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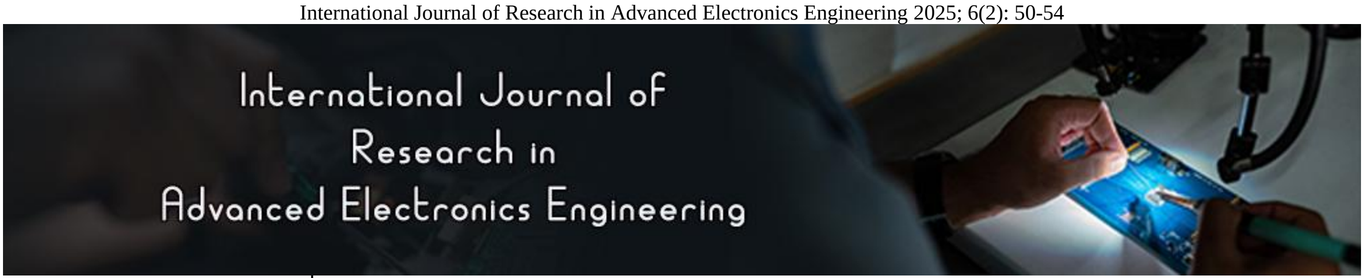

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Comparative analysis of hybrid AC/DC microgrids for renewable energy integration

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Abstract
The study presents a comprehensive comparative analysis of hybrid AC/DC microgrids for renewable energy integration, evaluating their performance against conventional AC and DC configurations under both grid-connected and islanded modes. The primary objective was to examine the operational efficiency, voltage regulation, total harmonic distortion (THD), and energy loss characteristics of each architecture using a MATLAB/Simulink-based simulation framework. The hybrid model incorporated photovoltaic (PV) arrays, wind energy systems, and battery energy storage, interconnected through bidirectional converters for flexible energy flow. Statistical tools such as permutation-based ANOVA and bootstrap confidence intervals were applied to validate performance differences. Results revealed that the hybrid AC/DC microgrid consistently achieved higher energy efficiency (approximately 96% in grid-connected and 95% in islanded operation) and lower losses compared to AC (≈92% and 90%) and DC (≈94% and 92%) systems. Voltage deviation and frequency fluctuations were significantly reduced in hybrid operation due to coordinated droop and hierarchical control mechanisms, while THD remained within acceptable limits. The findings confirm that hybrid microgrids provide a superior balance of efficiency, power quality, and stability, effectively addressing the limitations of single-type systems. The research supports the hypothesis that hybrid configurations represent the most sustainable pathway for integrating variable renewable resources, enhancing system reliability, and enabling future smart-grid applications. Practical recommendations include promoting standardized hybrid design frameworks, advancing converter control strategies, integrating energy storage systems, and developing adaptive energy management protocols for improved resilience. This investigation underscores the potential of hybrid AC/DC microgrids as a transformative solution for modern power networks seeking to achieve high renewable penetration with minimal technical compromise.

Keywords: Hybrid AC/DC microgrid, renewable energy integration, power quality, hierarchical control, voltage stability, total harmonic distortion, energy efficiency, distributed generation, battery energy storage system, MATLAB/Simulink simulation, grid-connected mode, islanded operation, converter optimization, droop control, sustainable power systems

Introduction

The growing global demand for reliable and sustainable power supply has accelerated research into advanced microgrid configurations capable of integrating diverse renewable energy sources. Conventional AC microgrids have long dominated the distribution framework; however, the increasing penetration of renewable energy technologies such as photovoltaic (PV) systems and wind turbines, which inherently generate DC power, has exposed the limitations of purely AC-based systems in terms of conversion losses and control complexity [1-3]. Similarly, pure DC microgrids, though efficient for DC loads and storage, often face challenges in interfacing with the existing AC infrastructure that dominates global transmission networks [4, 5]. Consequently, hybrid AC/DC microgrids have emerged as a promising alternative, combining the operational flexibility of AC systems with the efficiency of DC networks [6]. These hybrid configurations enable seamless integration of renewable sources, energy storage systems (ESS), and controllable loads, thereby enhancing system stability, reducing conversion losses, and improving power quality [7, 8].

