

# A STUDY ON DC MICROGRID DESIGN WITH EMPHASIS ON POWER QUALITY IMPROVEMENT MECHANISMS

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## Abstract

*DC microgrids have become essential topology with applying of the renewable energy resources in the today distribution systems especially where there is a permanent problem about power quality. In this paper, the design parameters of a DC microgrid are explored, focusing on strategies to enhance power quality such as voltage stabilization, harmonic reduction, ripple suppression, and also enhanced droop control techniques. Within this context, a simulation-based comparative approach is adopted, using validated data from the published experimental and/or simulation studies conducted in the years 2021 to 2025. This study presents the hypothesis that utilizing a well-established droop control with hierarchical energy management will achieve marked improvements in terms of voltage deviation and total harmonic distortion (THD) in voltage signals generated in a configurable DC microgrid. Results validate that DC microgrids with optimal control meet the requirement of voltage deviations below  $\pm 2\%$ , THD of less than 3.5% and the path to the efficiency improvement of the system is high as 94.3% compared with the comparable AC case. In the discussion, the results are compared with certain IEEE and MDPI literature, and the importance of layered control strategies remains significant for reliable power delivery. The common study and findings of active power quality mechanisms applied to DC microgrids has presented a superior characteristic of sustainable electrification suitable for ever-changing energy infrastructure of India.*

**Keywords:** *DC microgrid<sup>1</sup>; power quality<sup>2</sup>; droop control<sup>3</sup>; voltage regulation<sup>4</sup>; total harmonic distortion<sup>5</sup>*

## 1. Introduction

The growing penetration of renewable energy sources (RES) including solar photovoltaic (PV) and wind energy into conventional distribution grid is radically transforming global energy landscape. The traditional alternating current (AC) grid infrastructure that have been optimally designed to fit centralized power generation starts to show its limits with the unpredictability and widespread of RES. In this context, compared to existing state of the art research and technology, DC microgrids have seen a satisfactory amount of academic and industrial attention as architecturally superior solutions for urban and peri-urban distribution in the developing countries such as India. DC microgrids, on the other hand, do not require reactive power compensating principles or frequency synchronization as in AC systems, have fewer conversion stages, and directly connect to PV panels, batteries, and DC loads, leading to higher efficiency and simpler control architecture (Dragičević et al., 2016; Elsayed et al., 2015). But all those structural benefits can't preclude DC microgrids from suffering from power

quality (PQ) degradation. Among these issues, voltage deviations attributed to the disturbance from the dynamic behaviors of the load, ripple current generated by switching converters, and harmonic distortion brought by non-linear loads have continually plagued the trouble of DC distribution systems. When it comes to important issues such as these, we can understand better that in the case of DC microgrids working autonomously, isolated from the main utility grid, all regulation burden must be taken up by the onboard control strategy because there will not be any external voltage reference available. Poor power quality mechanisms, even for a well-designed DC microgrid, may lead to equipment malfunction, battery inferior performance, and energy loss.

With the accelerating deployment of distributed energy systems facilitated by India's National Smart Grid Mission and the Pradhan Mantri Sahaj Bijli Har Ghar Yojana (Saubhagya) scheme in most of the villages/district, so DC microgrid design becomes a practically urgent topic of research. Resource-saving empowerment of rural electrification involving low-voltage DC microgrids in the range of 48 V, 380 V, or 750 V DC bus levels usually has stringent power quality management requirements to comply with the second (load) section and the life of each system (Rangarajan et al., 2023). It has been consistently shown in studies that the DC bus voltage in the absence of hierarchical control can significantly oscillate during load-transients, exhibiting variations as high as  $\pm 8\text{--}12\%$ , beyond the IEEE 519-2022 and IEC 61000 recommended tolerance of  $\pm 5\%$ . To the best of our knowledge, this is the first extensive review that considers theoretically and conceptually, DC microgrid design, particularly with regard to power quality enhancement approaches. Relying on simulation-validated data from peer-reviewed publications retrodicted from 2021 to 2025, the paper surveys state-of-the-art control techniques especially adaptive droop control, virtual impedance-based compensation and model predictive control (MPC) and then, benchmarks their performance quantitatively. These findings add to the evidence base needed to support the sustainable, resilient, and quality-assured deployment of DC microgrids in India and similar developing-nation contexts while facilitating effective grid-tied and islanded operations.

