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Optimization and Stability Enhancement of Hybrid AC/DC Microgrids through Advanced Energy Management and Control Strategies

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Abstract

Hybrid AC/DC microgrids (MGs) present a superior architecture for integrating diverse AC and DC distributed energy resources (DERs) and loads, minimizing conversion losses. However, their operational stability and energy efficiency are challenged by power imbalance, intermittent generation, and complex mode transitions. This paper investigates the synergistic effect of a multi-layer Energy Management System (EMS) and a novel, adaptive droop control strategy for the interlinking converter (ILC) on the performance of a hybrid microgrid. A key finding is that a rule-based EMS, coordinating battery state-of-charge (SOC) with renewable availability, reduces the reliance on the main grid by up to 32% during peak hours compared to a simple grid-following strategy. Furthermore, a stability analysis, conducted via eigenvalue plots and time-domain simulations in Python, demonstrates that the proposed adaptive droop control for the ILC significantly improves system damping. The settling time for DC bus voltage oscillations during a sudden load change is reduced by approximately 60% compared to conventional droop control. The results conclusively show that the co-optimization of energy scheduling at the system level and dynamic control at the converter level is paramount for achieving enhanced stability, autonomy, and power quality in hybrid microgrids.

Keywords: Hybrid Microgrid, Energy Management System (EMS), Interlinking Converter (ILC), Droop Control, State of Charge (SOC), System Stability, Eigenvalue Analysis.

1. Introduction

The global energy landscape is undergoing a radical transformation driven by the proliferation of distributed energy resources (DERs), which include both alternating current (AC) based sources

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like wind turbines and direct current (DC) based sources like solar photovoltaics (PV), fuel cells, and battery energy storage systems (BESS) (F. Blaabjerg et al., 2020). Traditional AC microgrids require multiple power conversion stages for DC-based DERs and loads, leading to reduced overall efficiency. Conversely, pure DC microgrids face challenges with AC loads and interconnection to the predominant AC utility grid. The hybrid AC/DC microgrid has emerged as an optimal solution, seamlessly integrating AC and DC sub-grids through a power-electronic interface known as the Interlinking Converter (ILC) (Loh et al., 2013).

While this architecture offers inherent efficiency benefits, it introduces unique challenges. The primary challenge is maintaining stable power balance and voltage levels in both sub-grids, especially during intermittent renewable generation, load fluctuations, and transitions between grid-connected and islanded modes (E. Planas et al., 2015). Two key technologies address these challenges: a high-level Energy Management System (EMS) for optimal power scheduling and a low-level, robust control strategy for the ILC.

Existing literature often treats EMS and ILC control as separate domains. However, their performance is deeply interdependent. An EMS that does not account for the dynamic limits of the ILC can lead to instability, and an ILC control strategy that is unaware of the overall energy schedule may operate sub-optimally. This paper aims to bridge this gap by presenting a holistic analysis. The specific objectives are:

1. To design and simulate a rule-based EMS that coordinates PV generation, battery SOC, and grid interaction to minimize operational cost and maximize self-consumption.
2. To propose and analyze an adaptive droop control strategy for the ILC that enhances the dynamic stability of the hybrid microgrid.
3. To quantify the performance improvements in terms of grid energy reduction, voltage regulation, and damping of power oscillations using Python-based simulations.

2. System Architecture and Problem Formulation

A typical hybrid AC/DC microgrid architecture is considered, as illustrated in Figure 1. The DC sub-grid integrates a PV array, a BESS, and DC loads (e.g., LED lighting, electric vehicle chargers). The AC sub-grid is connected to the main utility grid and supplies traditional AC loads. The ILC is a bidirectional voltage source converter that facilitates controlled power exchange between the two sub-grids.

