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Design Strategies of Polymer Composite Components for Sustainable Renewable Energy Microgrids

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Abstract

Increasing power demand and variable performance requirements in renewable-energy systems motivate integrating advanced polymeric and composite materials into microgrid components to improve reliability and performance. This paper presents a design and control framework for a standalone microgrid that couples power-electronic and energy-conversion subsystems with polymer-composite–based components to enhance durability, thermal management, and electromagnetic shielding. The microgrid uses a doubly fed induction generator (DFIG) for wind generation to enable independent active and reactive power control, and a photovoltaic (PV) array interfaced through a boost converter implementing an incremental-conductance MPPT algorithm. A common DC bus links the subsystems, while an energy management system (EMS) orchestrates power flow between generation, a battery energy storage system (BESS), and loads. Polymer-composite elements—such as composite housings for power electronics, thermally conductive polymer composites for heat-sinking, and dielectric polymer layers for DC-link insulation—are proposed and characterized via material property inputs in the simulation model. MATLAB/Simulink results demonstrate DC-link voltage regulation at 750 V and stable load voltage and frequency under source intermittency and load transients. The paper discusses how polymer-composite selection and design (mechanical, thermal, and electrical properties) affect system reliability and offers guidelines for material-property-driven system optimization.

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INTRODUCTION

The global transition from fossil-fuel generation to renewable energy is accelerating due to environmental concerns and rising electricity demand [20]. Among renewable technologies, wind and solar are attractive for microgrid deployment because of abundant resource availability and low installation cost. However, their intermittent and partly unpredictable nature complicates stable power delivery and power-quality maintenance in standalone systems . Microgrids—local power systems that can operate grid-tied or islanded—offer a practical architecture to integrate these resources close to loads, but islanded operation poses challenges for voltage regulation, frequency control, and overall power balance [11, 14, 20].

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Hybrid wind–solar microgrids improve reliability relative to single-source systems by smoothing overall generation [7, 8] variability; reliability and operational flexibility increase further when an energy storage system (ESS) is incorporated to buffer supply–demand mismatches . For isolated operation, control strategies must therefore ensure both stable generator operation and maximum power extraction [3, 10] from renewable sources. [Doubly fed induction generator (DFIG) [9, 19]–based wind systems provide independent active and reactive power control and have shown strong performance for voltage and frequency regulation, including during unbalanced or nonlinear loading in islanded mode . On the solar side, DC–DC boost converters implementing incremental-conductance MPPT algorithms permit high-gain voltage boosting and efficient maximum-power tracking, helping to hold the DC link at a desired setpoint . Converter-based topologies paired with battery energy storage systems (BESS) and multiport power converters reduce conversion stages, enable bidirectional power flow, and simplify energy management, yielding improved overall efficiency [1, 2].

Coordinated control of converters, generation units, and storage is essential to maintain DC-link voltage and supply quality under source intermittency and load transients; such coordinated schemes also avoid inefficient dump-load strategies and reduce switching losses and harmonic distortion . Recent advances demonstrate that hybrid microgrids with properly designed control and converter architectures can significantly enhance power quality and system stability under nonlinear and unbalanced loads . These electrical and control improvements create an opportunity to reassess material and component design in microgrids—specifically, to leverage advanced polymer and composite materials to improve thermal management, electrical insulation, electromagnetic interference (EMI) shielding, structural robustness, and manufacturability of power-electronic housings and ESS enclosures.[18].

This paper presents an integrated design and control framework for a standalone wind–solar microgrid that explicitly couples power-electronic and control subsystems with polymer-composite–based components. We use a DFIG for wind generation and a PV array interfaced through an incremental-conductance MPPT boost converter; a common DC bus links all subsystems while an energy management system (EMS) orchestrates power flow with a BESS. Crucially, [6, 13]. we model polymer-composite elements (for example, thermally conductive polymer composites for heat dissipation, dielectric polymer layers for DC-link insulation, and fiber-reinforced polymer enclosures for structural and EMI performance) and evaluate their influence on electrical stability, thermal performance, and reliability through MATLAB/Simulink studies [4, 5, 12]. By integrating material-property data and sensitivity analysis into the system model, we quantify how composite selection and design choices affect DC-link stability, [15–17] thermal margins of power electronics, and estimated system lifetime. The results illustrate pathways for material-driven optimization of hybrid renewable microgrids and identify experimental characterization and prototyping steps for future work.

