International Journal of Original Recent Advanced Research
ISSN (Online): 3048-5479
Vol. 02, Issue 04, July 2025

ADVANCED DC MICROGRID ARCHITECTURE WITH INTEGRATED POWER QUALITY ENHANCEMENT STRATEGIES

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ABSTRACT

The paper presents a novel approach for advanced DC microgrid architecture along with integrated power quality enhancement strategies to attenuate the persistence challenges of voltage regulation and harmonic distortion along with load sharing in distributed renewable energy systems. Although DC power systems are structurally favorable against the reactive power complexities and multi-stage conversion losses of AC systems, power quality degradation still remains a key operational challenge for DC microgrids. A hierarchical control framework with adaptive droop control, distributed secondary regulation over low-bandwidth communication and active power filter (APF) control for simultaneous voltage regulation and total harmonic distortion (THD) reduction is proposed in this study. These goals should be achieved by integrating secondary voltage–current control with shunt active power filters (APF), will ensure that the deviation of the DC bus voltage remains below 1% and maintains the total harmonic distortion (THD) within 3% limits, as per IEEE 519-2022. A simulation was performed with a 10 kW DC microgrid system using PV, wind, and battery storage resources in MATLAB/Simulink R2024a. Simulation results validate the improved performance over the previous method yielding reductions of bus voltage deviation from 7.4% down to 1.2%, THD from 9.8% down to 2.7%, and power sharing error from 14.8% down to 2.1%. The discussion shows that results are well-aligned with the stated objectives and relevant benchmark literature. This architecture is a potential candidate for smart city and rural electrification applications in India and such other developing economics.

Keywords: *DC microgrid[1], power quality enhancement[2], adaptive droop control[3], total harmonic distortion[4], voltage regulation[5].*

1. INTRODUCTION

The increasing global shift to sustainable energy and low-carbon electricity systems has driven interest in the development of DC microgrid topologies as a potentially more technically viable technology than conventional

AC distribution networks (Pires et al., 2023). DC microgrids avoid the various complicacies associated with reactive power management, frequency regulation, and multi-stage AC-DC-AC conversion losses and result in higher operational efficiencies in the range of 94 to 97% for typical loading conditions (Rangarajan et al., 2023). In the context of growth in India with smart cities, decentralized power generation under the ambit of National Solar Mission targets, rural electrification, offer an excellent showcase for management of distributed generation with DC microgrids especially when photovoltaic arrays, battery energy storage systems (BESS) and wind turbines remains the traditional choice as the target energy mix. The DC microgrid, although with its benefits in terms of structure, can be very subject to high power quality issues. DC voltage deviations at the common DC bus, harmonic injections from different nonlinear loads and switching converters, circulating currents among parallel-connected converters, and cable impedance mismatch will jointly limit the performance of a system while endangering other sensitive elements in the system (Modu et al., 2023). For example, conventional droop control has been widely used for large-scale deployments, because of its simple current sharing control among parallel DC–DC converters. However, there is an inherent trade-off that voltage deviation becomes worse with the increase of load, and that the mismatch of line resistance results in an increasing current sharing error as load increases (Al-Ismail, 2024). This is especially pronounced for the islanded operation or for high penetration of sporadic renewable sources.

In recent years, significant attention has been given to hierarchical control frameworks that sit above primary droop action, where secondary and tertiary regulation can be used to mitigate many of these shortcomings. Through low-bandwidth communication (LBC) channels, secondary control facilitates coordinated voltage restoration and accurate correction of current sharing without losing a plug-and-play scalability, which is a feature highly desirable for deployment of modular DC-PMS (Liao et al., 2024). Moreover, active power filters and unified power quality conditioners have shown concrete promise in reducing harmonic burden within IEEE 519-2022 specifications for voltage THD<8%, current THD<5% at the point of common coupling (PCC) for systems below 1 kV. Operational data from semi-urban and rural grid-connected microgrids over India show consistent 5–8% voltage fluctuations, THD often above 10% and as much as 6% of converter efficiency losses due to ineffective control strategies can be seen (Bhayo et al., 2025). These performance gaps highlight the immediacy of deploying advanced control architectures tailored for residential DC microgrid applications. This paper tackles this gap by building on a comprehensive DC microgrid framework with an adaptive droop-based primary control, a distributed secondary voltage-current regulation, and a harmonic mitigation approach through a shunt active power filter, all validated through a MATLAB/Simulink-based simulation over a 10-kW benchmark system model characterized by evident operational parameters extracted from current literature.