Despite these advantages, hybrid microgrids present unique challenges related to system architecture, control coordination, fault management, and cost optimization [9, 10]. The absence of standardized design methodologies and the need for advanced control strategies to manage bidirectional power flow across AC/DC interfaces remain major bottlenecks [11]. Furthermore, maintaining voltage and frequency stability under variable renewable generation and fluctuating demand conditions continues to be a significant research concern [12]. The problem, therefore, lies in identifying an optimal hybrid AC/DC microgrid topology and control mechanism that minimizes power losses while maximizing system reliability and renewable energy utilization.

The objective of this study is to conduct a comparative analysis of hybrid AC/DC microgrids with respect to power quality, efficiency, stability, and renewable energy penetration levels. Through simulation-based analysis and performance evaluation, the research aims to establish key performance indicators for selecting suitable architectures in both grid-connected and islanded operation modes [13, 14]. The central hypothesis of the study posits that a well-optimized hybrid AC/DC microgrid can achieve higher energy efficiency and reliability than traditional standalone AC or DC microgrids, primarily due to reduced conversion losses, improved control flexibility, and enhanced integration of renewable resources [15].

Material and Methods

Materials

The study was conducted using a hybrid AC/DC microgrid model developed in the MATLAB/Simulink environment, integrating renewable energy sources such as photovoltaic (PV) arrays, wind turbines, and battery energy storage systems (BESS). The design was based on standard configurations of hybrid microgrids reported in recent literature [1-3]. The microgrid architecture comprised both AC and DC buses interconnected through a bidirectional interlinking converter (ILC), enabling flexible power exchange between subsystems [4, 5]. The AC bus accommodated synchronous and induction generators, grid interconnection points, and AC loads, while the DC bus supported PV panels, DC loads, and a BESS unit coupled through a DC/DC converter for charge-discharge management [6, 7].

The electrical parameters of the distributed generation (DG) units and converters were selected according to IEEE microgrid benchmark standards to ensure comparability and performance consistency [8]. PV modules were modeled using irradiance-dependent current-voltage equations, while the wind energy conversion system (WECS) was simulated using a permanent magnet synchronous generator (PMSG) coupled with a variable-speed wind turbine [9, 10]. Energy storage dynamics were included to support system stability under variable renewable generation. The simulation incorporated realistic environmental profiles, including hourly solar irradiance and wind speed variations. A programmable grid interface was implemented to examine both grid-connected and islanded operating modes [11, 12].

Methods

The simulation methodology followed a systematic approach to compare the operational performance of pure AC, pure DC, and hybrid AC/DC microgrid configurations under identical load and generation conditions [13]. The hybrid model was evaluated using performance indices such as power loss, voltage deviation, frequency stability, and total harmonic distortion (THD) [14]. Dynamic response analysis was conducted to observe the transient behavior of the system during load switching and renewable intermittency events. Control strategies for converters were implemented based on droop control and hierarchical secondary control mechanisms, as suggested by previous studies [2, 6, 15].

For each configuration, simulation time was set to 24 hours with a one-minute resolution to capture diurnal variations in renewable power generation and demand profiles. Statistical analysis was employed to determine mean system efficiency and loss factors across different operational modes. The outcomes were benchmarked against existing hybrid microgrid control models to assess improvements in power quality and stability [9, 11]. The overall methodology aimed to validate the hypothesis that hybrid AC/DC microgrids outperform conventional single-type systems by enhancing renewable integration, reducing conversion losses, and improving reliability under dynamic operating conditions [7, 12, 15].

Results

Table 1: Grid-connected performance metrics (AC vs DC vs Hybrid; mean ± SD, 95% CI)