SYSTEM DESCRIPTION AND OPERATING PRINCIPLE

The standalone microgrid comprises a PV array, a DFIG-based wind turbine, a battery bank, and power converters interconnected via a common ≈750 V DC bus; from a polymer-science perspective each subsystem offers materials research opportunities—polymeric encapsulants, backsheets and anti-reflective coatings for PV modules; high-performance polymer composites and nanocomposites for turbine blades; polymer electrolytes, separators, binders and casings for batteries; and advanced polymer dielectrics, thermal interface materials and enclosures for power electronics—while the DFIG stator is directly coupled to AC loads and the rotor is interfaced to the DC bus via a back-to-back converter to enable variable-speed operation, the PV array feeds a unidirectional boost converter to match the DC bus, the battery connects through a bidirectional converter for charge/discharge, and a three-phase voltage-source converter provides the AC voltage and frequency reference in island mode; the energy management system coordinates power sharing and maintains the DC bus near 750 V, and an overview of the system architecture and the material-relevant energy flows is shown in Figure 1

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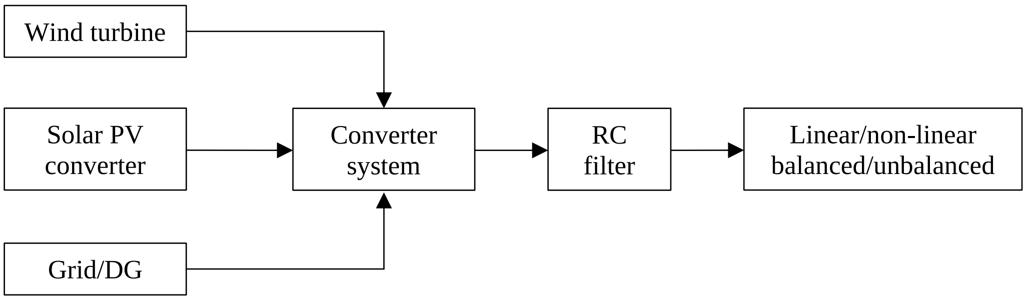

Figure 1. Block diagram Of Microgrid.

Wind Turbine and DFIG Subsystem

The wind energy part of this system uses a variable speed turbine connected to a DFIG. Wind hits the blades, creating torque on the shaft, which turns the generator. The amount of power that can be extracted from the wind depends on the wind speed and the aerodynamic efficiency of the blades, described by:

The wind power equation is:

$$P_w = 0.5 \times \rho \times A \times C_p(\lambda, \beta) \times V_w^{\ 3}$$

Here, ρ is air density (1.225 kg/m³), A is the blade sweep area using radius R = 3 m, V_w is wind speed, and C_p is a coefficient that changes depending on the tip-speed ratio and blade pitch angle. The shaft torque that results from this is:

$$T_m = \frac{P_w}{\omega_r}$$

where ω_r is rotor speed. On the electrical side, the DFIG torque is:

$$T_e = \frac{3}{2} \times \frac{P}{2} \times \frac{L_m}{L_s} \times \psi_s \times i_{rq}$$

where irq is the q-axis rotor current. For this system, the DFIG is rated at 10 kW, 400 V, 50 Hz, and the RSC is designed for about 30% of the generator's rated power, which keeps the losses low while still allowing precise torque and reactive power control. The DC link capacitor, ranging between 3000-5000 μF smoothens the voltage fluctuations and ensures stable operation during variations in wind speed or load.

By integrating these aerodynamic and electrical models with co-ordinated converter control this subsystem can constantly generate power and maintain the stability of DC link. It contributes to a balanced, effective hybrid energy system, which integrates seamlessly with the rest of the microgrid, and reacts swiftly to variations in wind conditions.

