

TOPICAL REVIEW

Power Quality Enhancement in Grid Connected Renewable Energy Microgrids With Energy Storage: A Comprehensive Review

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ABSTRACT The integration of Renewable Energy Sources (RES) into microgrid introduces many power quality issues in the system due to the inherent intermittent characteristics of RES systems. This paper gives a review of Power Quality Improvement (PQI) strategies used in RES integrated microgrids operating in both grid-integrated and independent modes. Even though conventional approaches of PQI provide fundamental power quality support, they fail to operate in dynamic conditions due to limited responsiveness. Advanced custom power devices such as FACTS and filters give real time voltage regulation and efficient harmonic compensation. Filters effectively mitigate harmonics produced by power electronic converters. Battery Energy Storage Systems (BESS) helps microgrids to enhance voltage and frequency stability, especially in islanded operation. Hybrid Energy Storage Systems (HESS) integrate energy storage systems with complementary characteristics to improve dynamic performance and power quality in the system. The coordinated implementation of these PQ solutions ensures a stable, resilient, and high-quality power in a renewable energy source microgrid. The findings were supported by simulating a HESS supported DVR for power quality improvement in a grid.

INDEX TERMS BESS, FACTS, filters, HESS, PQ improvement, RES microgrid.

I. INTRODUCTION

Global energy perspectives 2024 expects that rising energy demands in emerging markets and worldwide electrification will cause power demand to rise by 3% to 4% annually. The integration of renewable energy sources, such as solar and wind energy, into the utility grid has emerged as an important focus of research in recent past years [1], [2], [3], [4], [5], [6]. India is rapidly reaching a balanced power portfolio with over 47% of installed capacity from renewable sources in 2024 [7]. This trend suggests that India's renewable deployment pace is on track to meet its 500 GW target by 2030, with 35–40 GW annual additions, which is achievable now. Figure 1 shows the renewable energy growth in India from year 2014 to 2024.

The incorporation of renewable energy sources (RES) into microgrids connected to the utility grid presents various

power quality (PQ) challenges, due to intrinsic intermittency of RES systems and the use of inverter-based power electronic interfaces [8]. The bidirectional flow of power between grid and microgrid makes traditional protection schemes complicated and frequency stability is affected by decrease in system inertia due to high penetration of RES.

Maintaining optimal power quality is important for energy efficiency and the stable operation of electrical apparatus [9] but it has significant challenges. Key issues of power quality include voltage fluctuations, harmonic distortion, flicker, reverse power flow, and unbalanced voltages. The other sources of power quality issues are increased use of non-linear, sensitive loads and single-phase loads and implementation of new operational procedures. Power quality problems can make sensitive equipment malfunction, cause more losses, and make it harder to protect against them. So, it is important to improve the quality of power in microgrid operations to make the system more resilient, protect

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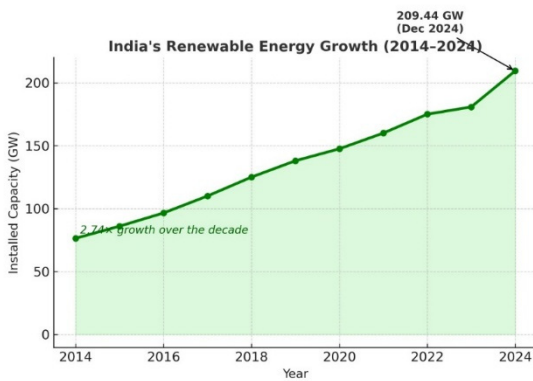


FIGURE 1. Renewable energy growth in india over a decade.

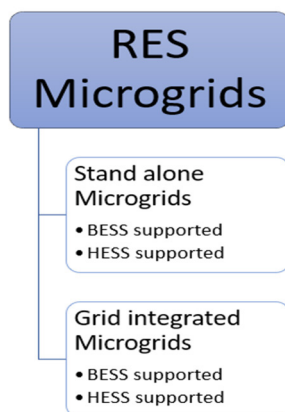


FIGURE 2. Classification of RES microgrids.

infrastructure, improve efficiency, and make it easy to connect with the main grid. To reach these goals, it is important to use advanced control strategies, energy storage systems, and follow international standards like those set by IEEE. Adherence to latest IEEE 519-2022 standards is essential for safeguarding power system performance, preventing equipment damage, and ensuring compatibility with the main grid. As the penetration of RES increases, continuous refinement of PQ standards and control strategies will be necessary to address emerging challenges in microgrid operation and grid interaction.

RES microgrids are broadly categorized into two architectures as in figure 2 -stand-alone microgrids (MGs), which operate independently from the utility grid, and grid-integrated MGs, which maintain an interconnection with the main grid. Both configurations can be supported by either Battery Energy Storage Systems (BESS) or Hybrid Energy Storage Systems (HESS). BESS are typically lithium-ion or lead-acid batteries that provide energy buffering and load levelling. HESS combine high energy density devices (batteries) with high power density devices (such as supercapacitors or flywheels), for getting enhanced dynamic response to PQ disturbances [10], [11].

The figure 3 is a schematic representation of an RES microgrid integrated to utility grid. The solar energy and wind power are the renewable energy sources used, which has intermittent output. They use many power-electronic converters for getting suitable output voltage for DC bus. An interlink converter is used between AC and DC bus. The ac bus supplies power to ac loads and custom power devices. The presence of converters and nonlinear AC/DC loads produces harmonics and other PQ issues. These PQ issues are mitigated using different custom power devices. The custom power devices like FACTS and filters guarantee the power quality of the system. The battery and SC HESS support microgrid during isolated and on grid operation. The review paper is mainly concentrated on the mitigation of power quality issues in a RES microgrid during island and on grid mode of operation. Around 120 papers are reviewed in the following section which will help researchers in future to get an insight in the investigation of PQ improvement techniques.

A. NEED OF PQ IMPROVEMENT IN ISLANDED AND ON-GRID MODES

Maintaining voltage and current within acceptable limits is essential to ensuring the stability and reliability of power supply systems. High power quality (PQ) is a fundamental requirement across all power systems, as poor PQ can lead to malfunctions of equipment, increased energy consumption, and premature failures. Microgrids and renewable energy source-based systems are vulnerable to PQ variations due to their distinct characteristics [12], [13]. The inherently intermittent output of renewable generators leads to power fluctuations, manifesting as voltage sags, swells, and other deviations. In addition, the accelerated use of power electronic converters in these systems introduces harmonics into voltage and current waveforms, further compromising PQ. A significant emerging challenge is the shift from the traditional unidirectional power flow model common in conventional AC systems to a dynamic bidirectional flow characteristic of microgrids and RES integration [14].