## 2. Literature Review

During the last ten years, papers about DC microgrid and power quality has been increased successfully in comparison with the previous decades due to the rapid development of solar PV and battery energy storage systems (BESS). Elsayed et al. Table of contents (from 2015). DC Microgrid Topologies and Distribution Architectures DC system can achieve fundamental reduction in conversion losses as compared to AC systems and indicates regulation of voltage as a key operational challenge Justo et al. A more detailed analysis of AC and DC microgrids with DOF was performed by (2013), who compared the performances of AC and different types of DC architectures to sustain distributed energy resources, and highlighted a potential 15–20% decrease in losses in DC microgrids, together with better integration of RES interfaces. Dragičević et al. In IEEE Transactions on Power Electronics, (2016) reported a seminal review of DC microgrid control strategies and stabilization techniques, and systematically compartmentalized hierarchical control into primary, secondary, and tertiary layers. In this hierarchy, the first level primary control, is the local voltage-current droop regulation where the output of the droop controller is set to return the bus voltage to its nominal value after droop manipulation; the second level secondary control is the economic dispatch and grid interaction at the tertiary level. The framework of three layers has since evolved as the canonical design reference for DC microgrid controllers. Saeed et al. Microgrid challenges revisited: A system of systems perspective (IEEE Access, 2021) Sarjakan de Freitas Guddal et al.

Zheng et al. (2024) derived a Distributed Economic Model Predictive Control (DEMPC) approach to islanded DC microgrids with PV, wind and battery sources that achieved stabilization of bus voltage under varying irradiance and minimized switching cost in batteries. In IEEE Access, Al-Ismail (2021) performed a complete review of DC microgrid in terms of planning, operation, and control in which he pointed out that protection architecture and grounding configuration need to be considered in the power quality studies since they are

essential design parameters that are mostly ignored. Van den Brom et al. A long-duration real-world power quality measurement campaign was conducted on a configurable bipolar 350 V/700 V DC urban microgrid between 2018 and 2019 and included the continuous recording of voltage and current signals sampled at 500 kSa/s. The results supplied clear evidence of ripple components and harmonic spectra in DC distribution that directly benefited standardization for DC PQ measurement methods. Almihat (2023) gave a systematic review of AC and DC microgrid energy management system in AIMS Energy, which covers iterative, mathematical programming, MILP, stochastic, and MPC-based EMS methods. Siddique et al. (2023) reviewed power quality problems in renewable-integrated microgrids such as voltage sag/swell, flicker and harmonic injection and reported that optimization and control strategies are the most common mitigation pathway in their complementary work Chartered by MDPI Sustainability. The conclusion was drawn in Chicco et al. (2024) in MDPI Applied Sciences that droop based control techniques effectively mitigated voltage fluctuations and ensured proportional load sharing among many distributed sources connected to a common workstation in dynamic conditions. An M-UPQC for hybrid microgrid power quality improvement using switched-inductor boost converters was discussed in with controllable parameters optimized via the BHO (Binary Habitat Optimization), HHO (Hydro-Harmonic Optimization), or GOA (Gravitational Optimization Algorithm); THD reductions were reportable. Simulation-based verification that DC microgrids can maintain stable bus voltages below 500 V within fewer transients and reduced settling times during load perturbations in aggregate this collection of literature establishes power quality in DC microgrids as primarily governed by control strategy selection, converter topology, and hierarchical energy management architecture.

### 3. Objectives

1. To analyze the impact of advanced control strategies specifically adaptive droop control and hierarchical energy management on voltage regulation and THD reduction in a DC microgrid system.
2. To comparatively evaluate DC microgrid power quality performance indices (voltage deviation, ripple, efficiency, THD) under varying load and generation conditions using verified simulation data.

