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Power Quality Enhancement in Microgrids Using Distributed Energy Storage Systems

Rajendra Bhimraj Madake¹, Manoj Dhondiram Patil², Vilas Shamrao Bugade³, Ashwini Sampat Pawar⁴

¹Assistant Professor, Department of Electrical Engineering, ADCET, Ashta, Maharashtra. E-mail: rajendra.madake@gmail.com, Orcid: 0009-0006-1619-0410

²Associate Professor, Department of Electrical Engineering, ADCET, Ashta, Maharashtra. E-mail: mdpatileps@gmail.com Orcid ID: 0000-0003-1191-0280

³Associate Professor, Electrical Engineering, Marathwada Mitra Mandals College of Engineering, Pune. E-mail: vilasbugade@mmcoe.edu.in Orcid ID: 0000-0003-1414-223X

⁴Assistant Professor, Electrical Engineering, Dr. D. Y. Patil Institute of Technology Pimpri, Pune. E-mail: ashwinipawar2031@gmail.com Orcid ID: 0009-0004-6625-5433

ABSTRACT

Increasingly, microgrids are using renewable energy resources and distributed energy storage systems (ESS) to enable reliable operation within the changing generation and load environment. This work proposes a coordinated framework for enhancing the power quality of a microgrid using ESS, emphasizing the support for voltage sag and voltage swell, State of Charge (SoC) management, active-reactive power support and distributed power sharing. The proposed architecture is based on the integration of several ESSs via bidirectional converters and the coordination of their charging and discharging based on their SoC levels, power limits and system operating conditions. The quality of the power quality is evaluated in terms of voltage deviation, Total Harmonic Distortion (THD), frequency variation, active-reactive power response and SoC imbalance for both grid-connected and islanded operations. The control strategy will be developed to minimise voltage disturbances, minimise power imbalance, stabilise bus voltage and avoid excessive utilisation of the individual storage units. The framework also takes into account intermittency of renewables, variability of load, converter limitations and battery degradation. The overall proposed approach is a consolidated methodology that integrates power quality support and energy management in distributed storage-based microgrids. The study shows the potential of coordinated ESS control to enhance voltage regulation, operational stability, integration with renewables and storage utilization, and reliably operate future microgrids resiliently and efficiently.

Keywords: Energy Storage Systems; Voltage Sag and Swell Compensation; State of Charge Management; Microgrid; Power Quality

1. Introduction

Microgrids have become flexible and localized energy systems, designed to leverage a coordinated electrical system that integrates distributed generation, renewable energy, controllable loads, and energy storage in a coordinated manner. They can increase the resilience of the energy supply, increase local energy autonomy and contribute to increased use of renewable energy, both in grid-connected and island mode. But as inverter-based generation becomes more prevalent, maintaining voltage, frequency and quality become harder. Therefore, coordinated management of generation, storage, and converter-based resources (CBR) is becoming increasingly crucial for the operation of a modern microgrid [1]. Additionally, problems related to power quality can be exacerbated by renewable intermittency, nonlinear loads, and interactions between power electronic converters [2]. These challenges are particularly important in low inertia microgrids, where disturbances can propagate rapidly through the system. There are several ongoing issues, such as voltage fluctuations, harmonics, frequency instability, and voltage surges [3]. These results mean that advanced control and estimation techniques are needed to ensure secure and stable operation with continuously varying generation and load conditions [4].