PV Array and Step up DC-DC Converter

The PV subsystem uses multiple panels connected in series and parallel to build up enough voltage and current. A boost converter with MPPT control takes this power and feeds it into the 750 V DC bus.

The MPPT algorithm used here is based on incremental conductance, which works by comparing the slope of the power-voltage curve and adjusting the duty cycle until the slope becomes zero, meaning the maximum power point has been reached. This method works well even when irradiance changes quickly throughout the day.

The electrical behavior of each panel is represented using the single-diode model:
where n is the ideality factor, V_t is thermal voltage, R_s and R_{sh} are the series and shunt resistances,

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The rated PV output is 8–10 kW at a voltage of 250–300 V. The boost converter raises this to 750 V using:

$$V_{dc} = \frac{V_{pv}}{1-D}$$

where D is the duty cycle set by the MPPT controller. An inductor of 2–4 mH is used to maintain continuous current flow, and the output capacitor reduces ripple. One thing to note is that the PV system does not directly regulate the DC bus voltage — it simply produces as much power as possible. The wind and battery systems handle any remaining bus voltage variation.

Battery Management System

Battery storage is important in this design because renewable sources alone cannot always match load demand exactly. A lithium-ion battery rated at 300–350 V and 6–8 kWh is used, operating between 20% and 90% state of charge to extend its service life.

The terminal voltage can be written as:

$$V_b = E_b - I_b R_b$$

where V_b is the terminal voltage, E_b is open circuit voltage, I_b is battery current, and R_b is the internal resistance . The state of charge changes over time as:

where C_b is the battery storage capacity in ampere-hours.

The battery is connected through a bidirectional DC-DC converter. When the DC link voltage goes above the set point, the converter charges the battery. When it drops below, the converter discharges. This converter can handle around 5–7 kW of power flow, which is enough to cover most transients in this system.

The EMS works alongside the battery to coordinate when it charges and discharges. Priority is given to using wind and solar power first. The battery is called in to fill the gap when generation falls short, or to absorb excess when generation is more than what the load needs.

Power Electronics Converter and EMS

To provide steady power to load, set of power electronic converters are connected to battery, PV, and wind subsystems to the shared DC link. The bidirectional battery converter controls energy storage, while the PV boost converter and the DFIG's rotor-side converter (RSC) controls their respective subsystems. A common DC link that is kept at about 750 V connects all these converters and serves as the hub for energy flow.

The voltage on the bus changes according to:

where I_{wind}, I_{pv}, and I_{bat} are the currents from the wind, PV, and battery subsystems, respectively, and I_{load} is the current consumed by the connected load. This equation emphasizes the importance of quick converter response and co-ordinated control to maintain voltage stability under variable generation and load conditions.

When microgrid is operating in standalone mode, the AC-side voltage controlled converter controls voltage and frequency and feeds power to the load. It ensures smooth and balanced power flow by using a current-controlled strategy with references obtained from the DC-link voltage and load demand. A neutral grounding transformer rated at 400/400 V stabilizes voltage and suppresses zero-sequence currents under unbalanced load condition. Inductive filters of 2–5 mH are included to minimize switching harmonics.

Power sharing between the wind, photovoltaic, and battery subsystems is co-ordinated by the Energy

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Management System (EMS), which oversees the entire operation. Priority is given to green energy sources, and the battery responds quickly to fill gaps or absorb excess energy. The overall power balance of the system is preserved in accordance with:

$$P_{wind} + P_{pv} \pm P_{bat} = P_{load} + P_{loss}$$

In order to reduce fluctuations, safeguard battery SOC limits, and guarantee dependable power delivery to the connected loads, the EMS continuously monitors generation and load and dynamically modifies converter set points. Through this integrated control, the converters and EMS enable the hybrid microgrid to operate smoothly under varying weather and load conditions, maximum maintaining stable DC voltage, frequency, and Stable Power Supply.

