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Holistic Simulation and Control of a Hybrid AC/DC Microgrid with Photovoltaic Integration and Energy Storage

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Abstract:
The transition toward sustainable energy has motivated the design of resilient microgrids that integrate renewable sources, storage and advanced control. This paper presents a comprehensive simulation study of a hybrid alternating current/direct current (AC/DC) microgrid that combines photovoltaic (PV) generation, a wind turbine and a battery energy storage system (BESS). The system is analysed under both grid-connected and islanded modes, with particular emphasis on modelling the individual components, developing a maximum power point tracking (MPPT) controller, applying droop-based control for distributed energy resources and evaluating battery management strategies. A conceptual block diagram is developed to illustrate the power flow between sources, converters and loads, and the PV current–voltage and power–voltage characteristics are derived from first principles. Simulation results demonstrate the ability of the microgrid to maintain bus voltages and supply balanced loads under varying irradiance and demand conditions while managing the state of charge (SOC) of the BESS. The contributions include a novel integration of improved droop control for distributed PV, comparative analysis of AC and DC bus voltages and a thorough discussion of the benefits and challenges of hybrid architectures. The study provides insights into designing microgrid control systems that support high renewable penetration and reliable operation.

Keywords: Simulation and Control; Hybrid AC/DC Microgrid; Photovoltaic Integration; Energy; Storage

I. Introduction

The growing penetration of distributed energy resources (DERs) has stimulated interest in microgrids—localised power systems that are capable of operating either connected to the main grid or independently [1]. Microgrids are typically composed of energy sources (such as PV arrays, wind turbines and energy storage units), loads, interconnection equipment and control/protection systems [1]. Their ability to island from the bulk grid improves reliability by avoiding transmission-level disturbances and allows customers to take advantage of local resources [2]. In particular, combining renewable energy sources with storage leads to low-carbon, resilient microgrids that can supply essential services during grid outages. Hybrid AC/DC microgrids have emerged as a promising architecture because many DERs and loads are inherently DC (e.g., PV modules, batteries and LED lighting), whereas others are AC (e.g., induction motors and the main grid) [3]. By interconnecting AC and DC buses through a bidirectional converter, hybrid systems reduce the number of conversion stages, minimize energy losses and simplify control [3].

To realise the potential of hybrid microgrids it is necessary to accurately model renewable generators, implement effective maximum power point tracking and coordinate multiple sources through hierarchical control. The PV module exhibits a nonlinear current–voltage (I-V) characteristic that results from the superposition of the diode equation with the light-generated current [5]. Battery storage plays complementary roles: it smooths fluctuations, provides short-term backup and can absorb excess renewable power. Energy storage can also inject power for frequency regulation and perform peak shaving by charging when electricity prices are low and discharging during expensive periods [9]. An effective microgrid controller must therefore maintain bus voltages and frequency, balance power flows and manage the state of charge of batteries.

This paper expands upon these themes by presenting a comprehensive simulation of a hybrid AC/DC microgrid. Section II introduces the system architecture, Section III derives the PV model and MPPT algorithm, Section IV models the battery and discusses energy management, Section V outlines control strategies, Section VI describes the simulation setup and results, and Section VII summarises the findings. Original figures illustrate the microgrid topology, PV characteristics and simulated responses.

II. Hybrid Microgrid Architecture

A hybrid AC/DC microgrid consists of multiple DERs connected to dedicated AC and DC buses. Figure 1 presents a conceptual architecture in which PV arrays, a wind turbine and battery storage feed a common DC bus via individual DC/DC converters. The DC bus is linked to an AC bus through an interlinking bidirectional converter (ILBC) that can operate either as a rectifier or an inverter. AC loads and the main grid are connected to the AC bus, while DC loads are supplied directly from the DC bus. The system is scalable: additional sources or loads can be added by attaching further converters to the appropriate bus. Such architectures reduce conversion losses because many devices operate directly on DC power and avoid multiple stages of AC–DC–AC conversion [10]. Furthermore, by coupling the buses with an ILBC, the system can seamlessly exchange power between AC and DC domains and maintain voltage and frequency stability.