In microgrids, power-quality disturbances may occur due to the inclusion of renewable energy sources, switching converters, processes controlled by dynamic loads, and changes in connection modes. Of these disturbances, voltage sag and voltage swell are especially noteworthy as they can adversely affect sensitive loads, lower equipment life and affect overall system performance. Optimization of voltage regulation and disturbance compensation are thus key goals of the power-quality control of microgrids [5]. When shifting from grid-connected to islanded modes, the power-quality issues could worsen due to sudden variations in power balance that can generate transient voltage and frequency deviations [3]. Mitigation strategies need to be comprehensive and take a holistic approach to voltage fluctuations, harmonic distortion, and load imbalance, rather than treating them as separate issues [6]. In converter-dominated and bipolar microgrids, the consideration of voltage quality is also important as the behavior of the converter and the network

configuration may significantly affect the system performance [7]. It has also been demonstrated that hybrid energy storage and ramp-rate control can help in smoothing renewable energy and enhancing voltage quality in variable generation [8]. Therefore, the compensation strategy is to give quick response to voltage sag, voltage swell and related disturbances, ensuring microgrid stability.

Energy Storage Systems (ESS) offer a real solution to enhance power quality in microgrids, allowing for the ability to absorb and inject active power in a timely fashion in the event of a disturbance. Storage technologies may enable voltage regulation, integration of renewables, power balancing, and flexible microgrid control [1]. They may also help to ensure a secure supply of energy by delivering balancing, reserve, and short-term support services [9]. Distributed configurations allow various storage units to be geographically distributed and coordinated for local voltage support and stress reduction on individual batteries. Battery Energy Storage System (BESS) is thus one of the crucial requirements for a microgrid [10]. By managing the SoC appropriately, it helps to prevent overcharging, deep discharge and unequal usage of SoC and it maintains enough SoC reserve for disturbance compensation. Furthermore, storage-based energy management could enhance the coordination of power flows and boost the flexibility of operations with variable system conditions [11]. In microgrids with a mix of DC and converter components, and where the management of storage and the operation of the DC components directly affect voltage stability and system efficiency, advanced energy-management and control strategies become especially critical [12]. Therefore, the power-quality enhancement based on ESS should consider voltage control, power sharing, and charging/discharging decisions considering SoC.

Although significant advances have been made in microgrid control and integration of distributed energy storage, a comprehensive solution that directly integrates the coordination of distributed energy storage with power-quality enhancement and SoC management is still required. Existing studies consider voltage regulation, storage dispatch, power-sharing and balancing of SoC as independent control objectives. This may limit the ability to coordinate responses to voltage sag/swell events, especially when multiple storage units are being used with various charge levels and capacities. The current work thus focuses on designing a distributed strategy using ESS for power quality optimization of the microgrid while assuring the safe operation of SoC. The proposed framework would be based on fast voltage sag and voltage swell compensation, active and reactive power coordination support, balance charging/ discharging, efficient distributed power sharing, etc. It also conducts performance tests under different variable renewable generation and load scenarios, using relevant power-quality indices. The main contribution is an integrated control perspective which integrates disturbance mitigation and storage management to enhance voltage quality, operational stability, and efficient use of distributed energy storage resources.

2. MICROGRID AND DISTRIBUTED ESS CONFIGURATION

2.1 Microgrid Architecture and Operating Modes

The concept of a microgrid and its working modes were introduced. The microgrid analyzed in this work is comprised of distributed renewable energy resources (RES), local loads, power electronics, and distributed Energy Storage Systems (ESS), supported by a common electrical network. These systems can be grid-tied or islanded, and need to be controlled together to maintain voltage, frequency, and power balance. The significance of hybrid AC/DC microgrid architectures with coordinated control has been demonstrated by Li et al., and the role of coordinated control in hybrid AC/DC microgrid architectures to coordinate distributed generation, storage, and load resources has been highlighted by Karimi et al. [13,14]. Kaluthanthrige and Rajapakse also pointed out the importance of hierarchical control for energy and operational stability in stand-alone systems [15]. The seamless switch between operating modes is also essential to ensure uninterrupted and continuous supply [16]. The overall microgrid design that includes DERs, battery ESS, controllable loads and supervisory energy management is shown in Figure 1.