RESULT AND DISCUSSION FOR DIFFERENT OPERATING CONDITIONS

A DFIG-based wind system, a PV array with MPPT, and a battery storage unit connected to a shared DC connection maintained at 750 V were used to simulate the hybrid microgrid. Power sharing, DC-link voltage, and load-side voltage were observed under various operating conditions created by varying load levels and switching renewable sources as given in Figure 2. What is seen in the simulation results for each case is explained in the discussion that follows.

. Steady Load with Wind Turbine Start and Stop

The micro grid is attached to a constant 10 kW three phase load. This is because the wind system is not connected, and it provides the load during the initial years of the simulation assuming the PV array and battery. The DC-link voltage will be near 750 V and load voltage will not fluctuate.

When the wind turbine is brought online at 10 m/s, DFIG output gradually increases to approximately 7.8 kW. This increase is not jagged because the rotor circuit current is modified by the RSC controls the rotor current carefully during startup. When wind is added to system, the battery is decreased automatically. The DC voltage only subjected to a mild and temporary disturbance which quickly subsides due to the activity of the LSC.

When the wind is then disconnected, power drops. The battery picks up immediately by increasing its discharge, and the bus voltage returns to reference within a short time. Load voltage and frequency stay normal throughout, which shows the system handles wind switching well as shown in Figure 3.

Constant Load, PV System Start and Stop

Under this case, PV array and battery provide same 10 kW load with the wind system disconnected. Initially, the system will initially utilize full-load of the battery when the PV system is disconnected.

The PV system in question generates approximately 9 kW at PV voltage of approximately 275 V. The boost converter steps this up to the bus. Battery discharge drops as PV power rises, and the bus stays near 750 V.

When the photo-voltaic system is turned off, zero contribution of PV takes place with an immediate reaction of a battery that starts to discharge more to balance the power supply. A minor drop in DC-link voltage is found which quickly recovers. This transition is made steady by the load voltage as shown in Figure 4.

Wind and PV Supplying a Constant Load Together

Both sources run at the same time here with the 10 kW load. Wind produces around 7–8 kW and the PV around 3–4 kW depending on irradiance. Total generation exceeds load, so the surplus flows to the battery. It charges at about 3–5 kW. The bus voltage stays within its normal range and the converters do not exceed their ratings. No oscillations were seen during this test.