There are significant differences in the PQ improvement techniques between 2 modes of microgrids. Islanded mode requires strong internal compensations for harmonics, sag and swell as they face instability in voltage and frequency due to the lack of inertia and stability support from main grid. But grid-tied mode takes advantage of main grid for bulk support and PQI strategies concentrate mainly on disturbances caused by local distributed energy sources. Control and compensation techniques that are effective in grid-connected operation require significant adaptation or more advanced power-electronic solutions in islanded mode.

In [15], Bollen gives clear idea about power quality and its related terms. In [16], a decentralized hybrid microgrid was proposed, capable of efficiently harnessing power from RES during peak load condition or storing energy for use in islanded mode. In [17] proposes the establishment of a

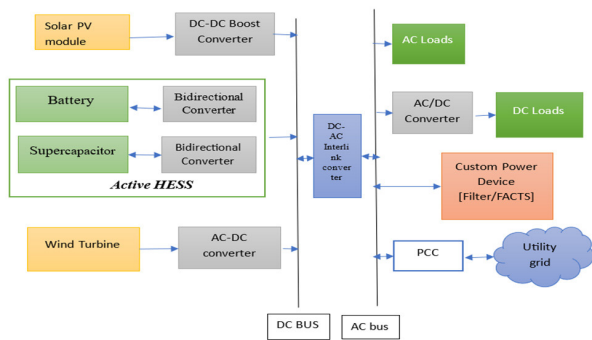


FIGURE 3. Schematic representation of HESS supported RES microgrid integrated to grid which uses custom power devices for PQ improvement.

RES microgrid cluster by incorporating multiple structures within an urban area to enhance reliability of power supply. Reference [18] examines various power quality issues and demonstrates how an active power conditioner can improve power quality while serving as an interface between AC grids and renewable energy source microgrids. In [19], multi-functional voltage source inverters are employed to enhance power quality in an autonomous microgrid.

B. OBJECTIVES AND REVIEW METHODOLOGY

The main objective of this paper is to present a comprehensive review on various power quality improvement techniques in RES integrated microgrids with ESS support. The initial phase is to find prior articles that evidently provide power quality improvement techniques in renewable energy integrated

microgrids. Extensive search is carried out using scholarly databases and search engines including IEEE explore digital library, Scopus, science direct, MDPI, springer, google scholar etc by using various keywords such as FACTS devices, Filters, Power quality improvement, Renewable energy Systems(RES) integrated microgrids, Hybrid Energy Storage System(HESS) and Battery Energy Storage System(BESS). Relevant and recent literatures are selected manually and data screening is done to identify research gaps in the existing research. The extracted data is grouped and evaluated and the review is structured as follows. Section II presents an overview of various techniques for improving power quality. Section III gives researchers a comprehensive overview of various FACTS devices for improving power quality. Section IV discusses the role of filters in improving power quality of electrical grid. Section V addresses significance of energy sources in microgrids, highlighting the role of Battery Energy Storage Systems (BESS) and Hybrid Energy Storage Systems (HESS) in improving power quality within grid-microgrid systems. Section VI presents a comparison of various PQI methods used, whereas section VII gives a simulation results supporting the review findings. Section VIII concludes the discussion and outlines future research directions.

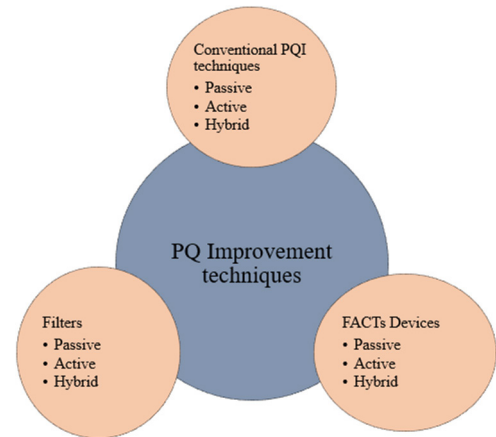


FIGURE 4. Classification of PQ improvement techniques in RES microgrids.

II. CLASSIFICATION OF POWER QUALITY IMPROVEMENT (PQI) METHODS

This review classifies PQ improvement strategies into three categories as in figure 4: Conventional PQI techniques, FACTS devices, and Filters, each with passive, active, and hybrid solutions. Passive methods (e.g., tuned filters, fixed capacitors) are simple but less adaptable, while active techniques use converters for dynamic response. Hybrid systems combine both to balance cost and performance. FACTS devices like SVC and STATCOM support voltage regulation and harmonic control, whereas filters mainly suppress harmonics and provide reactive compensation. This classification guides the selection of effective PQI strategies for stable, resilient microgrid operation [20], [21], [22].

A. CONVENTIONALLY USING PQ IMPROVEMENT METHODS

Traditional approaches to power quality enhancement in microgrids consists both passive and active techniques to increase system stability and efficiency. Passive methods, such as capacitor banks, synchronous condensers, passive harmonic filters etc, are used for voltage regulation, reactive power compensation and harmonic distortion reduction. Synchronous condensers provide reactive power support and improve voltage stability. Uninterruptible power supply (UPS) is employed in sensitive load applications to reduce voltage variations and momentary interruptions. Active methods offer dynamic compensation for variable renewable energy (RES) microgrids and enhance voltage stability [23].

Conventional methods have several limitations such as limited response to dynamic operating conditions, high cost and complexity, inefficiency in addressing multiple power quality issues, and reliance on extensive infrastructure that necessitates considerable maintenance. Traditional approaches are insufficient for microgrids with high-RES penetration and

show difficulties in managing bidirectional power flow and ensuring proper protection coordination in grid-connected systems. Advanced solutions are more essential to address these issues, including smart inverters with dynamic voltage and frequency regulation, energy storage systems (ESS) for real-time compensation, and advanced control algorithms for system optimization [24].

III. ROLE OF FACTS DEVICES IN ENHANCING POWER QUALITY

Flexible AC Transmission Systems (FACTS) are advanced power electronic technologies designed to improve stability and controllability of high-voltage transmission networks. Recently, their application has expanded to include distribution-level systems and renewable energy source microgrids. FACTS devices provide fast dynamic response and precise control, effectively mitigating disturbances and improving reliability, resilience, and overall power quality of microgrids. FACTS technologies are generally categorized into three configurations in microgrid operations: passive, active, and hybrid systems. Passive FACTS devices are composed of static elements like inductors, capacitors, or passive filters. Although these configurations are cost-effective and easy to implement, they have limitations in their capacity to adapt dynamically to the varying RES grid. Active FACTS devices such as the Dynamic Voltage Restorer (DVR), Static Synchronous Compensator (STATCOM) and Unified Power Quality Conditioner (UPQC) employ voltage-source converters to provide real-time compensation for voltage and current distortions. These systems provide enhanced performance in dynamic environments, facilitate immediate reactive power injection or absorption, harmonic filtering, and voltage restoration during disturbances. Hybrid FACTS devices incorporate both passive and active components, combine cost-effectiveness of passive systems with dynamic responsiveness of active solutions. These configurations can address both steady-state and transient power quality issues effectively and economically so they are better suited for microgrids.