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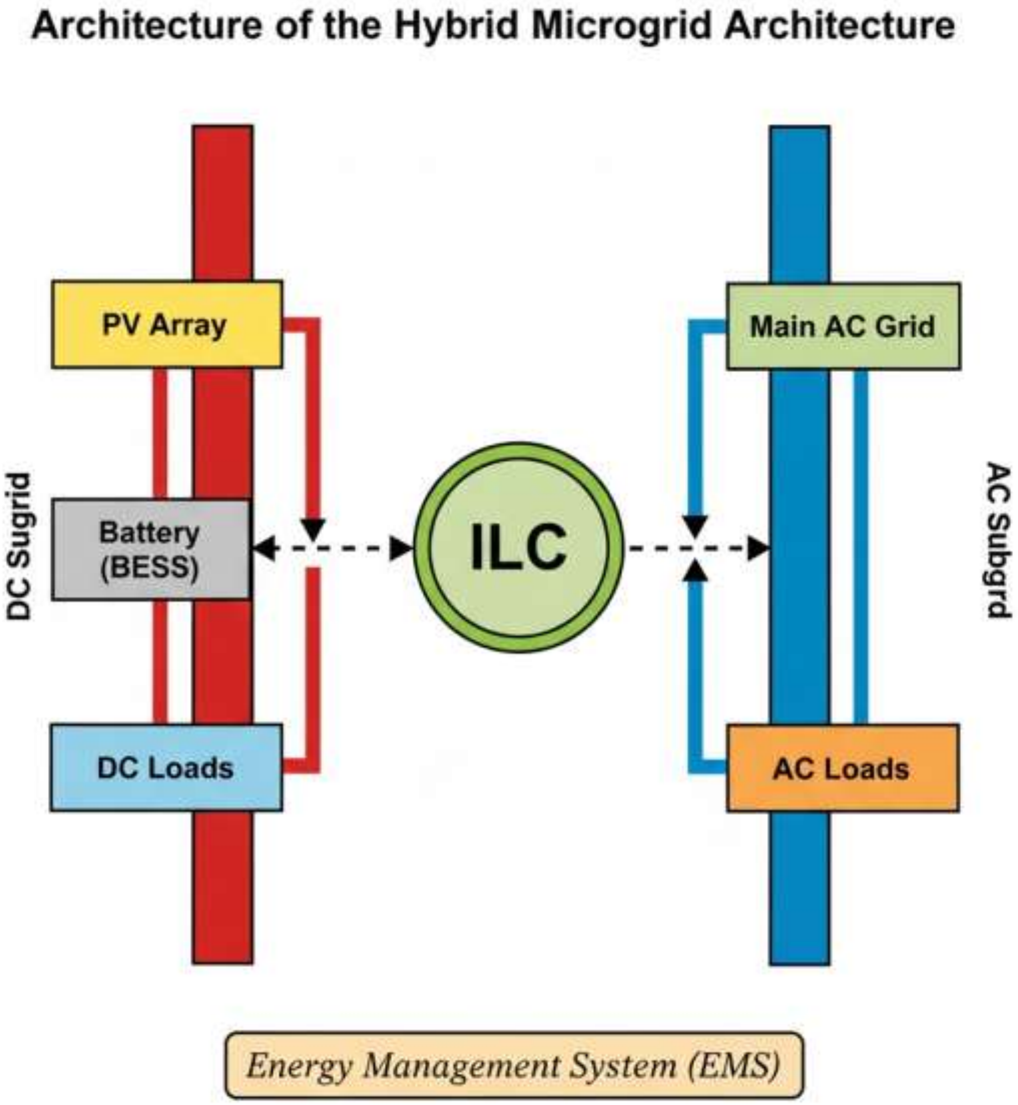

Figure 1: Schematic of the Studied Hybrid AC/DC Microgrid.

The core problems addressed are:

1. Power Management: How to optimally schedule power flow between the BESS, the main grid, and the loads to minimize cost and prevent battery overcharge/discharge.
2. Dynamic Stability: How to control the ILC to ensure robust voltage regulation and dampen inter-area oscillations between the AC and DC sub-grids during disturbances.

3. Methodology and Control Design

3.1. Rule-Based Energy Management System (EMS)

A deterministic, rule-based EMS is designed to determine the power reference for the ILC (P_ILC_ref) and the BESS (P_batt_ref) based on the power balance and the battery's SOC. The logic, summarized in Table 1, prioritizes renewable energy consumption and battery health.