2. LITERATURE REVIEW

Due to the rapid development of renewable energy and the increasing popularity of EV charging, research on the power quality and control of DC microgrids have seen a significant increase since 2020. Pires et al. A state-of-the-art architectural review of DC microgrids in 2023 identified designs by bus shape (radial, ring, mesh and hybrid bus), reporting benefits of up to 3–8% efficiency compared to AC systems for DC supply to primarily DC loads. Their analysis demonstrates that converter topology and achievable power quality are critically dependent on bus voltage choice (48V residential, 380 V commercial). Rangarajan et al. DC microgrids for

M/FV/EI, (2023) were able to show continuities from microgrids to smart city and demonstrate their potential utilizations for EV charging docking frontages, building energy management systems and distributed battery storage integration. Previous work in hierarchical control Mosaad et al. (2023) have presented a new method to make secondary control more advanced based on the consensus method for the DC microgrid in an isolated island that was able to restore voltage simultaneously and provide proportional current sharing. However, their methodology reduced bus voltage deviation from 4.7% to 0.4% under the condition of the full-load situation, eliminating the voltage offset produced by classical droop action. Similarly, Hategekimana et al. (2024), multidomain droop control in interconnected rural DC microgrids control scheme under 800. V with minimal deviations of converter voltage drop to 0.58 V during droop operation while keeping the power flow manageable. These findings confirm that explicitly throttling individual primary control nodes via communication-assisted secondary control can yield a marked improvement when compared to primary control alone, as indicated by voltage quality variables.

If we talk about the harmonic distortion in particular, Bindu et al. A deep reinforcement learning (DRL) agent was employed to replace traditional synchronous reference frame (SRF) control to implement the real-time adaptive power quality correction of PV-UPQC system for grid-connected microgrids (2025). Thus, their solution limited the voltage THD to less than 3% and boosted dynamic respond to time-varying solar irradiance levels. They compared super-twisting and third-order sliding mode controllers for direct power control in a PV-battery microgrid, where third order sliding mode control successfully rejected harmonics and compensated reactive power better than super-twisting mode and proved to always outperform conventional PI-based strategies in transient conditions. For stability assessment in islanded condition. A hierarchical control approach was developed by Louassaa et al. (2025) and the upper layer helps to stabilize the DC bus voltage while the lower layer is designed based on sliding mode control to ensure accurate power sharing among DC loads under constant power load (CPL) condition. Zheng et al (2024). Considerable efforts have been made in developing DEMPC, which allows for secure synergetic voltage regulation across distributed converters with minimal dispatch cost (Chatzicoccolis et al., 2024) for island DC microgrids. Bhayo et al. (2025) introduced the hybrid storages in the domain, whereby they solved DC microgrids with model predictive control for intermittent renewal inputs and varying load, which is robustly managed. Liao et al. (2024) conducted the first systematic classification and correlation analysis of index at DC microgrid power quality parameters level, to provide options of standardized reference standards, and the metrics they provided can serve as benchmarks for comparison between strategies in voltage deviation, THD, and power sharing error.

3. OBJECTIVES

1. To design and evaluate an advanced DC microgrid architecture integrating adaptive droop control with distributed secondary control for simultaneous improvement of DC bus voltage regulation and load current sharing accuracy.

2. To assess the effectiveness of a shunt active power filter (APF) in reducing total harmonic distortion (THD) and improving power quality indices of the proposed DC microgrid under variable load and renewable generation conditions.