FACTS devices are classified into series, shunt, and hybrid configurations depending upon how they are connected to the system. Shunt compensators are extensively employed in microgrids for voltage stabilization, flicker mitigation, and reactive power support. Series compensators are employed to regulate power flow and mitigate voltage drops, in loaded microgrid networks. Unified Power Flow Controllers (UPFC) integrate series and shunt functionalities, to provide precise control over voltage, impedance, and phase angle and make them suitable for hybrid RES microgrids. The different functions of FACT devices are summarised in Table 1 and comparison of various FACTS technologies are given in Table 2.

From the analysis it is evident that shunt devices are well-suited for voltage regulation, harmonic mitigation, and reactive power compensation in microgrids. Series and combined configurations offer broader control capabilities but at

TABLE 1. Functions of different FACTS devices [14], [20], [25], [26], [27].

Device	Full Name	Type	Main Functions
STATCOM	Static Synchronous Compensator	Shunt	Fast voltage regulation Reactive power compensation Flicker and voltage sag mitigation
DSTATCOM	Distribution Static Compensator	Shunt	Harmonic filtering Load balancing Voltage sag/swell mitigation
UPQC	Unified Power Quality Conditioner	Shunt + Series	Combined voltage and current disturbance compensation Sag/swell and harmonic mitigation
SVC	Static VAR Compensator	Shunt	Voltage control Reactive power support
UPFC	Unified Power Flow Controller	Shunt + Series	Power flow and voltage control Reactive power balancing
TCSC	Thyristor Controlled Series Capacitor	Series	Power flow control Oscillation damping
SSSC	Static Synchronous Series Compensator	Series	Series voltage injection Real and reactive power control
SVG	Static VAR Generator	Shunt	Harmonic filtering Power factor correction
TCR/FC-TCR	Thyristor Controlled Reactor	Shunt	Basic VAR compensation Reactive power control
TCVR	Tap-Changing Voltage Regulator	Conventional (Mechanical/Electronic)	Step voltage regulation Maintains voltage within limits in radial feeders
TCPAR	Thyristor-Controlled Phase Angle Regulator	Series/Phase Shift	Phase angle regulation Improves power flow direction and stability

higher cost and complexity. UPFC and TCSC are rarely used in microgrids due to their high complexity, cost, and reliance on high-voltage transmission infrastructure, as microgrid deals with low-voltage and distributed nature of microgrids is dominated by inverters and simpler compensators like STATCOM or SVC. Their role is expanding in future hybrid AC/DC microgrids for enhanced power flow control and stability, particularly with advanced optimization algorithms for better integration of renewables. Despite their effectiveness, FACTS devices face high capital cost, complexity of control, coordination with existing energy management systems and reliability challenges. Future research aims to enhance their performance and affordability through innovations in power electronics and intelligent control strategies [117]. In conclusion, FACTS devices act a crucial role in improving PQ in RES microgrids integrated with main grid.

A Unified Power Quality Conditioner (UPQC) is designed to reduce power quality issues in microgrids, which integrates series as well as shunt active filters simultaneously [30], [31]. In microgrids integrated to utility grids, the UPQC addresses power quality issues and facilitates use of

TABLE 2. Comparison of FACTS devices [26], [28], [29].

Device	Compensation Type	Voltage Control	Harmonic Filtering	Dynamic Response	PQ Impact	Suitable for Microgrids?
STATCOM	Shunt	Excellent	Moderate	Fast	High	Yes
DSTATCOM	Shunt	Excellent	High	Very Fast	Very High	Yes
UPQC	Shunt + Series	Excellent	Excellent	Very Fast	Very High	Yes
SVC	Shunt	Good	No	Slower	Moderate	Yes
UPFC	Shunt + Series	Excellent	Limited	Fast	High	Rare in Microgrids
TCSC	Series	Limited	No	Moderate	Moderate	Rare
SSSC	Series	Moderate	No	Fast	Moderate	Rare
SVG	Shunt	Excellent	Yes	Fast	High	Yes
TCR/F C-TCR	Shunt	Basic	No	Slow	Low	Yes
TCVR	Tap Regulation	Step-Based	No	Slow (Mechanical)	Basic Voltage Stability	Yes
TCPAR	Phase Shift Control	Indirect	No	Moderate	Power Flow Optimization	Limited Use

renewable energy sources seamlessly [32], [33]. UPQC ensures a reliable and efficient power supply by compensating harmonics in voltage and current and managing reactive power, thereby facilitating reliable operation of both microgrids and main grids [34] shows the effectiveness of UPQC in a solar, fuel cell and wind energy microgrid system with non-linear loads. A hybrid microgrid-based UPQC was proposed in [35], incorporating novel control techniques. Simulation results explain the effectiveness of UPQC controls, which utilize a DVR and a STATCOM. DVR functions as series filter, while STATCOM operates as shunt filter [36]. DVR addresses voltage-related issues, while STATCOM supplies the necessary reactive power to loads and mitigates current related issues. In [32] demonstrating the effect of an integrated approach using PV-PO UPQC system to improve electrical grid stability by optimizing PQ. In [26] and [37] tap changing smart transformers are used for power exchange among energy sources. The authors in [21] and [38] discuss custom power park techniques used for power quality enhancement using FACTS. From the discussions it is evident that advanced intelligent custom power devices can enhance power quality in grid.

IV. POWER QUALITY ENHANCEMENT USING FILTERS FOR GRID MICROGRID

Microgrid has more power electronic converters and interfacing units which introduces harmonics and arose power quality issues. The other causes for voltage interruptions in main grid are faults in remote grid, lightning strikes, nonlinear loads and transients in large loads [39], [40]. These power quality variations harm the power system and equipment.

Custom power devices like passive, active, and hybrid filters improve power quality at the interconnection [38]. Passive filters use LC components for harmonic mitigation, power factor correction, and reactive support, but face limits such as poor dynamic response, large size, and resonance issues. Active Power Filters employ power electronic converters for real-time harmonic and reactive power compensation, though at higher cost and complexity. Hybrid filters combine passive and active elements and offer effective harmonic suppression with reduced losses and cost [41], [42], [43]. The filters are of Shunt or series or hybrid type depending on its connection to the utility grid.