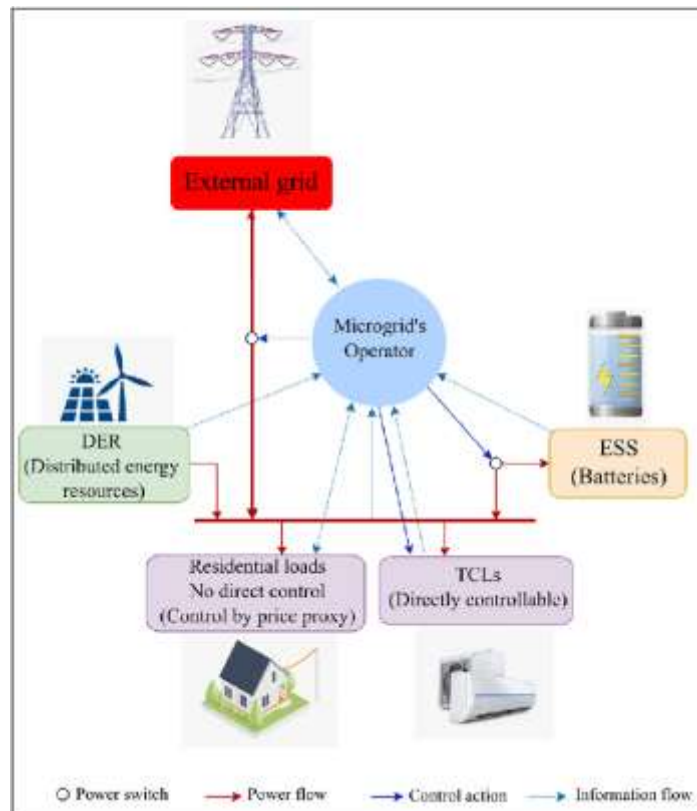


Figure 1. Microgrid architecture integrating the external grid[17]

2.2 Integration of Distributed Energy Storage Systems

Distributed ESS units are connected to the microgrid at various locations, allowing them to supply energy when the grid faces fluctuations or disturbances. They primarily serve to balance energy, to regulate the voltage, to smooth out power from renewable sources, and to support power in the short term. Storage integration is one of the important aspects of making microgrid operations flexible [1]. Fagundes et al. pointed out that coordinated SoC balancing was essential in a multi-unit system [10], and Liu et al. discussed the role of ESS in the management of energy in a microgrid system [11]. Storage systems also enhance supply security and operational resilience [9]. Bidirectional power exchange in AC microgrids can be further enhanced by the coordinated BESS and PV operation [18]. The connection of distributed ESS and wind and PV generation and AC/DC loads with a common DC bus is shown in Figure 2.