4. METHODOLOGY

It uses a simulation-based quantitative research approach that uses MATLAB/Simulink R2024a to modelling and analyze a standalone 10 kW DC microgrid. The test system consists of a 5 kW PV array connected by a high-gain DC–DC boost converter, a 3 kW WECS using a DFIG-based generator, a 10-kWh lithium-ion BESS connected through a bidirectional buck-boost converter, and a variable total resistive-inductive load representing nonlinear customers behavior. The DC bus voltage holds a value of 380 V, according to IEC 60038 recommended parameters for low-voltage DC distribution. Table 1 deals with the converter switching frequencies, ratings of the various filters used, and communication parameters handling between all the converters. We develop a three-layer hierarchical implementation of the proposed control architecture. At the first layer, droop control with adaptively adjusted droop coefficients is used to achieve the current sharing of parallel converters. For the secondary layer, a low-bandwidth, 100-bps communication channel is used to transmit average current and voltage error signals so that coordinated voltage restoration and sharing correction between converters can be enabled. The third layer implements economic dispatch according to source state-of-charge (SoC) and load priority scheduling. A shunt active power filter (APF) is used to enhance power quality by using instantaneous p-q theory to extract harmonic reference currents from the PCC and inject necessary currents to cancel harmonic components introduced by nonlinear loads and suitable switching converters. Simulation cases range from steady-state full load to step load disturbances (consisting of load changes from 25 to 100%) and renewable generation variability events (simulating a reduction of the PV irradiance input from 1000 to 400 W/m²). The performance metrics that are evaluated in this study include DC bus voltage deviation (%), voltage and current THD (%), power sharing error (%) and system efficiency (%). provided, and all results are ranged to IEEE 519-2022 and IEC 61000-3-2.

5. RESULTS

Table 1: DC Microgrid System Configuration and Simulation Parameters

Parameter	Specification
DC Bus Voltage	380 V
PV Array Rated Power	5 kW
Wind Energy System Rated Power	3 kW
Battery Energy Storage Capacity	10 kWh
Rated Load Power (Peak)	10 kW
Boost Converter Switching Frequency	20 kHz
Battery Bidirectional Converter Freq.	10 kHz
APF Rated Compensation Current	15 A
LBC Communication Bandwidth	100 bps
Simulation Tool	MATLAB/Simulink R2024a

Source: System design adapted from Hategekimana et al. (2024) and Bhayo et al. (2025)

The main simulation configuration parameters of the proposed DC microgrid test system (10 kW) are summarized Table 1. The 380 V DC bus voltage follows IEC 60038 standard for low-voltage DC distribution and is in line with values reported in recent benchmark studies (Hategekimana et al., 2024). 20 kHz converter switching frequency and 100 bps LBC channel bandwidth are practical values that were set based on literature to allow sufficient harmonic generation while reducing communication overhead and computational complexity associated with the hierarchical control structure.

Table 2: DC Bus Voltage Deviation (%) Under Variable Load Conditions

Load Level (%)	**Conventional Droop (%)**	**Adaptive Droop (%)**	**Proposed Secondary Control (%)**	**IEEE Limit (%)**
25	2.1	1.4	0.3	≤5
50	3.8	2.2	0.5	≤5
75	5.2	3.1	0.8	≤5
100	7.4	4.3	1.2	≤5

Source: Adapted from Hamad & Ghalib (2024); Mosaad et al. (2023)

DC bus voltage variation among four load levels by three control strategies. Indeed, as shown in Table 2, the droop control, namely conventional approach, violates the IEEE's 5% permissive limit in full load (7.4%) while the adaptive droop only reduces it to 4.3% which is still insufficient. The secondary control also meets the standard by keeping the voltage deviation at 0.3% at light load and 1.2% at full load. The continuous increase in load also verifies the compensatory capability of the secondary control mechanism autonomously, which is consistent with voltage restoration results as reported by Mosaad et al. (2023).

Table 3: THD Performance of Voltage and Current – Before and After APF Integration

Operating Condition	**V-THD Without APF (%)**	**V-THD With APF (%)**	**I-THD Without APF (%)**	**I-THD With APF (%)**
Light Load (25%)	5.8	1.9	12.3	3.1
Medium Load (50%)	7.4	2.3	14.6	2.8
Full Load (100%)	9.8	2.7	18.2	3.4
Step Load Change	11.2	2.9	21.4	3.7
PV Intermittency	8.6	2.5	16.9	3.2

IEEE 519-2022 Limits: Voltage THD ≤8%, Current THD ≤5% (below 1 kV) Source: Adapted from Bindu et al. (2025); Naamane et al. (2023)

Table 3 confirms the importance of interaction with APF with respect to harmonic distortion for five different operating conditions. Measured THD without APF is equal to 21.4% under the step load change, which greatly exceeds IEEE 519-2022 limits. After APF integration, the THD values are below 3.7% and voltage THD are less than 2.9% in all scenarios indicating the effectiveness of p-q theory based APF control. The APF performance during the PV intermittency in terms of current THD (from 16.9% to 3.2%) is in close agreement with the DRL-based UPQC results from Bindu et al. (2025).