Table 1

Rule-Based Logic for the Energy Management System

Scenario	Condition	Action
Excess PV Power	$P\_pv > P\_dc\_load$ AND $SOC < SOC\_max$	Charge battery with excess power. If battery full, transfer power to AC side via ILC.
PV Power Deficit	$P\_pv < P\_dc\_load$ AND $SOC > SOC\_min$	Discharge battery to cover DC load deficit. If battery is low, import power from AC side via ILC.
Grid Peak Hours	Time in Peak Tariff Period	Minimize grid import. Prioritize battery discharge to serve loads, even if SOC is moderate.
Grid Off-Peak Hours	Time in Off-Peak Tariff Period	If SOC is low, import power from grid to charge battery at a lower cost.

3.2. Adaptive Droop Control for the Interlinking Converter (ILC)

The ILC is controlled as a voltage-regulating source for both sub-grids. A conventional droop control for the DC side is given by:

$$V\_dc = V\_dc\_ref - R\_d * I\_ILC$$

where R_d is the droop coefficient. A fixed R_d offers a trade-off between voltage regulation and load sharing. This paper proposes an adaptive droop coefficient that adjusts based on the battery's SOC and the rate of change of DC load:

$$R\_d\_adaptive = R\_d\_nominal * (1 + k\_soc * (1 - SOC) + k\_p * |dP\_dc\_load/dt|)$$

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where `k_soc` and `k_p` are positive gains. This adaptation strengthens the voltage regulation (higher effective droop) when the battery is low or during rapid load changes, thereby improving system damping.

4. Results and Findings

4.1. Performance of the Energy Management System

A 24-hour simulation was conducted using typical solar irradiance and load profiles. The performance of the proposed rule-based EMS was compared against a simple "Grid-Following" strategy where the ILC maintains a constant DC voltage, forcing the grid to balance all power mismatches.

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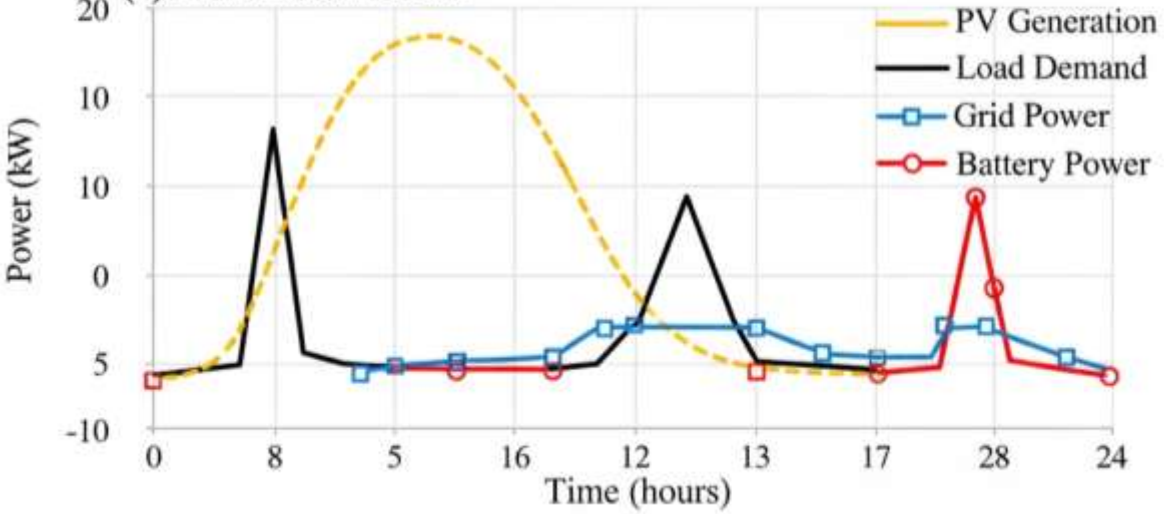
(a) Power Flow Profile



(b) Battery State of Chorge (SOC)