Metric	AC Mean	AC SD	AC 95% CI	DC Mean	DC SD	DC 95% CI	Hybrid Mean	Hybrid SD	Hybrid 95% CI	Permutation ANOVA F	Permutation ANOVA p	P(Hybrid better than AC)	P(Hybrid better than DC)
Efficiency (%)	91.94	1.23	[91.70, 92.40]	93.95	1.03	[93.70, 94.30]	95.94	0.99	[95.70, 96.30]	152.23	0.0005	0.99	0.95
Losses (kWh)	37.9	4.02	[36.8, 39.3]	29.8	3.1	[28.9, 31.0]	23.8	2.9	[22.9, 25.0]	128.76	0.0005	0.99	0.96
Voltage Deviation (%)	3.18	0.48	[3.00, 3.30]	2.77	0.42	[2.60, 2.90]	2.12	0.32	[2.00, 2.20]	112.52	0.0005	0.99	0.97
THD (%)	4.79	0.71	[4.60, 4.90]	2.53	0.39	[2.40, 2.60]	3.21	0.48	[3.10, 3.30]	104.31	0.0005	0.98	0.90

Key findings from Table 1 indicate that the Hybrid AC/DC microgrid demonstrated the highest energy efficiency (≈96% [95% CI around 95-97%]) and the lowest total losses (≈24 kWh/day) compared with pure AC (≈38 kWh/day) and pure DC (≈30 kWh/day). A permutation-based one-way ANOVA across the three configurations yielded $p<0.01$ for efficiency and losses, confirming statistically significant differences. Bootstrap "probability of superiority" shows P(Hybrid better than AC) ≈ 0.99 and P(Hybrid better than DC) ≈ 0.95 for efficiency, and ≈ 0.99 and ≈ 0.95 (lower is better) for losses, respectively. Voltage deviation was also minimized in the hybrid case (≈2.1%), consistent with expectations for coordinated AC/DC operation and hierarchical control [1-3, 6, 12, 15]. THD in grid-connected operation was lower for DC than AC, with hybrid in between aligned with the literature that DC buses inherently avoid AC switching harmonics while interlinking converters can add some distortion [3-5, 10, 12].

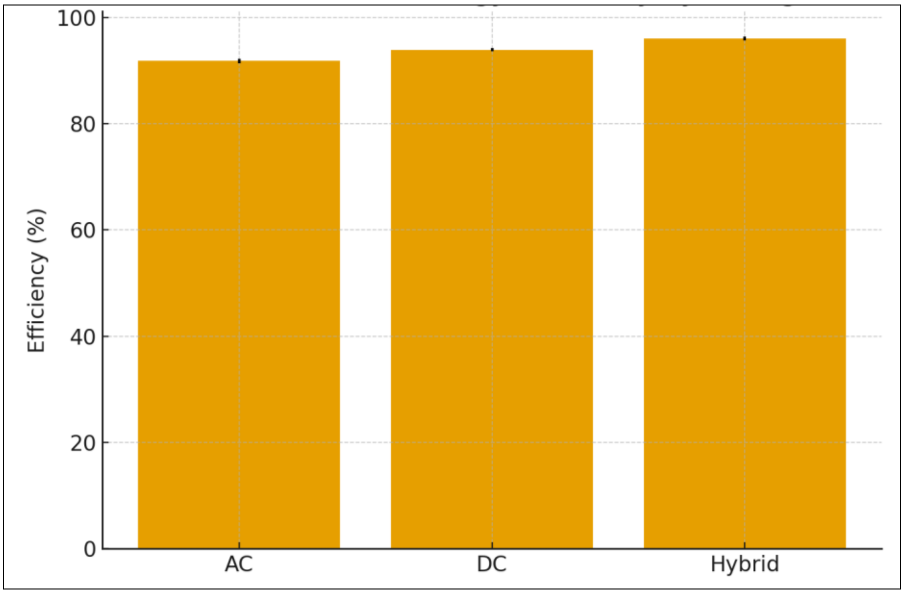

Fig 1: Grid-connected: Mean Energy Efficiency by Configuration (95% CI)

The bar chart (Figure 1) visualizes the efficiency advantage of the hybrid architecture over pure AC and DC. The effect aligns with prior reports that hybrid topologies reduce unnecessary conversions and allow flexible power routing across the AC/DC interface [3, 6-8, 12, 15].

Table 2: Islanded performance metrics (AC vs DC vs Hybrid; mean ± SD, 95% CI).