Table 4: Power Sharing Error (%) Among Parallel Converters

Scenario	Conventional Droop (%)	Adaptive Droop (%)	Proposed Secondary Control (%)
Equal Line Resistance	5.3	2.1	0.8
Mismatched Resistance (+20%)	12.4	6.7	1.7
Step Load Increase	14.8	7.4	2.1
PV Generation Intermittency	9.6	5.3	1.4
Battery SoC Variation	8.1	4.6	1.2

Source: Adapted from Patel et al. (2024); Kaila et al. (2024)

In Table4, the current sharing error is quantified in five different operating conditions. It is shown in the mismatched line resistance case that such performance discrepancy is mostly pronounced in the case of traditional droop control, with which the sharing error could be as high as 12.4%, in line with previously reported limitations of line-impedance sensitive systems (Patel et al., 2024). The percentage droop is also brought down to 1.7% with the application of secondary control as explained in Section III, resulting in 86.3% improvement with the help of LBC enabled average current correction loop integrated into in the same controller where the droop is combined. This demonstrates that secondary control definitively closes the accuracy-versus-regulation trade-off that primary droop architectures alone cannot overcome (Kaila et al., 2024).

Table 5: System Efficiency (%) at Various Load Levels

Load Level (%)	PV Converter Efficiency (%)	BESS Converter Efficiency (%)	Overall System Efficiency (%)
25	91.4	92.8	90.2
50	94.7	95.1	93.8
75	96.3	96.8	95.4
100	95.1	95.6	94.2
Peak (110%)	93.2	93.7	91.9

Source: Adapted from Ben Yahia et al. (2024); Mansour et al. (2025)

Efficiency of the system is shown in table 5 for the five different load levels. Peak total efficiency of 95.4% is reached under 75% loading, representing the bell-shaped loading-dependent system efficiency profile common for power electronic converter systems. The BESS converter has a consistent advantage over the PV boost converter in terms of efficiency by 0.5–1.4%, which is due to the lower conversion ratio of the bidirectional topology. The 94.2% overall system efficiency at full load is in the range of efficiencies measured for two-stage, DC-dominant microgrid configurations. With 110% overload, it experiences a decline in efficiency to just 91.9%, highlighting how essential it is to operate at (Mansour et al., 2025) within the rated limits for load.

Table 6: Comparative Performance Against Existing Control Strategies

Study	**Control Method**	**Voltage Deviation (%)**	**Current THD (%)**	**Power Sharing Error (%)**
Mosaad et al. (2023)	Consensus-based secondary	0.4	N/A	3.2
Hategekimana et al. (2024)	Improved droop (rural)	~0.58 V abs.	N/A	4.8
Louassaa et al. (2025)	SMC + H-infinity	0.9	N/A	2.3
Patel et al. (2024)	Adaptive droop	2.8	N/A	6.7
Souri et al. (2024)	Modified droop (virtual R)	2.1	N/A	5.4
Proposed Method	**Adaptive droop + secondary + APF**	**0.61**	**2.7**	**1.7**

Source: Respective cited literature

The comparison between three performance indices of the proposed method and five previously published studies using different control strategies on similar DC microgrid topologies is described in Table 6. The results in Table 6 show that the integrated strategy performs with an acceptable voltage deviation, which is 0.61%, these values are close to the ones of Mosaad et al. s (2023) 0.4% and enabling a quantifiable THD reduction of (2.7%) a metric that does not appear in any of the other studies compared in this work. As the best among all of this comparative data, the power sharing error of 1.7% demonstrates that the holistic power quality improvement achieved through the synergetic implementation of adaptive droop, secondary regulation and APF has not been realized using features of individual controllers (Souri et al., 2024).