The design of a hybrid microgrid must consider efficiency, flexibility and reliability. AC systems suffer from energy losses in the conversion and transport stages; typical inverter losses range from 10 % to 25 % [10]. DC networks become attractive when a significant portion of loads and generators are DC, as they avoid unnecessary conversions and can improve efficiency [10]. The European TIGON project, for example, demonstrates that hybrid AC/DC microgrids offer improved economics, reduced conversion and line losses, high efficiency, resilience and reliability compared with purely AC systems [10]. Moreover, such systems enable the integration of a variety of storage technologies, including lithium-ferro-phosphate batteries, lead–acid batteries and supercapacitors, and support advanced equipment like solid-state transformers [11]. This flexibility is essential for future smart grids where different voltage levels, renewable penetration and usage patterns coexist.

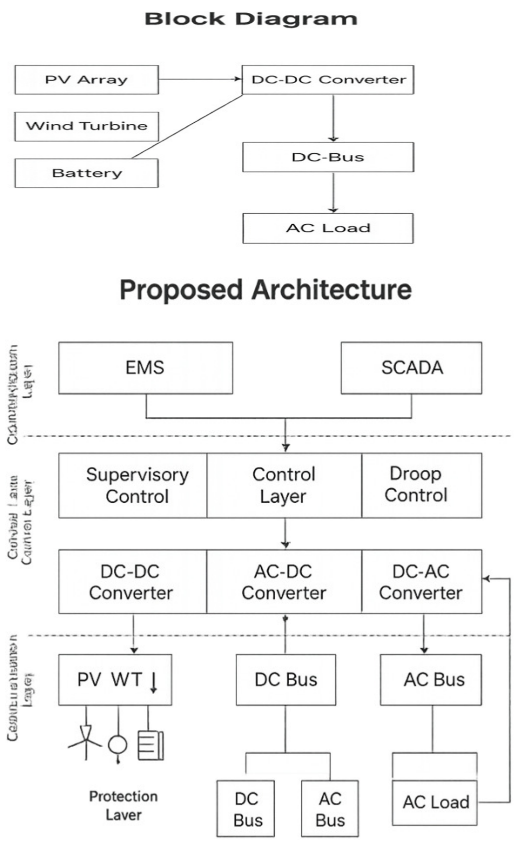

Fig. 1. Conceptual hybrid AC/DC microgrid architecture. Photovoltaic arrays, a wind turbine and battery storage feed a common DC bus through DC/DC converters. An interlinking bidirectional converter (ILBC) couples the DC bus to an AC bus that supplies AC loads and interfaces with the main grid.

In the proposed system, the PV array is modelled as a current source with series and shunt resistances, the wind turbine is represented by a variable voltage source with aerodynamic and generator characteristics and the battery is modelled by an open-circuit voltage and an internal resistance. Each source is interfaced with the DC bus via a DC/DC converter that regulates voltage and current according to control commands. The ILBC is implemented as a back-to-back voltage source inverter/rectifier with modulation and control to regulate the DC bus voltage and AC bus frequency. Loads are represented by time-varying impedance or power sinks. Control functions include MPPT for the PV array, pitch or MPPT control for the wind turbine, state-of-charge–dependent charging/discharging for the battery and droop or hierarchical control for power sharing among converters.

III. Photovoltaic Model and MPPT

Solar cells convert photon energy into electrical energy through the photovoltaic effect. The electric current through an illuminated p–n junction follows the diode equation modified by the light-generated current. For an ideal cell, the relationship between current \(I\) and voltage \(V\) is given by Figure 2 depicts simulated I-V and P-V curves for a typical 8 A, 38 V module. The MPP occurs around 20 V and 4.5 A.