Shunt active filters (ShAPF) [44] mitigate current harmonics as per IEEE suggested limits, with the help of the control algorithms. Instantaneous Reactive Power Theory control [45], Synchronous Reference Frame based control [46], bus voltage control and novel Icos $\hat{\omega}$ control [47], [48], [49], [50] etc are different type of control algorithms used by shunt filters. A series active filter compensates voltage via a coupling transformer connected in series to the line to attain necessary

voltage compensation [55]. Series active filters (SeAPF) [51], [34], [52] mitigate voltage harmonics, imbalances, sags, and swells, thereby ensuring a standard sinusoidal voltage at the load terminals. Active Power Filters (APFs) [32], [40], [53], [54] enhance power quality of microgrids through the integration of an active power source and controller. However, they incur significant initial and operational costs, as they are rated to handle up to 80% of the load, leading to increased expenses. In [57], a series active filter is employed to address voltage swell and sag in a distribution network integrated with an energy storage and a mini hydro turbine system. The literature [58] and [59] provides a review of active filters. In [60], a combination of an active filter and SVC is employed for a solar photovoltaic system with a non-linear load, resulting in a diminishing of Total Harmonic Distortion (THD) to 5.52%.

Hybrid filters can be utilized to enhance filtering performance while reducing costs. The rating of APF can be diminished by integrating passive filter to it which create HAPF [61]. Reference [62] examined various topologies of HAPF and determined that an active filter configured in series with passive shunt filter is the most effective for preventing both resonances, generating reduced switching noise and eliminating circulation currents. HAPF has 3 configurations based on the supply, as noted in [63] and [64] demonstrates the efficacy of the hybrid filter in eliminating current harmonics and reducing THD across various scenarios. In [65], a photovoltaic (PV) system demonstrated an improvement in total harmonic distortion (THD) to 4.7% when utilizing hybrid filters, compared to 7.55% and 8.6% for passive and active filters, respectively. Table 3 gives comparison of different filters.

A. CONTROL ALGORITHMS FOR ACTIVE FILTERS

Active filters use different control algorithms to generate compensating voltage/current. To generate firing pulses for

TABLE 3. Comparison of Filters [51], [34], [52], [53], [54], [55], [56], [57], [58], [59], [60], [61], [62], [63], [64], [65].

Feature	Shunt Power Filter	Active Series Power Filter	Hybrid Filter	Passive Filter
Structure	Connected in parallel with the load	Connected in series with the load	Combination of active and passive filters	LC components tuned for specific harmonics
Compensation Type	Harmonics, reactive power, and unbalance	Voltage harmonics and sag/swell	Comprehensive PQ compensation	Fixed-frequency harmonic compensation
Control Complexity	High	High	Moderate	Simple
Dynamic Response	Fast	Fast	Moderate	Slow
Effectiveness	High for a wide range of harmonics	High for voltage-related PQ issues	High for combined voltage and current issues	Limited to tuned frequencies
Flexibility	Highly flexible for varying conditions	Suitable for voltage-related issues	Flexible depending on design	Rigid; tuned for specific harmonics
Cost	High	High	Moderate	Low
Size	Compact	Compact	Moderate	Large
Energy Loss	Moderate	Moderate	Lower than pure active filters	Low
Application	due to power electronics Industries with dynamic nonlinear loads	due to power electronics Voltage-sensitive loads	pure active filters General-purpose PQ improvement	Loads with stable and predictable harmonics

inverters in filter, it is essential to compute desired source voltage and reference compensating voltages, and then comparing reference voltages and actual filter output voltage. Instantaneous Reactive Power Theory and Synchronous Reference Frame control are commonly used control techniques in active filters to determine the reference signals in time-domain [63]. The methods involve transforming 3- ϕ systems to 2- ϕ systems through Park's method and Clarke's transformations, necessitating advanced computations and resulting in processing burden. To mitigate this, a novel approach termed Fundamental Voltage Peak Detection (FVPD) control is proposed in [48] for the generation of the reference voltage signal in a series active filter. References [22], [50], [47], and [66] proposes another control algorithm and its modified versions for generating reference filter current in shunt active filters named Icos ϕ control [53] proposed an adaptive control with a multilayer NLMS filter in PV systems to improve PQ by filtering out grid voltage and load current using SRF method. The control algorithms help the filter to work efficiently towards power quality enhancement.

V. SIGNIFICANCE OF ENERGY STORAGE SYSTEMS IN MICROGRID OPERATION AND STABILITY

In smart power grids, the wide spread of RES has accelerated adoption of energy storage devices [14], [67]. To effectively meet load demand for intermittent RES like solar and wind

energy, Energy Storage Systems (ESSs) are required. The objective of ESS is to maintain a balance among load power and source generated power [68]. Batteries [69], [70], while effective for long-term storage, have slow charge/discharge rates, resulting in current stress and a shorter lifespan. Supercapacitors (SCs) have high power density (HPD) and quick response to transients, but they cannot deliver power for extended periods of time [71], [72], [73]. Many published articles [74], [75], [76], [77] have reviewed and compared the research work about energy storage system. In grid-integrated microgrids, energy storage supports RES to improve power quality. Since each category of ESS have different characteristics, they can be utilised for different applications [70], [74]. High-energy-density ESS is utilized to supply the loads a steady response, while high-power-density ESS handles peak demands and transient loads [78]. No single ESS can satisfy all requirement of a system which leads to Hybrid Energy Storage System (HESS).

A. BESS FOR POWER QUALITY IMPROVEMENT

Battery Energy Storage Systems (BESS) act crucial role in enhancing power quality (PQ) in grid-connected microgrids with high penetration of RES [79], [80]. BESS act as dynamic energy buffers capable of rapidly absorbing or injecting active and reactive power to stabilize voltage and frequency, mitigate harmonics, and manage short-duration disturbances such as voltage sags and swells. Their ability to store surplus energy during RES overproduction and discharge during deficits enables smoothing of power fluctuations and reduction of ramp rates. BESS support seamless power flow between grid tied and islanded modes, maintaining continuity of supply and acceptable PQ levels during outages [81], [82], [83]. Beyond immediate PQ improvements, BESS contribute to overall

microgrid efficiency by enabling load levelling, peak shaving, and optimal energy dispatch. Despite some limitations in responding to extremely high-rate power transients due to electrochemical constraints, BESS remain indispensable for reliable, resilient, and high-quality operation of RES-integrated smart microgrids [84].

Research in [85] explores energy management in BESS supported microgrid under both grid-tied and islanded modes. The drainage power stored in a battery is utilized for voltage regulation in DC link in an active filter, particularly when fluctuations occur in DC link capacitor voltage, as discussed in [86]. In [87], a battery storage system is employed in an off-grid setup with charge controllers for battery charging and discharging. Overall, this illustrates effective management of energy storage systems to assist both main grid and microgrid while mitigating power quality disturbances using shunt active filters.