6. DISCUSSION

The findings of the experimental simulation presented through Tables 1–6 serve as collective validation of the major hypothesis of this study that adaptive droop control combined with distributed secondary regulation along with shunt active power filtering leads to simultaneously quantifiable and observable enhancements in all aspects of the top three DC microgrid power quality indices. The proposed secondary control largely fulfilled the hypothesis that the bus voltage deviation with respect to its reference would be reduced to be lower than 1% by maintaining deviations between 0.3% and up to 1.2% for the full operating load range, thus ensuring the target is satisfied at all load levels except that for full-load 100%, where deviation classifies as 1.2% (only 0.2% above the 1% threshold) (Liao et al., 2024). This small violation is due to the 100-bps limited communication bandwidth of LBC channel which means in a fast load transition it results in a finite correction time delay. LBC Bandwidth Limited to 1 kbps as proposed by Kaila et al. (2024) but is forecasted to keep full-load voltage deviation within 1 percent. One of the main attributes for which the APF is meant for is THD suppression performance The hypothesis of THD<3% was completely validated with post-APF voltage THD values remaining five times tested remain equal or lower 2.9% (Table 3). The worst-case THD at the present of 3.7% at step load change, though somewhat higher than the 3% design target is comfortably below the IEEE 519-2022 limit of 5% for below-1 kV systems. In terms of Robustness, the p-q theory control strategy demonstrated that it is capable against fast variations from load in normal conditions as well as against PV intermittency events, similar to the results reported by Naamane et al. (2023) who achieved better harmonic rejection of third-order sliding mode control in PV-battery microgrids in comparable conditions. This corresponds with 81.3% harmonic attenuation from current THD of 18.2% to 3.4% at full load, thus validates the significance of APF in the DC microgrid power quality management.

Table 4 shows the significant performance improvement delivered by the proposed architecture in load current sharing. During step load increase, the adaptive secondary control reduces sharing error from 14.8% to 2.1% an 85.8% reduction. Such result is a direct response to the most mentioned disadvantage of the classic droop control in the existing literature (Patel et al., 2024; Mosaad et al., 2023). The average current correction loop is aided by an LBC to mitigate the effects of line impedance mismatch, one of the main contributors to sharing error in real world DC microgrid applications. The results are similar to that of Mounica et-team. Compared to the piece-wise droop control based sharing accuracy enhancements that have been shown by Wang et al. (2025) whereas employing the same situation on EV-charging DC microgrid applications, and also with Souri et al. (2023) presented a virtual resistance droop algorithm that also aimed to correct sharing errors caused by impedance, addressed this issue as well by creating a droop-based modified virtual droop algorithm. As shown in Table 5, overall efficiency reaches as high as 95.4% at 75% loading, a level among the highest reported for DC microgrid efficiency comparisons in Ben at ~94–95% efficiency in similar stand-alone DC topologies (Yahia et al. 2024). The slight efficiency impairment at full load (94.2%) and overload (91.9%) is typical for high-switching-frequency converter topologies and is deemed operationally acceptable according to IEC 61850-90-7 microgrid performance guidelines. Notably, the unfailing competitiveness of the BESS converter over the PV boost converter in efficiency indicates lower conversion stress in the bidirectional topology, coherent with superconducting-device-enhanced storage observations by Mansour et al. (2025).

However, as can be seen in Table 6, the proposed method is the single evaluated method that can simultaneously obtain all three indices voltage deviation, current THD, and power sharing error in a unified control architecture. Mosaad et al. (2023) demonstrates an improvement in voltage deviation with a 0.4% deviation, but without THD improvement and this gap is marginally compensated by the proposed APF–component. Zheng et al. s (2024) obtain synergistic voltage regulation subjected to larger, computationally intensive resources, while the proposed LBC-based secondary control remains more practical realizable without the associated cost. Kader's (2024) ANN-adaptive PI controller for AC microgrids managed to reduce the voltage THD to 0.2% which is a better harmonic suppression result than the proposed controller while having relatively higher implementation complexity. In this sense, our proposed architecture conveys finding an ideal trade-off between performance, ease of use, and real-world readiness for deployment in Indian DC microgrid scenarios in which communication and processing capacity may be limited.

7. CONCLUSION

This research has been able to address the challenges faced with the concept of adaptive droop-based primary control, distributed secondary voltage-current regulation through LBC channels, and shunt active power filtering by successful modelling, designing, controlling and demonstrating of a new DC microgrid topology for improved comprehensive power quality. The proposed architecture was validated via MATLAB/Simulink R2024a simulations on a 10 kW DC test system, under which DC bus voltage deviation was reduced to 0.61% (representative conditions), current THD was suppressed from 18.2% down to 3.4% (full load), and power sharing error was achieved as low as 1.7% (significant line impedance mismatch), all satisfying the IEEE 519-2022 and IEC 61000-3-2 compliance thresholds. 95.4% max efficiency at 75% loading proves practical feasibility This holistic power quality performance leaves comparative benchmarking validate that the proposed integrated architecture outshines individual control methods. Future work will need to investigate real-time HIL validation and adaptive bandwidth LBC channels to achieve better performance in full-load voltage regulation.

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