} \qquad (5)$$

The EV charging power is calculated as

$$P_{EV} = V_{ch} I_{ch} \qquad (6)$$

Here P_{Grid} = Utility grid power (W), P_{BESS} = Battery power (W), P_{EV} = EV charging power (W), P_{Loss} = System losses (W), V_{ch} = EV charging voltage (V), I_{ch} = EV charging current (A).

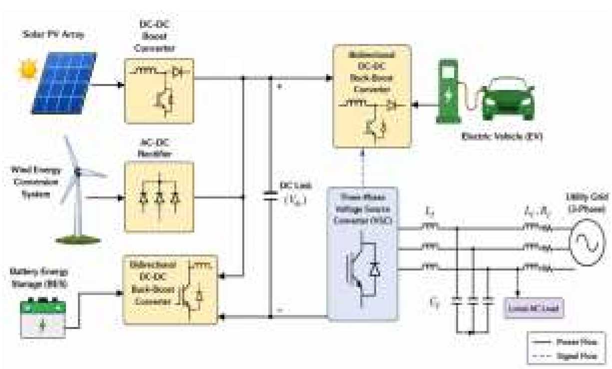

Fig. 2. Converter-level arrangement of the proposed station.

V. ENERGY MANAGEMENT STRATEGY

The EMS follows a simple priority order: use PV and wind first, charge the battery when renewable power is surplus, discharge the battery during renewable deficit, and import grid power only when renewable and battery support are insufficient.

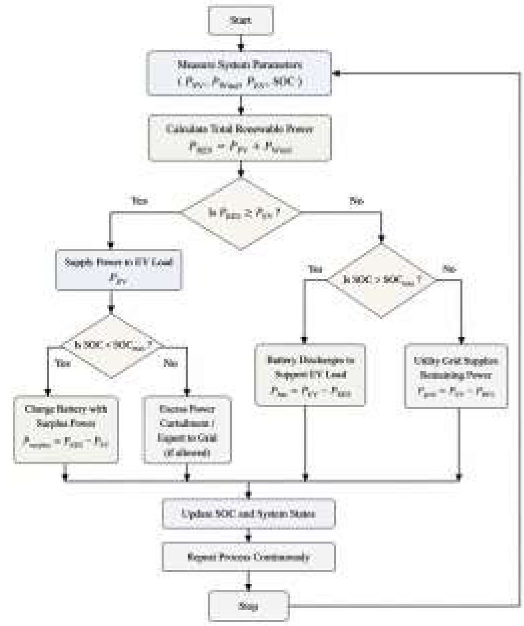

Fig. 3. EMS decision flow for renewable, battery, and grid operation.

TABLE 4: EMS Operating Rules

Condition	Source Priority	Battery Action	Grid Action
High PV + wind	Renewables	Charging	Off/Export
Renewables = demand	Renewables	Idle	Off
Low renewables, SOC ok	PV + wind + BESS	Discharge	Off
Low renewables, low SOC	PV + wind + grid	Protected	Import
Grid outage	PV + wind + BESS	Support load	Unavailable

VI. MATLAB/SIMULINK IMPLEMENTATION

The Simulink model contains PV generation, WECS, BESS, bidirectional converter, VSC, common DC link, grid, and EV charging load. The model is used to test whether the EMS maintains charging continuity and DC-link stability during changing renewable input and grid conditions.

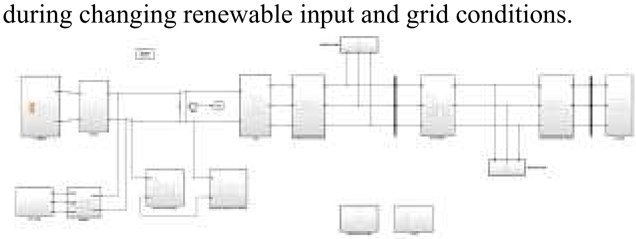

Fig. 4. MATLAB/Simulink model of the proposed hybrid EV charging system.