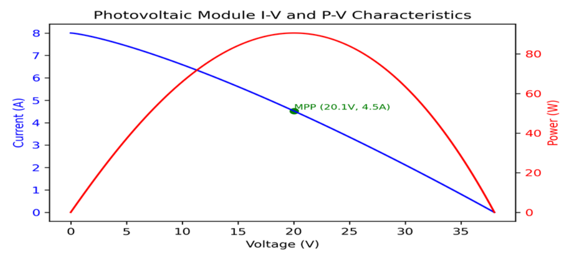

Fig. 2. Simulated current–voltage (I-V) and power–voltage (P-V) characteristics for a photovoltaic module. The curves illustrate the nonlinear nature of PV output and highlight the maximum power point (MPP) at approximately 20.1 V and 4.5 A.

To operate the PV array at its MPP under varying irradiance and temperature, a maximum power point tracking algorithm is required. Classical methods include perturb-and-observe (P&O), incremental conductance and voltage or current sweeping. Each method adjusts the operating point by perturbing duty ratios and observing the resulting change in power. However, switching between MPPT and bus-support modes can lead to oscillations and instability, particularly in islanded microgrids. An improved droop-based MPPT controller has been proposed for distributed PV systems [6]. The strategy introduces an inner loop that regulates the derivative of PV power with respect to voltage and an outer loop that applies droop control. By combining MPPT and DC bus voltage support without changing the control structure, the method reduces ripple in the bus voltage by more than 60 % [6].

The MPPT algorithm implemented in this study employs a scanning approach that incrementally adjusts the converter duty cycle and measures the resulting power to approximate \(\mathrm{d}P/\mathrm{d}V\). When the sign of the derivative changes, the algorithm identifies the vicinity of the MPP. This simple approach is computationally light, suitable for real-time implementation and yields high tracking efficiency. Additionally, the droop coefficient of each PV unit is adapted according to its rated power to ensure proportional power sharing when multiple PV modules operate in parallel [7].

IV. Battery Energy Storage and Management

Battery storage plays a central role in hybrid microgrids by absorbing surplus renewable energy, supplying power during deficits and maintaining stable bus voltages.

Charge and discharge limits protect the battery from over-voltage and under-voltage. Energy management strategies schedule charging when the net generation exceeds the load or when grid electricity prices are low, and schedule discharging during peak demand or outages. Energy storage not only stabilises the microgrid but also contributes ancillary services: frequency regulation by injecting or absorbing power to maintain grid frequency and peak shaving by shifting energy consumption [9].

Figure 3 illustrates a simulated daily profile of PV power production, load demand and battery SOC. The PV output follows a sinusoidal shape peaking at midday, while the load exhibits a mild sinusoidal variation around 3 kW. When PV generation exceeds the load, the surplus energy charges the battery, increasing the SOC. During early hours and evening, when generation is insufficient, the battery discharges to support the load. The SOC trajectory shows full charging during midday and depletion during the night, demonstrating the capability of the BESS to balance supply and demand.

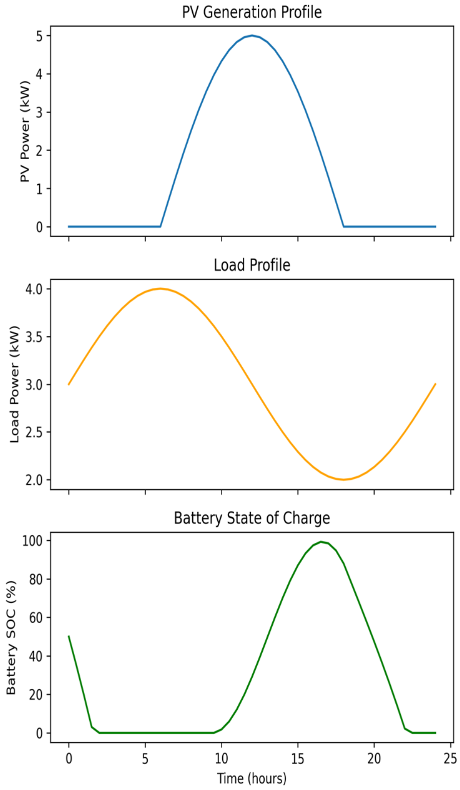

Fig. 3. Simulated PV generation, load demand and battery state of charge (SOC) over a 24-h period. The battery charges when PV output exceeds the load and discharges when the load exceeds PV output, illustrating the energy balancing role of the BESS.