### 4. Methodology

The present study uses a quantitative simulation-based comparative research design with secondary data from verified peer-reviewed publications via, Google scholar, IEEE Xplore, MDPI, Springer Nature and Frontiers, 2021-2025. The DC microgrid model implemented in this study is based on a reference low-voltage DC (LVDC) microgrid system operating at a nominal bus voltage of 380 V DC, the microgrid consists of 20 kW PV array, 10 kWh lithium-ion BESS and resistive-nonlinear mixed load profile, and the values in this study are consistent with the values reported in Tariq et al. (2024) and Chicco et al. (2024). The performance of the system is analyzed under 3 scenarios of operation: (i) clear day, light load, full PV generation; (ii) cloudy day, heavy load, partial shading and (iii) battery-only mode of supply in the islanded operation. The different power quality parameters investigated in this work include: Deviations of DC bus voltage (percent); ripple voltage (mV); THD (percent); and current sharing accuracy (percent) and system efficiency (percent). Buckling strategies compared are: traditional droop control, and adaptive droop control with virtual impedance compensation as well as distributed MPC. Data for each control strategy are obtained based on the simulation and experimental results in the referenced studies. MAPE is used for voltage deviation evaluation, and percentage improvement metrics are calculated for comparing THD and efficiency in statistical evaluation. All tabulated data are sourced directly from published articles vetted by subject matter experts, to which individual DOIs are provided for traceability and academic rigor.

## 5. Results

**Table 1: DC Microgrid Reference System Specifications**

Parameter	Specification
Nominal DC Bus Voltage	380 V DC
PV Array Rated Power	20 kW
Battery Energy Storage Capacity	10 kWh (Li-ion)
DC-DC Converter Type	Bidirectional Buck-Boost
Number of Terminals	6
Load Type	Mixed (Resistive + non-linear)
Control Architecture	Hierarchical (Primary + Secondary)
Operating Mode	Grid-tied and Islanded

**Source:** Tariq et al. (2024); Chicco et al. (2024)

The configuration parameters of the baseline DC microgrid system used for this study are found in Table 1. The system specification system has a 20 kW PV source and a 10 kWh BESS connected to a 380 V DC nominal bus voltage which reflects a representative small-scale urban microgrid; however, the proposed method does not limit to this system architecture only. This six-terminal architecture can support multiple generation as well as load nodes, which is critical for evaluating the power quality analysis under the distributed loading. The voltage regulation and THD standards indicated in the following tables are directly controlled by these specifications.

**Table 2: DC Bus Voltage Performance Under Different Control Strategies**

Control Strategy	Nominal Bus Voltage (V)	Voltage Deviation (%)	Settling Time (ms)	Voltage Overshoot (%)
No Control (Open Loop)	380	±9.2	>200	11.4
Conventional Droop Control	380	±4.8	85	6.5
Adaptive Droop + Virtual Impedance	380	±1.9	32	4.6
Distributed MPC	380	±1.2	15	2.3

**Source:** Chicco et al. (2024); Zheng et al. (2024); Siddique et al. (2024)

A comparison of voltage deviation reduction is shown within Table 2, which illustrates progressively higher levels of sophistication in the control strategy. As shown in Table 2, the voltage deviation of the open-loop case amounts to ±9.2% which largely violates the IEEE 519 ±5% limit. Distributed MPC has minimum deviation of ±1.2% at 15 ms settling time which also confirms its dominant performance in transient response. Adaptive droop with virtual impedance: This mid-tier approach offers a modest example of reduction in overshoot, 59.6% as compared to the uncontrolled case.

**Table 3: Total Harmonic Distortion (THD) Values Before and After Control Implementation**

Control Method	Voltage THD Before (%)	Voltage THD After (%)	Current THD Before (%)	Current THD After (%)	% Improvement (Voltage THD)
Conventional PI Controller	0.99	0.65	10.73	7.80	34.3%

ANN-Adaptive PI + Droop + VIT	0.99	0.20	10.73	3.36	79.8%
BHO-Optimized M-UPQC	1.12	0.38	9.45	3.12	66.1%
Backstepping Controller	1.05	0.41	8.90	3.53	61.0%

Source: Patel et al. (2024); Naderipour et al. (2022)

Table 3 summarizes THD performance in four recent comparative studies of different control methods applied to DC/hybrid microgrids. The ANN-adaptive PI Controller in conjunction with droop control mode and virtual impedance technique (VIT) provides the highest voltage and current THD improvement illustrated in Table 3, which is 79.8% reduction in voltage THD from 0.99% to 0.20% (compliance with IEEE-519 standard limit of 5%) and 68.6% reduction in current THD from 10.73% to 3.36% (compliance with IEEE-519 standard limit of 8%). This makes adaptive controllers as intelligent and will capable of giving the best results concerning harmonic mitigation.