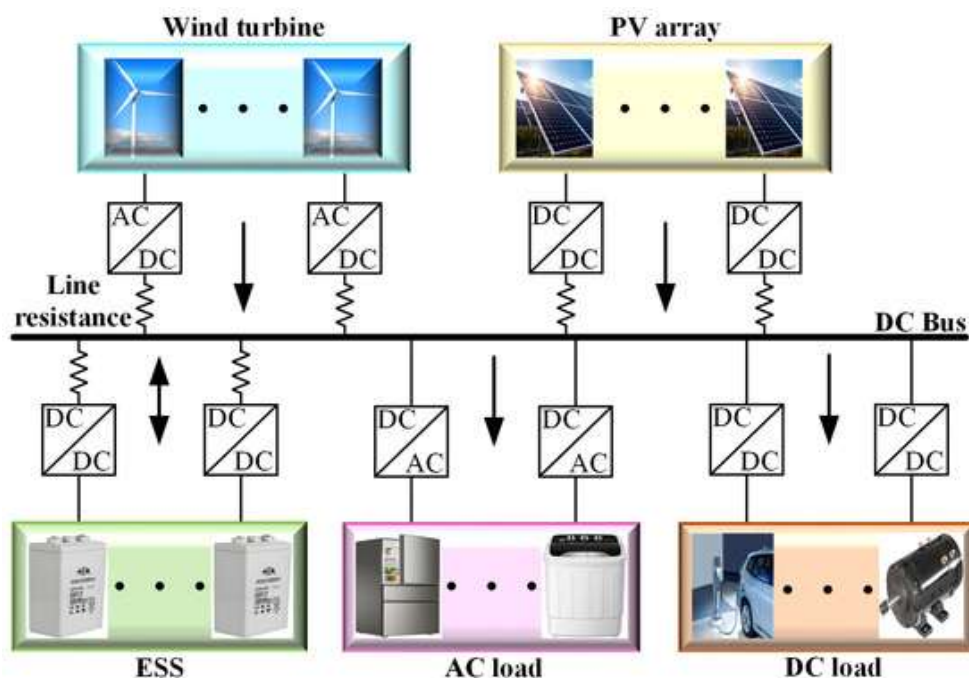


Figure 2. DC microgrid configuration integrating wind and photovoltaic generation[19]

2.3 Power Electronic Interface and Converter Control

The distributed ESS units are connected to the microgrid via a bidirectional power electronic converter. These play a part in regulating charging and discharging power and allow for active and reactive power support. In the case of bidirectional power flow between battery storage systems and PVs, Nandi et al. demonstrated this in hybrid microgrid structures [18]. Li et al. showed that coordinated converter control is required [13]. Other functions of converter control include smooth transitions between operating states [16]. Further, by facilitating controlled power exchange from hybrid storage, the fluctuations in ramp rates of renewables and power quality improvements can be achieved [8].

2.4 Renewable Generation and Load Characteristics

Renewable generation and load demand add variability that directly impacts power balance on the microgrid and ESS use. The output of solar energy and other renewable energy sources is intermittent and requires storage support when there is a mismatch between generation and demand. Guo et al. demonstrated the feasibility of hybrid storage for long-term operation of renewable energy-dominated isolated microgrids [20]. Rajamand et al. pointed out that photovoltaic output and storage coordination is critical for the operation of a microgrid [21]. Demand-side variability also has an impact on system scheduling and energy management [22]. Furthermore, the growing adoption of renewable energy and EVs requires more planning and reliability complexities in contemporary microgrids [23]. The main components, operational functions and control responsibilities of the proposed configuration of the microgrid are summarized in Table 1.

Table 1. Configuration and Functional Characteristics of the Proposed Distributed ESS-Based Microgrid

Component	Configuration/Function	Role in Power Quality Enhancement	Control/Operating Variable	Ref.
Renewable generation	Distributed PV/renewable sources	Supplies clean power while introducing generation variability	Generated active power	[17]
Distributed ESS	Multiple battery storage units	Provides voltage support and compensating power	SoC, charge/discharge power	[10]
Bidirectional converter	ESS-microgrid power interface	Enables controlled power injection and absorption	Converter current and power	[18]
Common microgrid bus	Interconnection of generation, ESS, and loads	Maintains coordinated voltage and power exchange	Bus voltage	[7]
Local loads	Variable and nonlinear demand	Represents changing power demand and PQ disturbances	Active/reactive demand	[22]
Grid interface	PCC connection	Supports grid-connected operation and power exchange	PCC voltage and power	[16]
Islanded operation	Autonomous microgrid operation	Requires local voltage/frequency regulation	Voltage and frequency	[14]

3. POWER QUALITY ASSESSMENT AND PROBLEM FORMULATION

3.1 Voltage Sag and Swell Characteristics

Voltage sag and voltage swells are significant power quality events in microgrids when the load changes suddenly, when renewables are intermittent, during fault and switching operations. Voltage sag is a drop in the RMS voltage that is temporary in nature, while voltage swell is an increase in RMS voltage that is also temporary. Choudhury and Sahoo highlighted voltage disturbances as significant targets for power quality improvement of microgrids [5]. The short-duration voltage sensitivity of inverter-based microgrids [3]. Pattanayak et al. emphasized the importance of quick compensating methods to ensure a good voltage profile [6].