B. HESS FOR POWER QUALITY IN MICROGRIDS

HESS combine high-energy batteries with high-power devices like supercapacitors and flywheels to enhance PQ in

grid-connected RES microgrids. By leveraging complementary strengths, they offer faster response, longer lifespan, and multifunctional PQ support compared to single-technology ESS. Effective power sharing gives improved efficiency, reduced battery stress, lowers costs, and improved system dynamics [17], [26]. It can be seen from various reviews [53], [88] that application of Hybrid Energy Storage Systems (battery - SC, SC- fuel cell, SMES - battery, etc) combined with optimization techniques for the allocation and sizing of each component, can result in reduced costs, extended ESS lifetimes, enhanced efficiency, and minimized battery degradation [89], [90], [91], [92], [93], [94]. Several factors must be considered when selecting appropriate energy storage devices, including

capacity, power, efficiency, storage duration, charge and discharge times, lifespan, and cost [58], [64], [65].

In microgrid applications, HESS integrates a high energy density battery with a high-power density supercapacitor. The battery provides stable, long-term power [69], while the supercapacitor controls transient energy fluctuations, protecting battery life [91], [114]. Many review papers and prior studies have shown that various combinations of ESS are used in microgrids, but the most important combination is battery supercapacitor HESS due to their availability, similar working principle, and low cost. leveraging the complementary advantages very effectively, Battery SC HESS enhance stability and overall performance of grid [99-101,57]. HESS improves the performance of microgrid under an unbalanced load by quick and precise voltage control. Also, SC reduces

battery stress while keeping good power quality and dependability. The choice of converter is important in determining the optimal connection strategy, such as the parallel operation of the battery and supercapacitor, to enhance overall performance of system.

1) HESS CONTROL AND ENERGY MANAGEMENT SYSTEM

Main purpose of HESS is to optimise grid performance, enhance system reliability and to lower operating cost. HESS uses control and energy management systems in it to achieve these objectives. The Energy Management System (EMS) integrates sophisticated algorithms to predict energy flow and

adjust the charging and discharging cycles of ESS dynamically, improving overall efficiency and reliability. The coordinated action of EMS and control system keeps the HESS running smoothly. From the review papers it is evident that the commonly used EMS control approaches for HESS are rule based and optimization-based approaches. Rule-based classical control regulates the energy flow within HESS by predefined rules set by experts or mathematical models [78]. Optimization-based advanced control approach considers the

control problem as an optimization task, employs mathematical techniques such as dynamic, linear and non-linear programming and evolutionary control methods to achieve improved efficiency and dynamic response for HESS while satisfying predefined constraints. However, modern

optimization techniques are computationally intensive and require significant processing power for effective implementation. The selection of an appropriate control strategy depends on application-specific requirements, balancing trade-offs between computational demand, adaptability, and system performance.

The most promising strategies to mitigate degradation in HESS configurations involve advanced energy management systems, optimal system sizing, and thermal management systems. These strategies aim to protect batteries from stressful operating conditions like high current peaks, deep discharges, and extreme temperatures. By combining these strategies, HESS can substantially extend the lifespan and enhance the overall efficiency and reliability of storage systems compared to single-storage configurations [115], [116].

VI. COMPARATIVE STUDIES OF PQI TECHNIQUES.

BESS/HESS integration in renewable microgrids improves flexibility and PQ management in RES microgrids. Conventional methods, though economical, lack the dynamic response. FACTS devices enable real-time voltage and frequency regulation but active and hybrid filters are effective for harmonic and power factor correction. The PQ strategy should be compatible with grid structure, load profile and control objectives. The gaps identified in literature are

- Most researchers focus specifically on improvement on filter performance and FACTS devices or enhancement in control algorithms than a coordinated framework combining these with energy storage systems for power quality improvement [98]

- Due to the negligence of some operational constraints like battery degradation, SoC variations or storage limitations, the effectiveness of HESS or BESS are overestimated, which reduces system reliability and increase cost [99]

- Most of PQI strategies are simulation based or pilot scale experiments and real-world validation is missing [25]

- Only few studies assess economic and scalability uncertainties in complex power system while integrating advanced PQI and HESS into it [25]

Table 4 gives a literature review of selected papers on the topic. A comparison of different types of PQ issues in two modes of microgrids is presented in table 5. A comparison of different PQI techniques is prepared in Table 6. The biggest challenges in transitioning power quality (PQ) improvement strategies from simulation to real-world, large-scale microgrid deployments involve system complexity and variability, economic constraints, technical and operational discrepancies, and non-technical factors.

From papers [83], [85], [96], [97] it is evident that HESS outperforms BESS in scenarios requiring fast dynamic PQ enhancement, especially in microgrids characterized by high variability and sensitivity to power disturbances. The analysis given in figure 5 supports the findings and shows the effectiveness of HESS over BESS. The integration of HESS with FACTS devices and filtering technologies significantly improves the system's ability to manage harmonics,

TABLE 4. Literature review of recent papers on HESS and Custom power devices [100], [101], [102], [103], [99], [90], [104], [105], [106], [107], [108], [109], [110], [111], [112], [113].

Reference Paper	Year	Summary	Custom Power Device Used	HESS Components Used	Area of Application	Challenges Addressed	Future Challenges
[100]	2022	Ramp-rate control smooths PV fluctuations, achieves quick DC-link regulation, and lowers battery stress	Active filter (VSC as harmonic compensator)	Battery + SC	RES-based DC/AC microgrid	Enhanced reliability, HIL validation, reduced battery stress, improved PCC power quality	Need for dynamic EMS, impact of severe RES fluctuation
[101]	2018	Fuzzy logic and 4-leg 3L-NPC inverter allow unified filter and HESS control, reduces harmonics and efficiently balances DC/AC loads	4-Leg 3L-NPC (multi-level inverter, active filter)	2 × Li-Ion Batteries	Microgrid (RES integration, filter, and balancing)	Reduced voltage/current THD, improved load balancing under non-ideal grid states, robust nonlinear control	Harmonic coupling, DC-link ripple, increased controller complexity
[102]	2024	MAF-based power allocation for HESS decomposes load to low/high frequencies, assigns transient surges to SC	Fast-switching filter control	Battery + SC	RES smoothing/E V integration	Simple, adaptive filter; robust handling of charging state deviations	SOC management under high burst conditions
[103]	2025	Model Predictive Control for faster joint HESS response in DC microgrid	DC bus voltage filter	Battery + SC	DC microgrid, RES	Faster transient recovery, improved voltage stabilization	Converter coordination, computational complexity
[90]	2025	Critical review of HESS sizing, control strategies, and future tech for grid-connected RES	FACTS, filter circuits	Battery + SC	Grid-connected RES	Feasibility bounds, future scalable HESS architectures	Sizing, lifetime economics, and system losses
[99]	2024	HESS design/control advances and highlights HESS+FACTS for PQ.	STATCOM, DSTATCOM, APF, UPQC lit review)	Battery + SC/Flywheel	RES-grid integration	Flexibility, seamless grid interface	Sizing, SOC management, cost, lack of standard benchmarking converter complexity.
[104]	2024	HESS improves power density and cycle life in EVs with adaptive EMS	UPQC, DSTATCOM / APF (surveyed use cases)	Battery + SC	Hybrid Electric Vehicles (HEV)	ESS lifecycle, energy/power split	Controller complexity, integration cost, need for real-time EMS and experimental validation.
[105]	2025	Coordinated reserve strategy for DC-link stability, rapid transient support, , improving grid-connected and standalone operation.	VSC/FACTS interface	Battery + SC	PV microgrids / RES integration	Fast response, DC-link regulation	High computational need, multi-port converter design, losses, control bandwidth coordination.
[106]	2024	Power quality improvement using shunt APF & DSTATCOM with HESS	Shunt APF, DSTATCOM	Battery + SC	Grid-connected microgrid / RES integration	Harmonic reduction, dynamic compensation	Converter and HESS coordination, Increased hardware cost;