**Table 4: Load Sharing Performance and Current Deviation Under Droop Control Variants**

Droop Control Type	Source 1 Load Share (%)	Source 2 Load Share (%)	Current Deviation (%)	Load Sharing Accuracy
Conventional Droop	48.2	51.8	±6.3	Moderate
Adaptive Droop (with real-time feedback)	49.7	50.3	±1.8	High
Virtual Impedance-Enhanced Droop	50.1	49.9	±1.2	Very High
Cooperative Consensus-Based Control	50.0	50.0	±0.6	Excellent

Source: Nasirian et al. (2015); Saeed et al. (2021); Firmansyah & Ramli (2024)

Table 4 shows that how with the increasing number of droop control variants the correct balance between the current sharing of distributed generation units is progressively improving. As shown in Table 4, the current deviation due to conventional droop control is ±6.3% with an uneven load distribution compared to ±0.6% in consensus-based control, which approaches ideal sharing. Such enhancement becomes crucial in DC microgrids due to imbalanced current-sharing results in increased battery degradation and over-heated converters.

**Table 5: Energy Efficiency Comparison DC Microgrid vs. AC Microgrid**

System Type	Conversion Stages	Conversion Loss (%)	Overall Efficiency (%)	Reactive Power Losses (%)	Harmonic Filter Requirement
AC Microgrid	3–4	8.5–12.0	82.0–87.0	4.5–6.0	Required
DC Microgrid (Conventional)	1–2	4.2–6.5	89.0–91.5	0	Not Required
DC Microgrid (Optimized Control)	1–2	2.8–4.0	92.0–94.3	0	Not Required

Source: Tariq et al. (2024); Justo et al. (2013); Elsayed et al. (2015)

In table 5 a tabular comparison of the energy efficiency for the two possible topologies as AC and DC microgrid have been provided. Overall efficiencies for DC microgrids with optimized control fall within a range of 92.0–94.3% significantly higher than the 82.0–87.0% range typical of AC microgrids due to the elimination of reactive power losses and fewer necessary energy conversion stages in a DC system outperforming a similar design in AC (Table 5). The efficiency edge is one of the most fundamental arguments for the employment of DC structure within the Indian rural electrification programs.

**Table 6: Power Quality Indices at Different Load Conditions in Islanded DC Microgrid**

Load Condition	DC Bus Voltage (V)	Ripple Voltage (mV)	Voltage Deviation (%)	THD (%)	Efficiency (%)
Light Load (20% rated)	381.4	18	0.4	1.2	93.8
Medium Load (50% rated)	379.2	32	0.8	2.1	93.1
Heavy Load (80% rated)	376.1	57	1.0	2.9	91.7
Full Load (100% rated)	373.6	84	1.7	3.4	90.2
Overload (120% rated)	368.9	112	2.9	4.8	86.5

**Source:** Van den Brom et al. (2023); Chicco et al. (2024)

Evolution of some power quality indices at various load conditions in the islanded DC microgrid are given in Table 6. From table 6, all parameters are maintained within IEEE limits up to 100% rated load, where THD flag is highest as 3.4% and voltage deviation flag is 1.7%. At overload, THD increase to 4.8% just below 5% and maximum efficiency quickly decrease to 86.5%, highlighting the importance of controlling the load dynamically at such high operating points.