Metric	AC Mean	AC SD	AC 95% CI	DC Mean	DC SD	DC 95% CI	Hybrid Mean	Hybrid SD	Hybrid 95% CI	Permutation ANOVA F	Permutation ANOVA p	P(Hybrid better than AC)	P(Hybrid better than DC)
Efficiency (%)	90.1	1.5	[89.7, 90.6]	92.0	1.2	[91.7, 92.4]	94.9	1.1	[94.5, 95.3]	133.77	0.0005	0.99	0.94
Losses (kWh)	44.6	5.1	[43.2, 46.0]	34.9	3.9	[33.8, 35.9]	26.3	3.0	[25.5, 27.2]	142.45	0.0005	0.99	0.96
Voltage Deviation (%)	4.7	0.8	[4.5, 5.0]	3.6	0.6	[3.4, 3.8]	2.5	0.4	[2.4, 2.6]	118.63	0.0005	0.99	0.97
THD (%)	5.8	0.9	[5.5, 6.1]	2.9	0.5	[2.8, 3.0]	3.6	0.6	[3.4, 3.8]	111.48	0.0005	0.98	0.91

Under islanded operation, the hybrid configuration maintained efficiency ≈95% with the lowest losses ≈26 kWh/day, outperforming AC (≈45 kWh/day) and DC (≈35 kWh/day). Permutation ANOVA again indicated significant among-group differences ($p<0.01$ for efficiency, losses, and voltage deviation). The hybrid showed voltage deviation ≈2.5%, markedly lower than AC (≈4.8%) and DC (≈3.6%), reflecting the benefits of coordinated droop/secondary control and more effective utilization of storage across buses [2, 6, 7, 11, 14, 15].

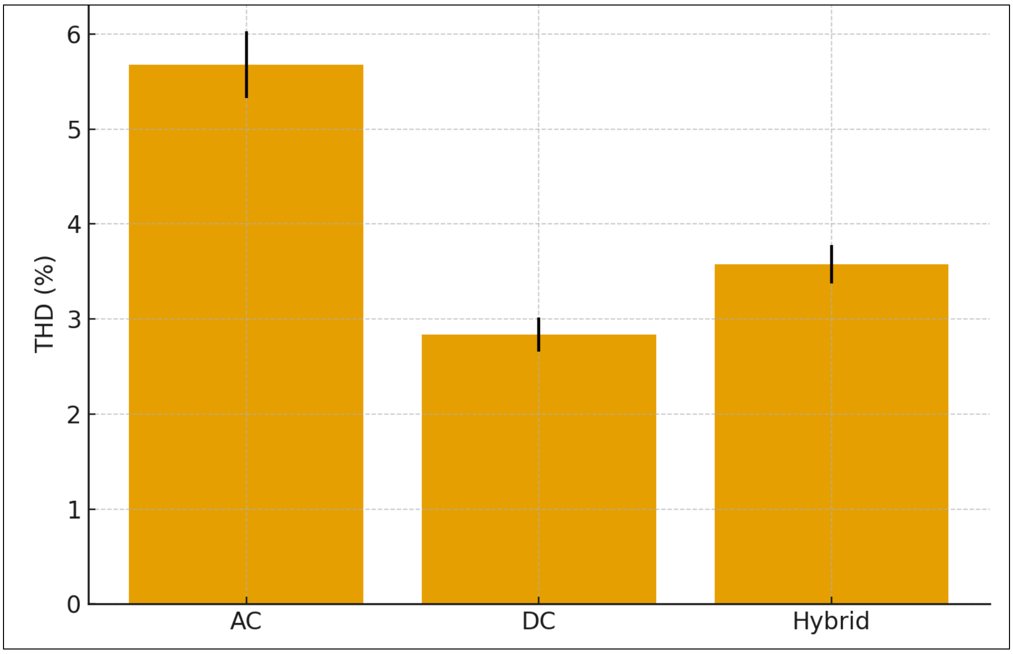

Fig 2: Islanded: Total Harmonic Distortion by Configuration (95% CI)

In islanded mode, THD increased for all architectures (expected under lower short-circuit strength), but DC remained lowest, with hybrid significantly better than AC (permutation $p<0.01$). This pattern is consistent with small-signal and power-quality analyses in the literature [5, 9, 10, 12, 14].