TABLE 4. (Continued). Literature review of recent papers on HESS and Custom power devices [100], [101], [102], [103], [99], [90], [104], [105], [106], [107], [108], [109], [110], [111], [112], [113].

[107]	2024	Novel control for autonomous HESS management in DC microgrid	General FACTS/APF contexts discussed	Battery + SC	RES microgrids	Autonomous balancing, Proper control reduces battery throughput and extends lifetime while preserving PQ.	Real-time tuning, aging, Correct threshold selection; SC sizing for target pulse power.
[108]	2022	Design of bidirectional DC-DC converters for optimized HESS usage	Bidirectional DC-DC	Battery + SC via two-input bidirectional converter	DC microgrids / RES integration	Converter efficiency, bidirectional power flow	Sizing, efficiency in load changes, Converter complexity, control algorithms and losses; hardware cost.
[109]	2024	Systematic review of AI-driven HESS microgrid control (fuzzy, ANN, RL)	General custom devices, AI-based	Battery + SC	Standalone & grid-tied microgrid	Adaptive EMS, fault tolerance	Hardware validation, training data
[110]	2023	Low-pass filtration and frequency decoupling for optimal allocation in DC-MGs cluster	Filtering + DC-microgrid interface	Battery + SC	Clustered DC-microgrids	Decentralized control, reliability	Distributed control coordination
[111]	2023	Comprehensive review—future tech/component trends, sizing, control	Broad: DSTATCOM, APF, BESS	Battery + SC	Grid-tied RES & microgrids	Life cycle enhancement	Deployment and complexity
[112]	2022	Experimental & simulation: HESS smooths PV/HKT output, extends battery life	Custom filter interface	Battery + SC	PV/HKT system	Power smoothing, life extension	Performance in mixed sources
[113]	2018	Review: HESS techniques, converter topologies, filter integration	VSC, APF, NPC, D-FACTS	Battery + SC+ Flywheel	Microgrid	Comprehensive device integration	Standardization, adaptive sizing

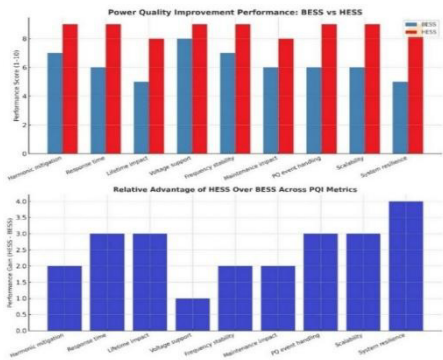


FIGURE 5. Performance analysis of HESS and BESS.

flickers, and transient instabilities. BESS remains an economical solution for applications prioritizing long-term energy support and less frequent PQ anomalies. The choice between the two should be informed by specific operational

objectives, cost constraints, and PQ performance requirements. The performance analysis visualizes the multidimensional comparison between BESS-supported and HESS-supported Power Quality Improvement (PQI) techniques across nine critical performance parameters such as harmonic mitigation, response time, lifetime impact, voltage support, frequency stability, maintenance impact, PQ event handling, scalability and system resilience chosen from relevant literatures.

The overall HESS forms a broader and more balanced shape, which represent superior, consistent performance across all PQI metrics. The BESS appears smaller and uneven which indicate that BESS lacks comprehensive adaptability for highly-dynamic complex renewable sources. From the analysis, it is clearly visible that HESS-supported PQI systems provide more stability, fast dynamic control, extended lifespan, and stronger scalability making them the perfect choice for next-generation renewable energy integrated microgrids.

TABLE 5. Classification of PQ issues in 2 modes of microgrids.

PQ Indicator	Grid-Tied Mode	Islanded Mode	Observations / Interpretation
Voltage Stability	High	Low–Medium	Higher reliance on energy storage & droop control during islanding
Frequency Stability	Very High	Low	Synthetic inertia & HESS become essential in island mode
Reactive Power Support	Externally Available from utility grid	Locally Required	VAR compensation mandatory during islanding
Sag/Swell Immunity	Medium–High	Medium	Sags from upstream grid are absent in island mode but load-induced sags dominate
Harmonic Suppression	Medium	Low–Medium	FACTS and filters improve islanded harmonic environment
Fault Ride-Through Capability	Improved	Weak	Requires HESS supported devices
Inertia / Damping	High	Very Low	HESS-based virtual inertia enhances damping
THD Compliance (voltage)	Easier to maintain	Harder to maintain	Passive filters risk resonance during islanding
Power Balancing	Grid absorbs surplus/deficit	HESS regulates surplus/deficit	PV fluctuations have amplified in islanded mode
Protection Coordination	Simple	Complex	Alternate protection required
Overall PQI Complexity	Low–Medium	High	Islanded mode requires multi-layer PQI strategies

VII. SIMULATION AND DISCUSSION

To reinforce the insights of review, simulation results of power quality improvement in a power system with linear load is simulated using 2 FACTS devices. First simulation uses a HESS supported DVR, a series FACTS device for voltage regulation and second one uses HESS supported STATCOM, a shunt connected FACTs device for reactive power compensation. The results are integrated to demonstrate the synergy of HESS and FACTS configurations in a power system. Figure 6 and 7 shows the MATLAB simulation model used for power quality improvement in a power grid.