## 6. Discussion

The results listed in Table 1–6 collectively confirm both study objectives and provide significant information regarding the relation between control structure and power quality in DC microgrids. Tables 2 and 3 relate most directly to the first objective, which is to assess what influence advanced control strategies have on the host side voltage regulation and the THD reduction mentioned above. The gradual enhancements from open-loop to the distributional MPC indicate the potential to reduce voltage deviation from  $\pm 9.2\%$  to  $\pm 1.2\%$  by selecting proper controllers (Zheng et al., 2024). This is extremely important since there is no utility voltage reference in islanded DC microgrids and thus all regulation relies on the internal control structure (Dragičević et al., 2016). Of special significance are the THD results presented in Table 3. The traditional PI controllers attain only 34.3% reduction on voltage THD + ANN-adaptive PI controller with virtual impedance technique reduces current THD by 79.8% to 3.36% which is below limits specified by IEEE-519 (Patel et al., 2024). This difference is important from the perspective of Indian DC microgrid deployment, where non-linear loads like LED drivers, variable-speed motor drives, and battery chargers make up a substantial part of domestic and commercial demand with increasing share. These loads inject harmonics, which if not mitigated, propagate along the distribution bus and degrade the supply quality. Sensitive loads such as medical devices and communication infrastructure are affected by harmonics, if not mitigated (Saeed et al., 2021).

Tables 4, 5 and 6 are tackling the second objective the comparative evaluation of power quality indices under different load and generation conditions. As can be seen in Table 4, cooperative consensus-based droop control is very high in computational requirements; however, it is effective in achieving an almost ideal current sharing

(i.e., with  $\pm 0.6\%$  deviation from the ideal current sharing), in strong contrast to the  $\pm 6.3\%$  achieved for the conventional droop configurations. It directly affects the battery aging in multigene source microgrid because it causes non-homogeneous current distribution that leads to SoC imbalance among lead batteries with different SoC, affecting such batteries to have various cycle-life during the operation thus resulting to fast capacity fade of lead storage systems (A I-Ismail,2021; Firmansyah & Ramli, 2024). The efficiency comparison in Table 5 directly calls into question the legacy assumption that AC infrastructure is a default choice for distribution system design. DC microgrids have an inherent efficiency advantage of 5–7 percentage points due to the elimination of reactive power losses, which are 4.5–6% of total power in AC systems (Justo et al., 2013; Elsayed et al., 2015), and smaller number of conversion stages. Combined with optimal control, this allows us to achieve an efficiency envelope that peaks at 94.3%, making DC microgrids a more credible option for energy-limited environments.

In practice, the data in Table 6 reveals that while all power quality indices remain within acceptable limits at full load, the step to overload (120% rated) yields promotes a fast 7.3 % drop in efficiency, along with an almost-threshold THD of 4.8%. This finding agrees with Van den Brom et al. (2023) measured real-world harmonic spectra in an asymmetrically loaded bipolar 350/700 V DC urban microgrid and observed sharp escalation of ripple components in real time. Therefore, strong over-load detection and demand-side management are required to avoid long-time operation in degraded zone coupled with the microgrid EMS. Overall, the results are in good agreement with the systematic review by Siddique et al. In their review of contemporary microgrid literature (2023), droop control, virtual impedance and MPC were found to be the three most common power quality management strategies. Droop-based strategies are also known for balancing the load and preventing voltage disturbances, which the authors of Chicco et al. (2024) confirm as well in the case of renewable-dominant DC topologies. The fact that the tabulated results from this paper correspond to those reported in these independent studies increases the external validity of both this paper and the independent studies. The recurring daily operational & economic costs imposed upon power quality failures in an integrated Indian national grid will also apply directly to MNRE's off-grid solar program as well as the agricultural DC pump electrification PM-KUSUM scheme, where the efficiency and power quality benefits demonstrated by optimally designed DC microgrids are thus evidenced.

## 7. Conclusion

This paper presents a systematic review in DC microgrid design, but with a specific concentration on power quality enhancement methodologies. While extensive simulation and experimental data were analyzed and validated in a peer-reviewed approach, it was demonstrated that using adaptive droop control, virtual impedance compensation, and distributed MPC results in a voltage deviation within  $\pm 2\%$ , THD compliant with IEEE-519, and an improvement in the efficiency of the system to 94.3%. The efficiency and harmonic performance advantages of inherent simplicity of DC microgrid architectures over AC systems in terms of reduced conversion stages and the absence of reactive power components have been confirmed in this study. These results have direct consequences for integrating renewable energy sources into the grid and rural people access to the grid in India where power quality is a major obstacle to successful and sustained distributed energy implementation. Future research may consider designing fault-tolerant control through communication failure and applying artificial intelligence-based predictive EMS to optimize real-time power system operation to enhance power quality management.

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