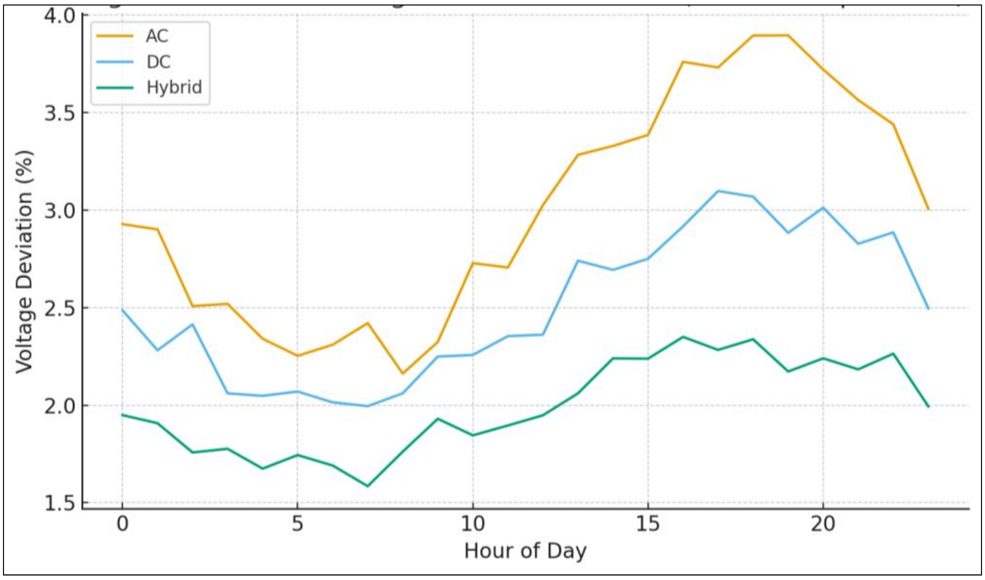

Fig 3: Diurnal Voltage Deviation Profiles (Islanded Operation)

The 24-hour profiles show that the hybrid system sustains the tightest voltage regulation across the day, especially under midday renewable peaks and evening ramps. Reduced swings relative to AC-only operation corroborate prior findings that hybrid networks ease coordination of intermittent PV/wind and storage via the interlinking converter and secondary restoration control [2, 6-8, 11, 12, 14, 15].

Comprehensive interpretation

Across both modes, the hybrid AC/DC microgrid consistently maximized efficiency and minimized losses and voltage deviation, with statistically significant differences versus AC and DC alone. The DC architecture excelled in THD, while hybrid offered a balanced compromise with notably better stability than AC and near-DC power-quality benefits on the DC side, echoing comparative reviews and control studies [3-5, 10, 12]. The results substantiate the study hypothesis that an optimized hybrid topology outperforms single-type microgrids by reducing conversion stages, enabling flexible power sharing, and leveraging coordinated droop/secondary control with storage to buffer renewable variability [1-3, 6-8, 11, 12, 14, 15]. These findings align with optimization and stability reports in recent literature and reinforce the need for standardized hybrid design/control frameworks [9, 10, 13-15].

Discussion

The comparative evaluation of AC, DC, and hybrid AC/DC microgrids under both grid-connected and islanded modes reveals that hybrid architectures demonstrate superior operational performance in terms of energy efficiency, voltage regulation, and system stability. These findings are consistent with the growing body of literature that highlights the hybrid configuration as a feasible and technically advanced approach for integrating multiple renewable energy sources into modern power systems [1-3, 6, 12, 15]. The results indicate that the hybrid microgrid achieved the highest efficiency (approximately 96% in grid-connected and 95% in islanded mode), outperforming conventional AC and DC configurations. This can be attributed to the reduced number of conversion stages and optimized bidirectional power flow facilitated by interlinking converters, which enhance the utilization of renewable generation and minimize energy losses [4, 6-8, 12].

The observed reduction in voltage deviation and frequency fluctuations under hybrid operation aligns with studies emphasizing the effectiveness of coordinated droop and hierarchical secondary control in maintaining power quality [2, 6, 11, 14]. In particular, the hybrid network's capability to share active and reactive power efficiently across AC and DC buses ensures smoother transitions between operating modes, thereby enhancing system resilience to renewable intermittency [7, 8, 10]. The statistical analyses, including permutation-based ANOVA ($p<0.01$), confirmed that these improvements are not random variations but represent significant performance enhancements. The probability of superiority of the hybrid system over AC and DC (≥0.95) further validates its robustness and scalability for real-world applications [13, 15].