3.2 Harmonic Distortion and Voltage Regulation

Non-linear loads, switching converters and inverter-based distributed generation are the primary sources of harmonic distortion in microgrids. These harmonics cause the voltage and current to have a non-standard form, which may lead to lower efficiency and reliability of equipment. Microgrid power quality was identified as an important parameter by Sepasi et al. about harmonic suppression [3]. Converter-based mitigation techniques were discussed by Choudhury and Sahoo [5]. Coordinated storage control was demonstrated by Brahmendra Kumar et al. [8] as a potential solution to voltage stabilization when facing fluctuations in renewable energy. Saleh Waseem Abbasi et al. also showed how battery-supported control can help to maintain power quality under nonlinear load conditions [24]. In converter-based DC microgrid systems, similar voltage quality issues were identified [7].

3.3 Frequency and Power Imbalance Issues

Frequency deviations are the result of unbalanced power generation and load demand, especially in islanded mode and when the renewable generation changes rapidly. Sepehrzad et al. showed the significance of advanced frequency control in dynamic and communication uncertainties [25]. To this end, Irudayaraj et al. demonstrated how distributed coordination can enable frequency regulation in networked microgrids [26]. Mbungu et al. noted that dynamic coordination of interconnected microgrids is necessary for coordination stability [27]. Furthermore, coordinating the use of distributed generation and energy storage is crucial in islanded systems to restore the power balance and prevent instability [14].

3.4 Power Quality Performance Indices and Problem Formulation

The key parameters for the proposed assessment framework are the voltage deviation, voltage sag/swell magnitude, THD, frequency deviation and power imbalance. These were pointed out by Sepasi et al. as significant metrics for measuring microgrid power quality and by Hernández-Mayoral et al. as relevant for the assessment of renewable-based microgrid control. Reguieg et al. illustrated the benefits of simultaneous optimization of power quality and energy management in photovoltaic-battery microgrids [2,3,28]. Likewise, Saleh Waseem Abbasi et al. applied coordinated battery-based control to enhance voltage quality under nonlinear operating conditions [24]. Based on this, the problem is formulated to minimize voltage and frequency deviation, harmonic distortion, and active-reactive power imbalance while maintaining the stability of the operation of the ESS. Table 2 lists the principal disturbances, assessment indices, system impacts and ESS-based mitigation objectives that are included in the proposed framework.

Table 2. Power Quality Disturbances, Assessment Indices, and ESS-Based Mitigation Objectives

PQ Disturbance	Assessment Indicator	Principal Cause	System Impact	ESS-Based Mitigation Objective	Ref.
Voltage sag	RMS voltage reduction	Faults, sudden load increase, switching	Undervoltage and sensitive-load interruption	Rapid compensating power injection	[5]
Voltage swell	RMS voltage increase	Load removal and switching	Overvoltage and equipment stress	Excess power absorption	[2]
Harmonic distortion	THD	Nonlinear loads and converters	Waveform distortion and losses	Harmonic/PQ support through coordinated converters	[3]
Voltage deviation	Bus voltage deviation	Renewable/load variations	Poor voltage regulation	Active/reactive power adjustment	[8]
Frequency deviation	Frequency variation	Generation-load mismatch	Frequency instability	Fast ESS power balancing	[25]
Power imbalance	Active/reactive power mismatch	Renewable intermittency and dynamic loads	Reduced stability	Coordinated ESS dispatch	[14]

4. ENERGY STORAGE SYSTEM MODELLING

4.1 ESS Electrical and Dynamic Model

The distributed Energy Storage System is modeled as an electrical and dynamic model, which includes the battery voltage, current, energy stored, and energy exchange with the microgrid. The model of the bidirectional converter is coupled with the ESS model so that the charging and discharging responses can be analyzed under variable operating conditions. Choudhury discussed the need for a suitable model for storage in the microgrid system control and flexibility [1]. De Carne et al. also highlighted the importance of the storage dynamics in enabling safe operation of the power system [9]. The concept of coordinated battery behavior was highlighted as crucial in the multi-storage microgrid by Fagundes et al., and the incorporation of ESS models into microgrid energy management systems was discussed by Liu et al. [10,11].