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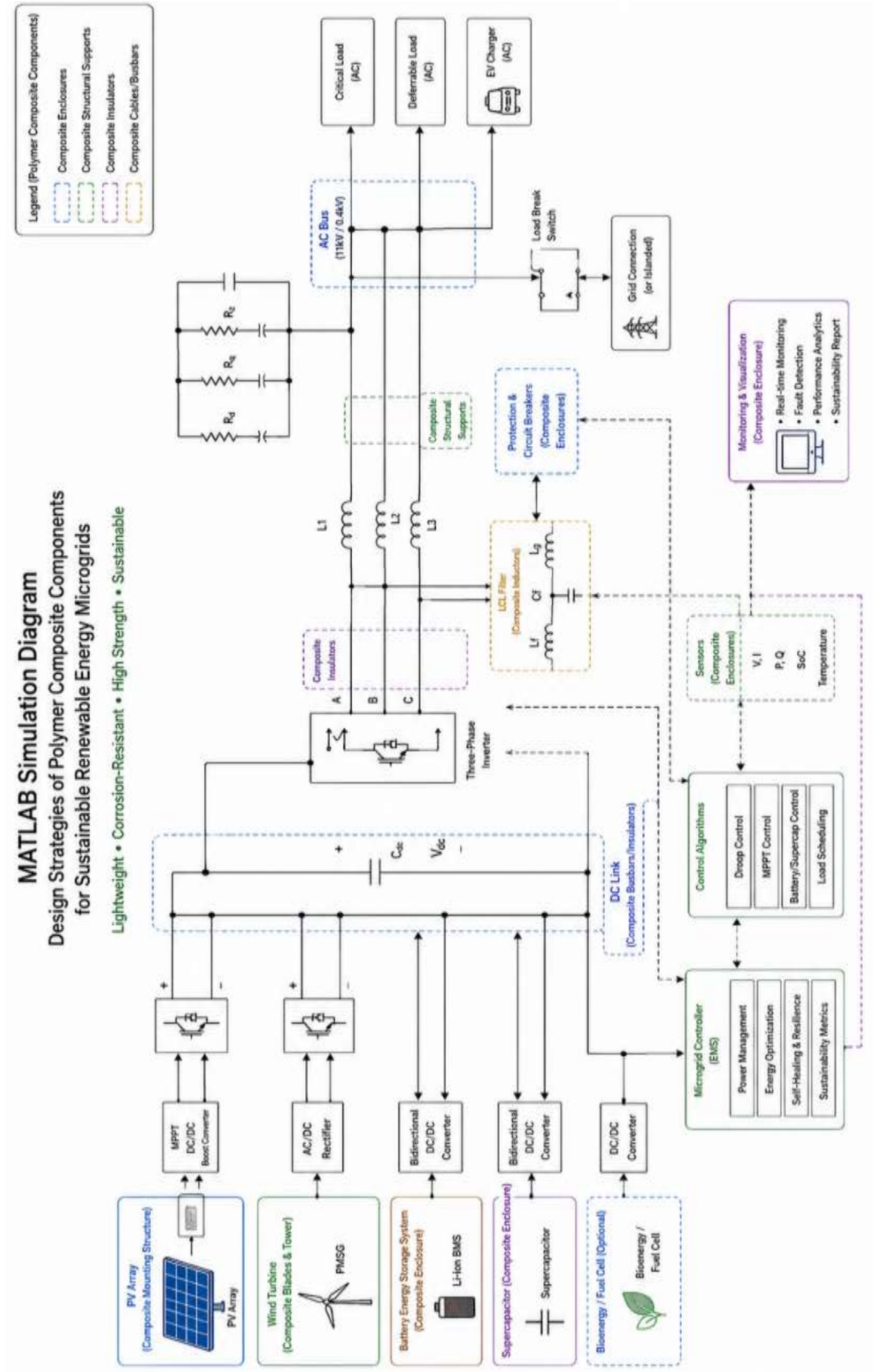