The key things used in the simulation are sunlight strength, how hot it is, how fast the wind is blowing, how much charge is left in the battery, how much electricity the electric vehicle needs, and whether the power grid is working or not. The monitored outputs are PV power, wind power, BESS response, grid power, DC-link voltage, and charging behavior.

TABLE 5: Simulation Inputs and Outputs

Subsystem	Input	Output
PV array	Irradiance, temperature	DC power
WECS	Wind speed	Rectified DC power
BESS	SOC, charge/discharge command	Battery power
VSC	DC-link voltage	Grid-synchronized AC power
EV load	Charging command	EV battery power

VII. CONTROL AND PERFORMANCE INDICES

The EMS evaluates renewable surplus, power deficit, grid dependency, and battery operating limits. These indices make the control logic easier to implement and also provide measurable performance criteria for the simulation.

Renewable Power Generation

The total renewable power generated by the hybrid system is

$$P_{RES} = P_{PV} + P_W \qquad (7)$$

Here P_{RES} is the total renewable power (W), P_{PV} is Photovoltaic power (W), P_W is Wind turbine power (W).

Surplus Renewable Power

The extra renewable energy left over after meeting the electricity needs of electric vehicles is.

$$P_{sur} = \max\left(P_{RES} - P_{EV}, 0\right) \qquad (8)$$

Here P_{sur} is Surplus renewable power (W), P_{EV} is EV charging power demand (W).

When $P_{sur} > 0$, the excess renewable energy is used to charge the Battery Energy Storage System (BESS).

If P_{sur} is positive, the EMS charges the BESS subject to the maximum SOC limit. If P_{def} is positive, the EMS first discharges the BESS when SOC is safe, and then imports the remaining power from the grid.

Power Deficit

The power deficit occurring when renewable generation is insufficient is calculated as

$$P_{def} = \max\left(P_{EV} - P_{RES}, 0\right) \qquad (9)$$

Here P_{def} = Required deficit power (W).

If $P_{def} > 0$, the Battery Energy Storage System supplies the deficit before drawing power from the utility grid.

Battery Operating Constraint

The Battery Energy Storage System operates within the allowable State of Charge (SOC) limits

$$SOC_{min} \le SOC(k) \le SOC_{max} \qquad (10)$$

Here $SOC(k)$ is Battery state of charge at sampling instant k, SOC_{min} is Minimum allowable SOC, SOC_{max} is Maximum allowable SOC.

Grid Power Requirement

The utility grid supplies only the remaining power after battery support, which is expressed as

$$P_{Grid} = \max\left(P_{def} - P_{BESS}, 0\right) \qquad (11)$$

Here P_{Grid} is Utility grid power (W), P_{BESS} is Battery discharge power (W)

Grid Dependency Index (GDI)

The Grid Dependency Index is used to measure how much the charging station relies on the utility grid.

$$GDI = \frac{E_{Grid}}{E_{EV}} \qquad (12)$$

Here E_{Grid} i represents the total energy supplied by the utility grid (Wh), E_{EV} is the total energy needed by the electric vehicle charging load (Wh)

A lower value of GDI indicates reduced dependence on the utility grid.

Renewable Energy Utilization (REU)

The Renewable Energy Utilization factor is calculated as

$$REU = \frac{E_{RES,used}}{E_{EV}} \qquad (13)$$

Here $E_{RES,used}$ is the renewable energy used for charging electric vehicles (Wh), E_{EV} is the total energy needed for charging all electric vehicles (Wh)

A higher REU indicates better utilization of renewable energy resources.

Here, GDI is the grid-dependency index, and REU is renewable-energy utilization. A good hybrid charging station should reduce GDI and increase REU while keeping the DC link stable and protecting the battery.

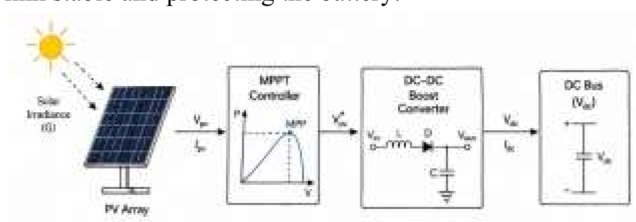

Fig. 5. PV generation block with MPPT converter and DC-bus interface.