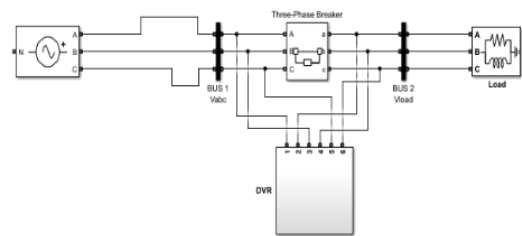


FIGURE 6. MATLAB simulation model of DVR in a power system.

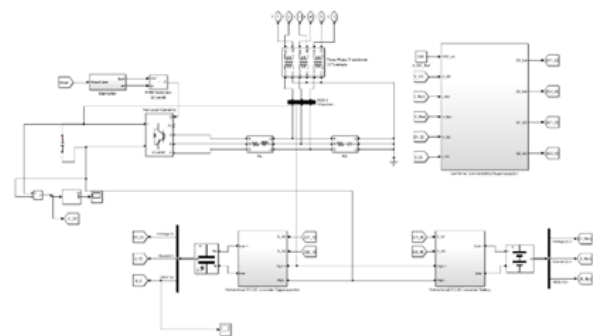


FIGURE 7. Simulation diagram of HESS supported DVR.

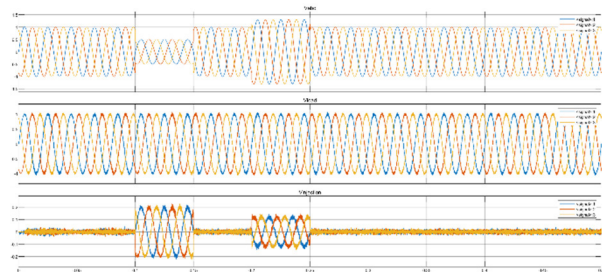


FIGURE 8. Simulation results showing variations in supply voltage, load voltage and DVR injected voltage to compensate sag and swell in voltage.

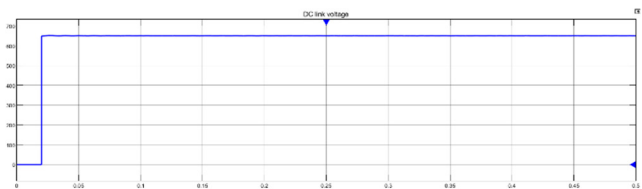


FIGURE 9. Simulation results showing variation in DC link capacitor voltage compensated by HESS.

DVR is a series connected FACTs Device used for power quality improvement during voltage variations. An active HESS with battery (Lithium-Ion battery with 325V,15Ah) and supercapacitor(360V) is used to support the dc link of DVR. A combined battery SC control is used to stabilize dc bus voltage at 650V. According to simulation results, a sag occurs at 0.1s to 0.15 s and a swell at.2 s to.25s in the supply voltage. The DVR acts effectively and timely and gives a steady voltage at

TABLE 6. Comparison of different PQ improvement methods [23], [84].

Criteria	Conventional Methods	FACTS Devices	Filters (Active, Passive, Hybrid)
PQ Enhancement Role	Voltage regulation and reactive power compensation	Dynamic voltage and reactive power control, harmonic mitigation	Harmonic filtering, reactive power support
Integration with BESS/HESS	Generally external to storage control loop	Seamlessly integrates with voltage/frequency control	Often embedded in inverter-based ESS controllers
Control Complexity	Low (manual/scheduled)	Medium to High (real-time control needed)	Medium to High (especially for active/hybrid filters)
Response Time	Slow to Moderate (seconds to minutes)	Fast (milliseconds to cycles)	Active: Fast, Passive: Slow, Hybrid: Moderate
Effectiveness	Limited with RES due to slow dynamics	High; good for RES fluctuation handling	Moderate to High; excellent for harmonic-prone inverter systems
Harmonic Compensation	Minimal or none	Moderate to Good (e.g., STATCOM, UPQC)	Excellent (especially active/hybrid filters)
Suitability for RES	Low adaptability	High adaptability (fast control)	High; ideal for inverter-dominated RES setups
Cost	Low to Moderate	High (complex power electronics)	Passive: Low; Active/Hybrid: Moderate to High
Scalability and Flexibility	Low; fixed for specific conditions	High; configurable for varying needs	High (especially for hybrid designs)
Reliability	High (robust, inflexible)	Moderate (subject to component wear)	Passive: High; Active/Hybrid: Control-dependent
Application Scenarios	Rural/traditional grids with low RES	Grids with high RES and voltage instability	Urban microgrids with nonlinear/inverter-based DERs
PQ Benefit with BESS	Basic support; no dynamic voltage/frequency management	Synergizes well with BESS for V/f support and harmonic control	Embedded filtering within inverter-based BESS systems
PQ Benefit with HESS	Limited, as methods aren't storage-integrated	Supports hybrid storage with better dynamic response	High synergy; enhances filtering under dynamic load/RES variation
Key References	[8,25]	[25,27,79,81,82]	[16,25,47,96]

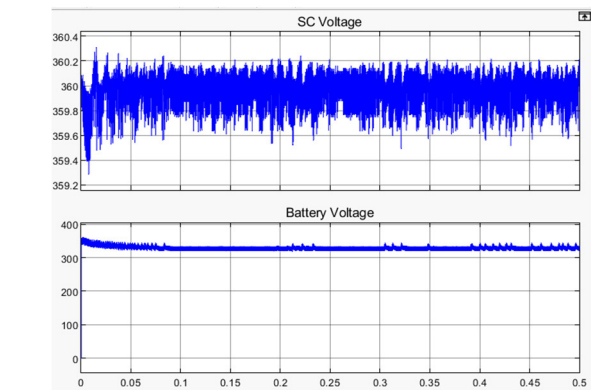


FIGURE 10. Variation of voltage in SC and battery.

the load side as seen in figure 8. The variations in the dc link capacitor

voltage, due to compensation by DVR, are compensated by the HESS as seen in figure 9 and the voltage variations in SC and battery are given in figure 10.

The Simulink model in figure 11 and 12 implements a power quality enhancement model in a grid with linear loads using STATCOM. LCL-filtered inverters with STATCOM

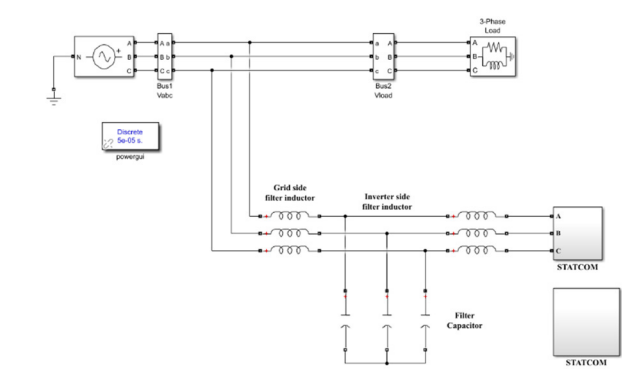


FIGURE 11. Simulation model of reactive power compensation using STATCOM.

interfacing active battery and supercapacitor HESS storage ensure seamless grid-connected/islanded transitions, regulating DC-link voltage at 800V and compensating sags via coordinated PI controllers. Simulation validates robust PQ under transients, with HESS extending battery life by offloading peaks while enabling bidirectional flows.