Figure 2. MATLAB Simulation

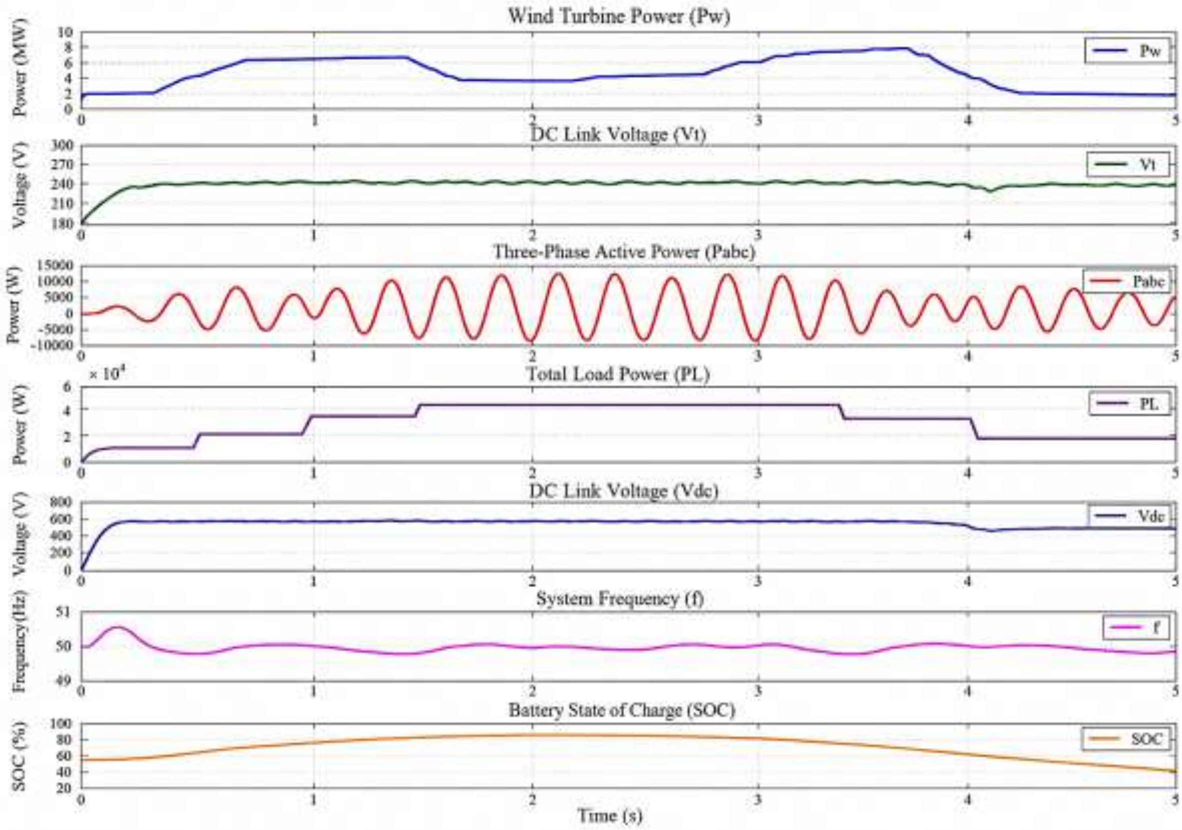

Figure 3. Microgrid response during wind energy connect and disconnect.