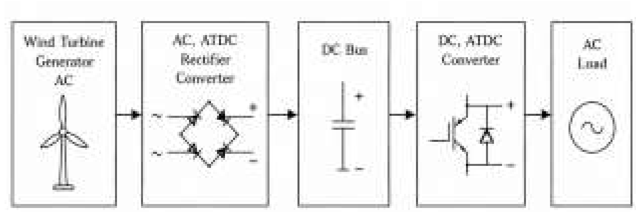

Fig. 6. Wind energy conversion path with rectifier and DC-bus interface.

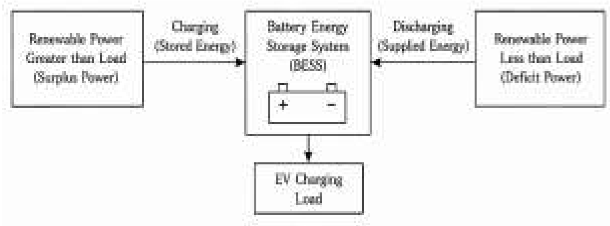

Fig. 7. BESS charging and discharging power-flow representation.

VIII. RESULTS AND DISCUSSION

A. Renewable Variation

During renewable variation, PV and wind power jointly support the charger. The battery compensates for short deficits and absorbs surplus energy. The DC-link response remains stable, showing effective source coordination.

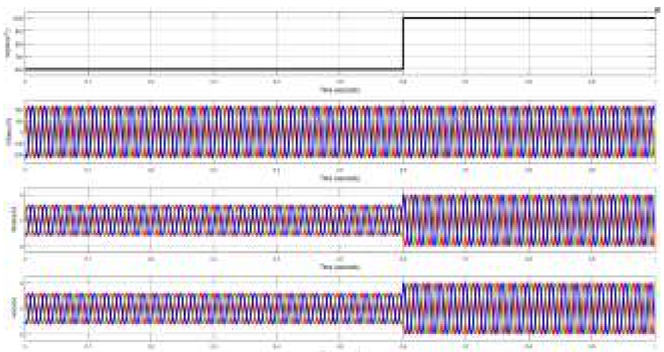

Fig. 8. Simulated responses under varying renewable generation.

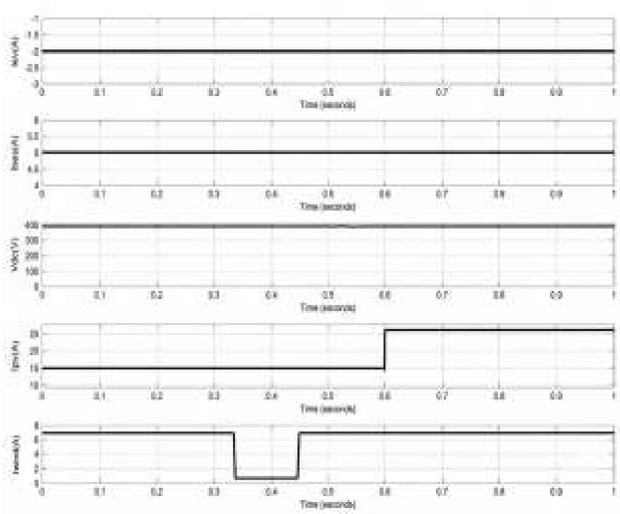

Fig. 9. DC-link and operating signal response for renewable variation.

B. Grid Disconnection

When the grid is disconnected, the EMS changes the station to renewable-battery mode. The BESS supports the DC bus when there's not enough renewable energy coming in, which allows EV charging to continue but only as much as the available energy permits.