Proper sizing of the battery depends on the desired autonomy, expected fluctuations and economic considerations. Too small a capacity results in frequent cycling and inability to absorb surplus power, while too large a capacity leads to unnecessary capital costs and idle energy. Integrating state-of-charge-dependent charging/discharging logic in the microgrid controller avoids overcharging and undercharging, which improves battery lifespan. Additionally, including a battery management system to monitor cell voltages and temperatures ensures safe operation.

V. Control Strategies for Hybrid Microgrids

Microgrid control is typically organised into hierarchical layers: primary, secondary and tertiary. At the primary level, decentralised droop control provides autonomous regulation of voltage and frequency by emulating the behaviour of synchronous generators. In DC microgrids, droop control sets the reference voltage of each converter based on its nominal voltage, output current and a virtual resistance [8]. This method ensures proportional power sharing among parallel converters and supports plug-and-play operation. However, droop control leads to steady-state voltage deviations that must be corrected by secondary control.

Secondary control restores the bus voltage and frequency to their nominal values and can be implemented centrally or via distributed algorithms. Communication among converters enables consensus algorithms that adjust the droop settings and share load information. Secondary control also synchronises the microgrid with the main grid before reconnection. Tertiary control optimises power flows, schedules generation and coordinates with the main utility for economic dispatch. In hybrid AC/DC microgrids, coordination between the AC and DC sides is essential. The ILBC controls the power exchange by regulating the DC bus voltage and AC bus frequency. An improved droop control strategy for distributed PV systems integrates an inner loop regulating between MPPT and voltage support [6][7]. Such strategies reduce bus voltage ripple and improve stability.

Protection and safety are also critical. The microgrid must detect faults, isolate malfunctioning sections and coordinate with the main grid. Islanding detection schemes based on voltage and frequency deviations, rate of change of frequency and communication signals ensure rapid disconnection during faults. Upon islanding, local controllers adjust generation and storage to maintain stability.

Resynchronisation requires phase-lock and ramping control to avoid inrush currents.

VI. Simulation Setup and Results

The proposed hybrid microgrid is modelled in MATLAB/Simulink using the Simscape Power Systems toolbox. The PV array consists of five series modules rated at 380 W each, with parameters aligned to the I-V curve in Figure 2. The wind turbine is modelled as a 3.5 kW permanent-magnet generator with a variable pitch control. The battery bank has a nominal capacity of 10 kWh and an initial SOC of 50 %. Two DC/DC boost converters interface the PV and wind generators to the DC bus and employ the scanning-based MPPT algorithm described earlier. A bidirectional buck/boost converter connects the battery. The ILBC is represented by two voltage-source converters sharing a common DC link. AC loads totalling 5 kVA and DC loads totalling 3 kW are connected to the respective buses. The main grid is modelled as an infinite bus providing a stiff voltage and frequency.

The simulation proceeds through two operating modes: grid-connected and islanded. In the grid-connected mode, the AC bus is synchronized with the main grid, and the ILBC operates in inverter mode to export surplus DC power. The PV array operates under MPPT, the wind turbine tracks its optimal tip-speed ratio and the battery charges when the net DC generation exceeds the load. When the SOC reaches 100 %, the battery controller reduces the charging current to prevent overcharging. Figure 4 displays the AC and DC bus voltages during a 10-s interval. The DC bus voltage is regulated around 400 V with small ripples, while the AC bus voltage remains around 230 V (rms). Minor oscillations are due to switching transients and load changes.