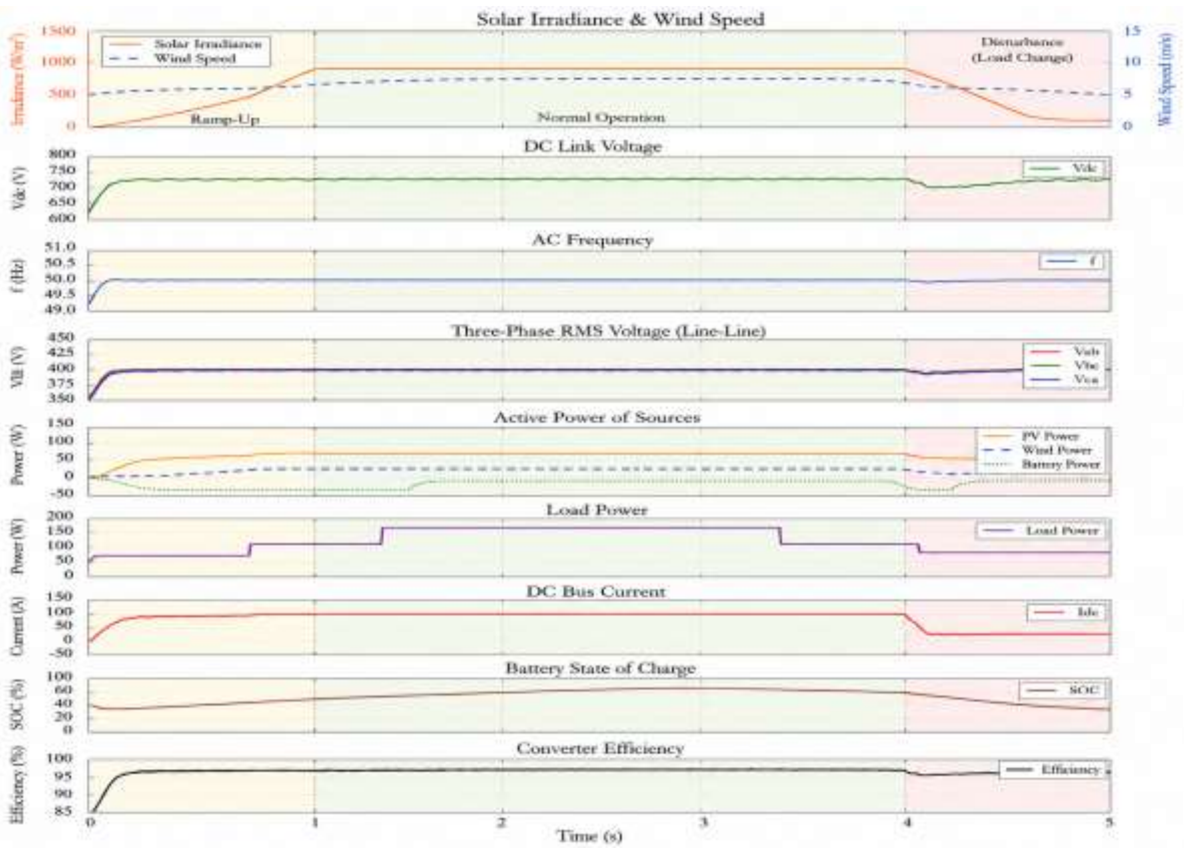

Figure 4. Microgrid response during solar energy connect and disconnect.

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Performance of Polymer-Enabled Batteries under Low Renewable Supply

The microgrid scenario representing poor weather reduced wind and solar inputs so the DFIG wind system produced 4 kW and the PV array 3 kW against a 12 kW load; with combined renewables at 7 kW the battery supplied the 5 kW deficit while the DC-link stayed near 750 V. From a polymer-materials perspective, this event highlights demands on polymer components used in energy storage and power electronics: battery separators, polymer electrolytes, binders and casings experienced elevated discharge stresses that affect ion transport, mechanical integrity, and thermal stability; insulating polymers and potting compounds in converters were subject to sustained electrical and thermal loading while maintaining dielectric and flame-retardant performance; and polymeric sensors and flexible interconnects provided state-of-health data for EMS control. The state of charge declined gradually but remained within safe limits, and load voltage and frequency were maintained, indicating that polymer-enabled battery and electronics materials performed reliably under transient high-discharge conditions—an outcome relevant to evaluating polymer stability, aging, and safety in off-grid energy systems.

Unbalanced and Nonlinear Load Operation

A nonlinear, asymmetrical load was applied to the islanded microgrid while wind and PV sources remained online; the three-phase VSC used current control and filtering to compensate unbalanced currents and harmonic components, maintaining nearly balanced load voltages despite asymmetric load currents. The DC-link voltage remained stable, indicating that converter control handled the disturbance without disturbing the EMS. From a polymer-materials perspective, this test stresses insulating polymers, potting compounds, and polymeric substrates in power electronics—materials that must retain dielectric strength and thermal stability under harmonic and asymmetric loading—and underscores the role of polymer-based sensors and flexible electronics for real-time monitoring of converter and battery health.

CONCLUSION

This study investigated a standalone hybrid microgrid integrating a DFIG wind system, an MPPT-controlled PV array with a boost converter, and a battery bank interconnected via a ~750 V DC link. The proposed control architecture effectively decouples generation and load, maintains the DC-link near unity regulation at ~750 V, enforces regulated power sharing, and provides smooth transient response. Simulations under varying wind speed, solar irradiance, and load disturbances demonstrated DC-link stability, reliable power sharing, and attenuated transients. The DFIG's rotor-side and grid-side converters enable near-optimal active power extraction and reactive power support, while the PV subsystem operates at peak power via MPPT; the bidirectional battery converter rapidly compensates both deficits and surpluses, preserving system stability without direct DC-link regulation. From a polymer-materials perspective, these operational results highlight critical demands on polymeric components across the system: battery separators, electrolytes, binders and casings must withstand repeated high-rate discharge and thermal cycling; encapsulants, backsheets and anti-UV coatings for PV panels require long-term stability under fluctuating electrical/thermal stress; and insulating polymers, potting compounds and substrates in power electronics must retain dielectric, thermal and flame-retardant performance during transient and harmonic loading. Overall, the findings support coordinated converter control and EMS as enablers of resilient microgrid operation and identify specific polymer research directions—stability, aging, safety, and interface engineering—that will improve the reliability and life span of polymer-enabled microgrid components.

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