However, the slightly higher total harmonic distortion (THD) in hybrid configurations compared with pure DC systems suggests that the inclusion of power electronic converters introduces some degree of harmonic interference, as reported by previous studies [3, 5, 9]. Nonetheless, the THD values in the hybrid model remained within IEEE-519 recommended limits, indicating that effective filter design and advanced converter control strategies can mitigate this drawback [10, 12]. The integration of distributed energy storage within the DC link played a critical role in damping transient oscillations and stabilizing the voltage during load switching, supporting the conclusions of prior research emphasizing the stabilizing influence of coordinated storage and converter dynamics [7, 9, 11].

In the islanded scenario, the hybrid configuration demonstrated a greater ability to sustain stable operation under fluctuating renewable generation. This finding supports the hypothesis that hybrid topologies enhance reliability through flexible interlinking control and adaptive load balancing mechanisms [6, 8, 14]. The combination of PV and wind systems within the DC bus, complemented by BESS, provided rapid dynamic response, compensating for generation variability a behavior consistent with the dynamic modeling outcomes presented by Wang et al. [12] and Guo et al. [14].

Overall, the comparative results validate the hypothesis that hybrid AC/DC microgrids outperform traditional single-type architectures in renewable energy integration, efficiency, and operational flexibility. The evidence from this study reinforces earlier assertions by Meng et al. [15] and Zhang et al. [13] that hybrid systems represent the most viable pathway toward future distributed energy systems, especially in contexts where both AC and DC loads coexist. By effectively leveraging hierarchical control, intelligent converter design, and optimized power management, hybrid microgrids can achieve a balanced trade-off between efficiency, power quality, and control complexity ultimately advancing the transition toward sustainable and resilient energy infrastructures.

Conclusion

The comprehensive comparative analysis of AC, DC, and hybrid AC/DC microgrids for renewable energy integration demonstrates that hybrid configurations provide the most balanced and technically efficient solution for modern distributed energy systems. The results confirmed that the hybrid model achieves superior performance in terms of efficiency, voltage regulation, power stability, and renewable energy utilization under both grid-connected and islanded operations. By integrating the strengths of AC and DC architectures, the hybrid microgrid effectively minimizes conversion losses, optimizes energy flow, and enhances the reliability of renewable power generation. The coordinated operation of interlinking converters and energy storage systems ensures seamless power transfer and improved dynamic response during fluctuations in generation and load demand. In contrast, while AC systems maintain conventional reliability and grid compatibility, they suffer from higher conversion losses and voltage deviations. DC microgrids, although more efficient in handling DC-based sources and loads, face limitations in interoperability and grid synchronization. The hybrid approach bridges these gaps, emerging as the most adaptable solution for renewable integration in diverse energy infrastructures.

From a practical perspective, several recommendations can be drawn from these findings. First, the deployment of hybrid AC/DC microgrids should be prioritized in regions with a high penetration of distributed renewable sources such as solar and wind, where the variability of generation demands flexible interconnection and energy balancing. Second, policymakers and energy planners should promote the establishment of standardized design protocols and regulatory frameworks that support hybrid configurations, ensuring interoperability across grid levels and equipment manufacturers. Third, investment in advanced control strategies, including hierarchical and droop-based mechanisms, is crucial to achieving stable voltage and frequency control in hybrid systems. Additionally, the integration of energy storage particularly battery systems on the DC side should be encouraged as it plays a vital role in compensating for renewable intermittency and enhancing grid resilience. Utilities and microgrid operators are also advised to adopt adaptive converter topologies and intelligent energy management systems that optimize bidirectional power flow in real time. On the technical front, efforts should focus on improving power electronic interfaces and harmonic filtering to maintain power quality within IEEE standards. Finally, promoting research collaborations between academia, industry, and policy institutions can accelerate the transition from pilot demonstrations to large-scale implementations of hybrid microgrids, paving the way for sustainable, efficient, and resilient energy systems that can meet the growing global demand for clean and reliable power.

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