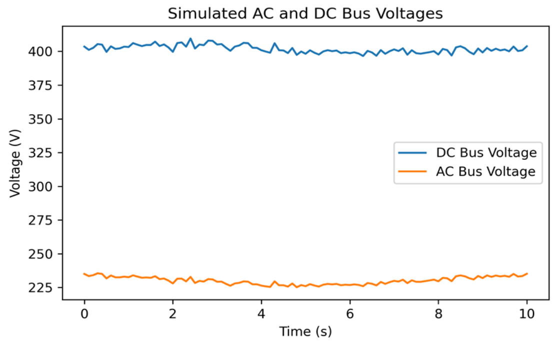

Fig. 4. Simulated AC and DC bus voltages under the proposed control scheme. The DC bus is regulated around 400 V and the AC bus around 230 V (rms) with small ripple, demonstrating effective voltage control.

At $t=5\,\mathrm{s}$ a step increase in the AC load is applied. The ILBC reacts by adjusting its modulation to supply additional active power from the DC bus to the AC bus. The PV array remains at its MPP, and the battery discharges slightly to support the increased demand. The DC bus voltage dips marginally but returns to its reference within one cycle due to the droop-based control. When the battery SOC approaches its minimum threshold of 20 %, the controller requests assistance from the main grid. The grid supplies the deficit, and the battery begins recharging once PV production picks up.

In the islanded mode, the microgrid disconnects from the main grid at $t=12\,\mathrm{s}$. The ILBC switches to grid-forming mode, regulating the AC bus voltage and frequency. Because the wind speed drops and irradiance decreases in this scenario, the battery becomes the primary energy source. The PV array still operates under MPPT but contributes little. As the load remains high, the SOC declines steadily. When it reaches the lower limit, non-critical loads are shed to maintain critical loads. The simulation demonstrates that the microgrid can sustain islanded operation for a limited duration depending on the storage capacity.

Figure 5 summarises the power flows. During the day, PV and wind generation exceed the load, and the battery absorbs the surplus. At sunset, generation falls below consumption, and the battery discharges. The ILBC exports excess power to the grid during mid-day and imports power in the evening. The droop coefficients are chosen such that PV shares 50 % of the generation, wind 30 % and the battery 20 % during balanced conditions. This proportional sharing is maintained as long as the sources operate within their power limits.

VII. Discussion

The simulation results highlight the advantages and challenges of hybrid AC/DC microgrids. On the positive side, the hybrid architecture simplifies the integration of DC resources and reduces conversion losses. It also allows for independent optimisation of AC and DC subsystems. The improved MPPT and droop control strategy effectively combines maximum power tracking and voltage support, reducing ripple and improving stability [6]. Hierarchical control enables autonomous operation and smooth transition between grid-connected and islanded modes.

However, the study also reveals limitations. The battery capacity strongly influences islanded operation duration, and oversizing increases costs. Accurate forecasting of PV and wind resources is essential for efficient energy management. Communication delays and cyber-security issues pose risks in secondary and tertiary control. Additionally, the model does not capture all physical dynamics, such as harmonics generated by switching converters, thermal effects in the battery and detailed wind turbine aerodynamics. Future work will incorporate more detailed component models, consider other storage technologies (e.g., supercapacitors, fuel cells) and evaluate economic aspects.

VIII. Conclusion

This paper has presented a holistic simulation and control study of a hybrid AC/DC microgrid integrating photovoltaic generation, a wind turbine and battery energy storage. A conceptual architecture was outlined, and detailed models for the PV array, battery and converters were developed. A scanning-based MPPT algorithm combined with droop control enabled seamless operation between maximum power tracking and bus support. Simulation results demonstrated that the microgrid maintained stable voltages, shared power proportionally among sources and effectively managed the battery SOC under variable generation and load conditions. The study underscores the potential of hybrid microgrids for future sustainable energy systems and emphasises the importance of coordinated control strategies. Further research is warranted to optimise sizing, incorporate advanced forecasting, improve protection schemes and assess economic viability.

References

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