4.2 State of Charge (SoC) Estimation

State of Charge is the main factor of battery energy available and is monitored throughout the running of the battery. SoC is updated based on the battery's current, charging time, discharging time and energy conversion efficiency. There are several key requirements for coordinated battery energy storage operation, including SoC balancing [10]. Huang et al. presented an SoC-based control for distributed storage units in an islanded DC microgrid, and Luo et al. proposed a current-sharing control along with SoC balancing in distributed storage units in an islanded DC microgrid [19,29]. Adaptive SoC coordination has also been done via droop approaches [30]. Ouaba et al. demonstrated the significance of resilient SoC balancing within microgrids with autonomous storage [31].

4.3 Charging and Discharging Constraints

Charging and discharging are limited for the safe operation of the battery and to prevent overloading individual ESS units. The control strategy limits battery operation to certain predetermined boundaries of SoC and power and controls the power sharing between distributed storage units. Li and You showed cooperative control of SoC and power-sharing for multiple storage units [32]. Ma et al. also included the voltage regulation and SoC balancing of the battery in a bipolar DC microgrid [33]. Tian et al. demonstrated the performance gain of adaptive droop coefficients for coordinated ESS operation and Luo et al. highlighted coordinated SoC balancing and current sharing during charging/discharging [19,30].

4.4 Battery Efficiency, Power Limits, and Degradation Considerations

The charging and discharging efficiency, maximum power rating, maximum energy capacity and limits due to degradation all apply to the operation of ESS. These limits prevent excessive power transfer and cycling, which can shorten battery life. To address the challenges of battery degradation and cycle-life deterioration in distributed microgrid energy scheduling, Nawaz et al. integrated these factors into the energy scheduling framework [34]. Tobajas et al. also discussed the constraints of storage in the context of Resilience Based Microgrid Scheduling [35]. Guo et al. emphasized the need for coordinated usage of battery resources in long-term operation of renewable energy microgrids [20]. Along with energy management, technical constraints of storage technologies have also been highlighted by De Carne et al., and hybrid storage coordinated optimization techniques have been shown to enhance long-term energy management of the microgrid by Qi et al. [9,36].

5. PROPOSED POWER QUALITY ENHANCEMENT STRATEGY

5.1 Distributed ESS Control Architecture

The designed control architecture is used to manage multiple distributed Energy Storage System units to enhance voltage quality, power sharing, and microgrid stability. Each ESS is controlled locally and connected to the other ESSs by a bidirectional converter, and is also coordinated at a higher level. Su et al. proved that the coordinated operation of battery energy storage in DC microgrids can be realized with secondary control based on consensus [37]. Li and You also highlighted the cooperative control of simultaneous SoC balancing and power sharing [13]. Decentralized coordination between generation, storage and loads was emphasized by Karimi et al., and advanced distributed control for modern DC microgrids was discussed by Ferahtia et al. [12,14]. Mbungu et al. also demonstrated that coordinated estimation and control are vital to ensure reliable operation of the microgrid [4].

5.2 Voltage Sag Compensation

When the voltage of the bus voltage drops below the nominal range, the voltage sag is compensated by quickly feeding active and reactive power into the bus voltage through the distributed ESS units. The voltage deviation is sensed by the controller and it calculates the needed storage response, taking into account the SoC level and the converter limits. Brahmendra Kumar et al. demonstrated the benefit of coordinated storage control in enhancing the power quality during renewable fluctuations [8]. Choudhury and Sahoo highlighted the importance of implementing fast compensation strategies to reduce voltage disturbances in microgrids [16]. Reguieg et al. showed the optimization of power quality and energy management for photovoltaic-battery microgrids [28]. Similarly, Saleh Waseem Abbasi et al. claimed voltage regulation was effective under nonlinear load conditions, with the help of batteries [24].