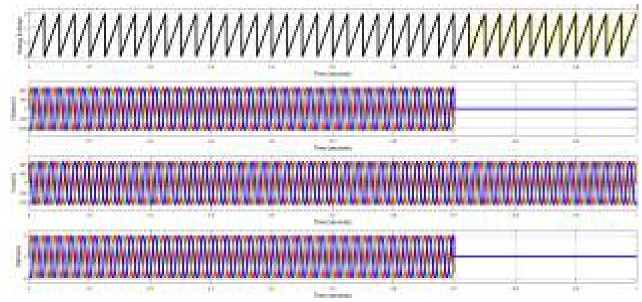

Fig. 10. Source and load response during grid interruption.

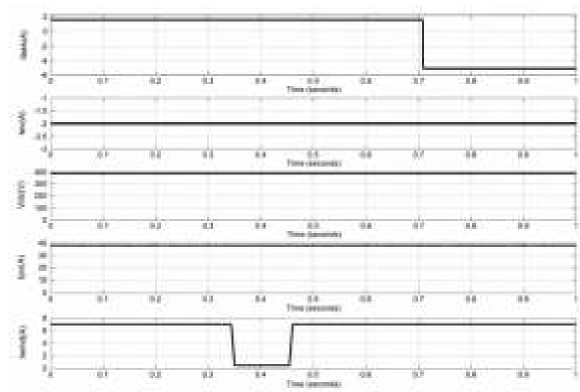

Fig. 11. System response during grid disconnection.

C. Grid Reconnection

After grid restoration, the VSC resumes synchronized operation. The EMS redistributes power smoothly between renewable sources, BESS, grid, and load, avoiding charging interruption.

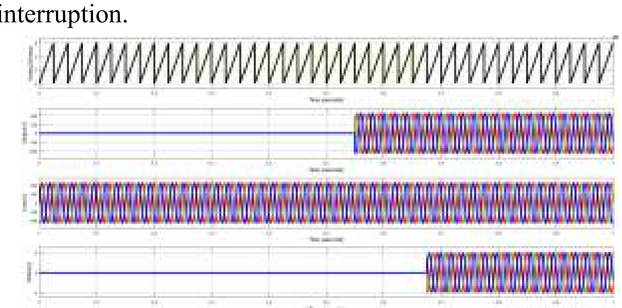

Fig. 12. Renewable and grid-supported response during reconnection.

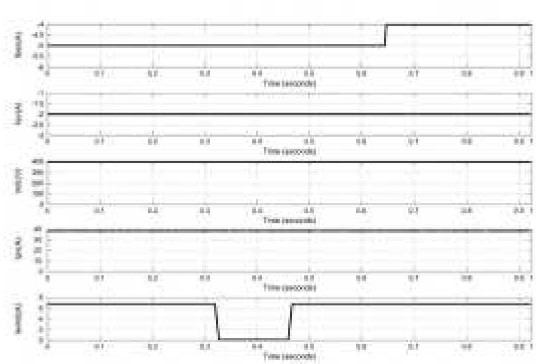

Fig. 13. System response during grid reconnection.

IX. ADVANTAGES AND LIMITATIONS

The hybrid station improves renewable utilization, reduces grid import during low-solar periods, and provides better charging continuity than a PV-only station. The common DC-bus structure is modular, so additional renewable or charging units can be added.

The present work is simulation-based. Practical deployment requires component sizing, converter-loss analysis, protection design, communication reliability, battery aging evaluation, and real-time controller validation.

TABLE 6: Technical Benefits of the Proposed Hybrid System

Evaluation point	Expected improvement
Renewable availability	Higher because PV and wind complement each other.
Battery stress	Lower because wind can reduce frequent discharge.
Charging continuity	Improved during low solar and grid events.
Grid dependency	Reduced through renewable priority control.
Scalability	Improved through common DC-bus modularity.

X. CONCLUSION

A concise conference-style model of a grid-connected PV-wind-battery EV charging station has been presented. The proposed WECS addition improves renewable availability while retaining the PV-battery station structure. The equations for photovoltaic output, wind power, battery energy storage system state of charge, DC-link balance, and electric vehicle charging power explain the technical foundation of the system.

Simulation results verify stable operation during renewable variation, grid disconnection, and reconnection. Future work can include hardware-in-loop validation, optimized EMS control, economic sizing, battery degradation analysis, and vehicle-to-grid operation.

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