The simulation results in figure 13 shows that reactive power in the load is supported entirely by STATCOM and

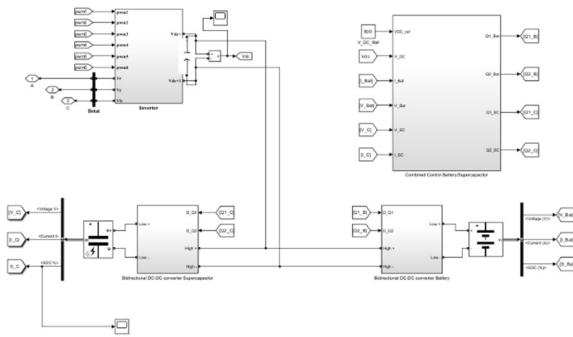


FIGURE 12. Simulation model of HESS supported STATCOM.

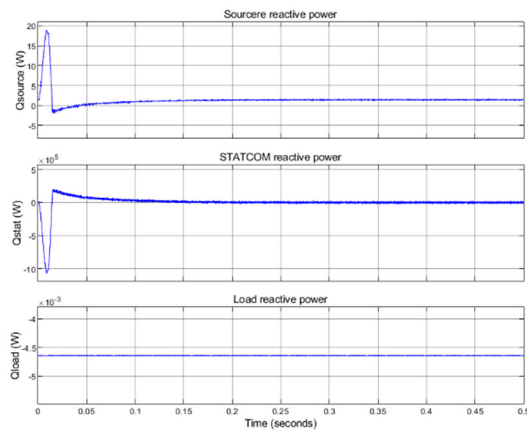


FIGURE 13. Reactive power in the source, load and STATCOM.

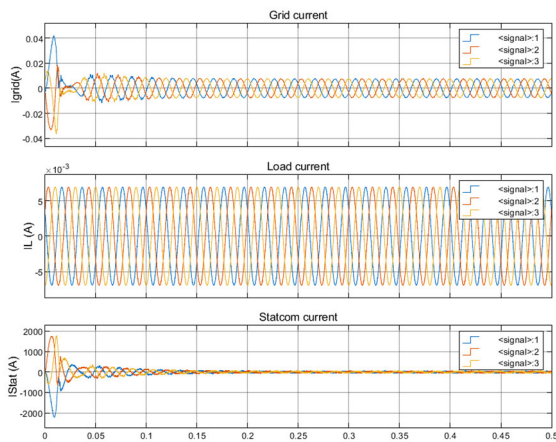


FIGURE 14. Compensation of load current using Stacom showing variations in source current, load current and injected current.

the active power is taken from main grid. The variation of current in the STATCOM is such that to make the load current steady even though there are disturbances in source current. as shown in figure 14. The combined battery and SC control regulates the dc capacitor voltage to 800Vas in figure 15.

Hence the key findings of the literature review are

- Filter based techniques, FACTS based devices and energy storage-based solutions are used to improve power quality and stability in RES integrated microgrids.

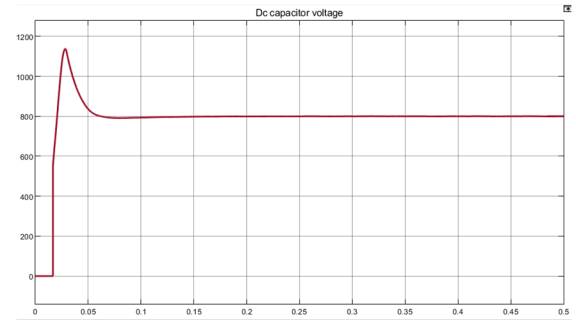


FIGURE 15. Variation of DC capacitor voltage of STATCOM.

- Filtering based methods are used for harmonic mitigation and reactive power compensation. FACTS- based devices provide dynamic voltage and current regulation. Energy storage systems smoothen intermittency of RES.

- Integration of BESS and HESS upgrades conventional PQI approaches by providing dynamic, multi-scale storage capability to support custom power devices in grid-connected and islanded microgrids.

- BESS Integration with power quality devices improve voltage, power quality issues and frequency stabilization. Also supports buffer-based filtering, but lead to rapid battery degradation under frequent, high-intensity PQ events [98]

- HESS combine batteries with supercapacitors or SMES for power quality improvement under transient and steady conditions with multi-timescale flexibility. This configuration serves longer storage life, superior harmonic mitigation and excellent voltage regulation

- Coordinated Techniques among filters, FACTS, BESS, and HESS offer the most comprehensive PQ mitigation, excellent transient response (active/HESS), sustained regulation (BESS/FACTS), and robust harmonic control (filters/FACTS) [98]

- Advanced control algorithms and adaptive EMS are essential for maximizing the benefits of coordinated techniques for seamless integration of resources, adaptive operation, low power loss and maintenance and to support energy management even under severe fluctuations in RES.

- The synergy between custom power devices and energy storage systems make microgrids sustainable with IEEE 519-2022 compliance and ensure continuous, high-quality power supply for diverse loads and operating conditions.

VIII. CONCLUSION & FUTURE SCOPE

The power quality improvement is necessary in systems integrated with RES. Various power quality improvement techniques in grid microgrid systems were reviewed in detail in this paper. The study shows that advanced filtering technologies, such as passive, active, and hybrid filters, in conjunction with solutions like UPQC and tailored FACTS devices are more capable for PQ improvement in decentralized renewable energy-integrated microgrids. BESS can effectively balance supply-demand and regulate system frequency. Integration of HESS in microgrids and grid-connected systems improve

power quality, system resilience, and facilitate increased renewable energy penetration. The coordinated utilization of PQI and energy systems provide an efficient solution for power quality improvement in RES integrated microgrid. Future researches should direct for the development and implementation of advanced control algorithms for custom power devices that mitigate power quality issues. Future research should prioritize in minimizing the implementation costs and integration durations of hybrid energy storage systems and custom power technologies in grid-connected microgrids. Furthermore, it is essential to use real-time data management and cybersecurity to guarantee secure and efficient operations. Researchers should focus on optimizing HESS configurations, refining control algorithms, and developing cost-effective solutions which integrate effectively with real-world grid operations and its management.

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