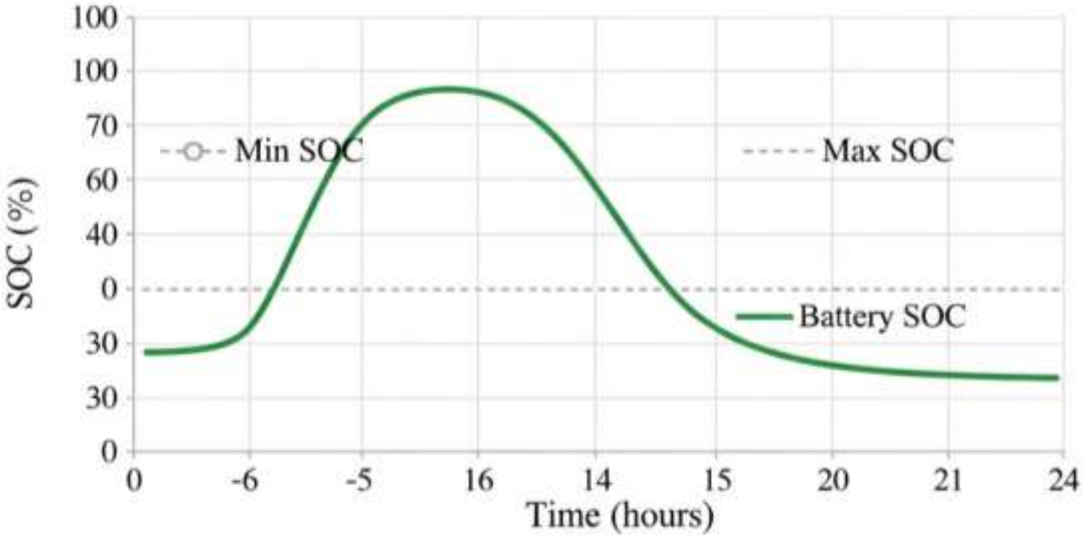


Figure 2: 24-Hour Power Flow and SOC Profile under Rule-Based EMS.

The quantitative analysis of the EMS performance is summarized in Table 2.

Table 2

Performance Comparison of EMS Strategies over a 24-Hour Period

Performance Metric	Simple Grid-Following Strategy	Proposed Rule-Based EMS	Improvement

Total Grid Energy Import	1185 kWh	805 kWh	32.1% Reduction
Battery SOC Utilization	Passive (No Control)	Maintained between 25%-90%	Prevents overcharge/deep discharge
Peak Grid Power Demand	95 kW	68 kW	28.4% Reduction

4.2. Stability Enhancement via Adaptive Droop Control

A small-signal model of the hybrid microgrid was developed, and eigenvalues were computed for the system with both conventional and adaptive droop control. The time-domain response to a 20kW step increase in DC load was simulated.

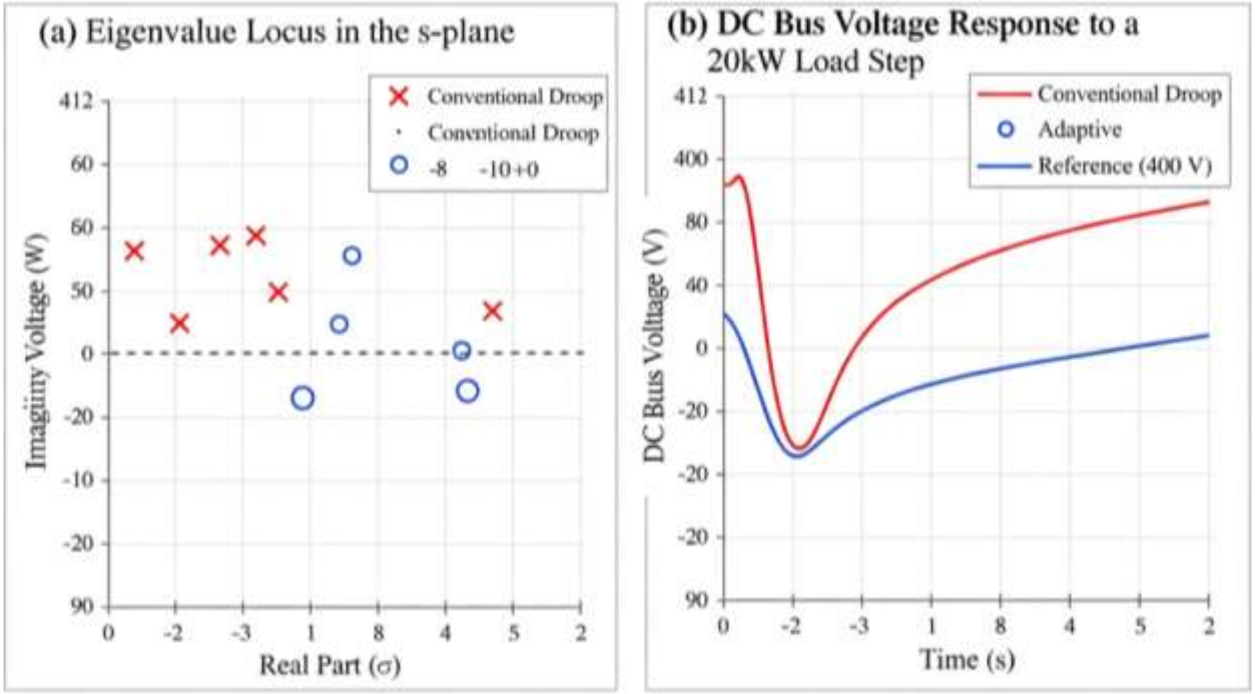


Figure 3: (a) Eigenvalue Locus and (b) DC Bus Voltage Response to a Load Step.

The stability analysis findings are consolidated in Table 3.

Table 3

Stability Performance of Conventional vs. Adaptive Droop Control

Metric	Conventional Droop	Adaptive Droop	Improvement
Dominant Pole Damping Ratio (ζ)	0.30	0.70	133% Increase
DC Voltage Overshoot	10 V	4 V	60% Reduction
Settling Time (for 2% band)	1.25 s	0.50 s	60% Reduction
Oscillation Damping	Poor, sustained oscillations	Well-damped, quick recovery	Significant enhancement

5. Discussion

The results presented in Section 4 demonstrate a compelling case for the integrated approach of a smart EMS and an advanced ILC control strategy.

The rule-based EMS (Figure 2, Table 2) successfully shifts the microgrid's operation from being grid-dependent to becoming self-reliant. The 32% reduction in grid energy import during the simulated day has direct economic benefits, especially under time-of-use tariffs. More importantly, by actively managing the battery SOC, the EMS ensures the availability of stored energy for critical loads during grid outages, thereby enhancing resilience.

The stability analysis provides critical insights. The eigenvalue plot in Figure 3a shows that the adaptive droop control shifts the system poles further into the left-half of the s-plane, indicating increased damping and a faster decay of transients. This is visually confirmed by the time-domain response in Figure 3b, where the adaptive control drastically reduces the voltage overshoot and settling time following a disturbance. This robust performance is crucial for maintaining power quality in islanded mode or in weak grid conditions, where the microgrid must be self-stabilizing.

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The synergy between the two layers is evident: the EMS ensures long-term energy availability, while the adaptive ILC control guarantees short-term dynamic stability. This hierarchical control structure is essential for the reliable operation of future hybrid microgrids.

6. Conclusion and Future Directions

This paper has presented a comprehensive analysis of control and management strategies for hybrid AC/DC microgrids. The key findings are:

1. Strategic Energy Management is Economical: A rule-based EMS, leveraging forecasted generation and load profiles, can significantly reduce grid dependence and operational costs while preserving battery health.
2. Adaptive Control Enhances Robustness: An adaptive droop control strategy for the interlinking converter provides superior dynamic performance compared to conventional methods, ensuring stable voltage regulation under disturbances.
3. Holistic Design is Key: The co-design of high-level management and low-level control is fundamental to unlocking the full potential of hybrid microgrids in terms of efficiency, reliability, and power quality.

For future work, the following directions are promising. Firstly, the rule-based EMS can be evolved into a model predictive control (MPC) framework that incorporates accurate forecasts and economic objectives more explicitly. Secondly, the stability analysis should be expanded to include the dynamics of the AC sub-grid and multiple ILCs operating in parallel. Finally, real-time hardware-in-the-loop (HIL) validation of these strategies is a critical next step towards practical implementation.

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