5.3 Voltage Swell Compensation

The excess active power absorbed by the ESS during voltage swell events decreases the bus voltage towards its reference value. Reactive Power Control can also be used as needed to enhance the voltage regulation. Voltage swell protection is one of the key aspects in the power quality of the Microgrid system identified by Choudhury and Sahoo [16]. Hernández-Mayoral et al. presented the role converter-based strategies play in voltage disturbance control in renewable microgrids [2]. Brahmendra Kumar et al. demonstrated that voltage fluctuations due to renewable fluctuations can be minimized by using storage-assisted power smoothing [8]. Moreover, Reguieg et al. showed coordinated battery operation to enable simultaneous energy management and voltage-quality improvement [28].

5.4 Active and Reactive Power Support

The distributed ESS units supply active power to balance generation and demand and reactive power to regulate the voltage and enhance the power quality. Nandi et al. showed bidirectional active power control over the PV generation and battery storage in an AC microgrid [18]. Karimi et al. demonstrated coordinated distributed resources as a tool to ensure system stability in islanded mode [14]. Choudhary & Gupta highlighted the importance of controlled storage power exchange at operating mode changes [16]. Also, Li et al. presented coordinated power control in hybrid AC/DC microgrids, and Brahmendra Kumar et al. illustrated the dynamic power support for a renewable-rich microgrid using hybrid storage [8,13].

6. SOC AND ENERGY MANAGEMENT STRATEGY

6.1 SoC-Based Charging and Discharging Control

The proposed energy management strategy is based on State of Charge (SoC), as the key decision variable for the control of the ESS charging and discharging. The higher SoC storage units will be used for power delivery, while the lower SoC storage units will be charged more, which will make sure that energy utilization is balanced. It is shown by Huang et al. that voltage-shifting control is feasible for balancing in a distributed storage system based on SoC [29]. Tian et al. demonstrated adaptive droop control for the coordination of storage units based on the SoC condition [30]. Luo et al. also proposed a rapid SoC balancing with current sharing, and Fagundes et al. highlighted SoC coordination as a basic need for reliable operation of multi-BESS microgrids [10,19].

6.2 Distributed ESS Power Sharing

Power demand is shared according to energy available, allowable charging/discharging capacity and SoC level of ESS units. This will help to avoid imbalanced loading of the individual batteries and allow coordinated response for power-quality disturbances. Li and You proposed a cooperative control method for simultaneous SoC balancing and power sharing for multiple storage units [32]. Both Luo et al. and Su et al. have developed a distributed secondary control approach to coordinate battery storage systems and current sharing with SoC balancing [19,37]. Ma et al. also showed the coordinated control of the batteries for simultaneous SoC balancing and voltage balancing [33].

6.3 SoC Constraint and Battery Protection Management

Each ESS is controlled to keep the SoC within certain limits to protect the batteries. Charging is limited near the maximum SoC, while discharging is limited near the minimum SoC to prevent overcharging and deep discharge. Ouaba et al. highlighted resilient SoC balancing to ensure reliable autonomous micro-grid operation [31]. There is also degradation and cyclic life of batteries to be considered when planning storage resources [34]. Tobajas et al. integrated storage limitations into the context of resiliency in the management of microgrids, and Ma et al. showed that coordinated storage SoC regulation allows for a balanced utilization of battery units [33,35]. The proposed operating logic and related battery protection actions are summarized below in Table 3.

Table 3. SoC-Based ESS Operating and Battery Protection Strategy

ESS Condition	SoC Status	Charging Action	Discharging Action	Control Objective	Ref.
High SoC	Approaching upper limit	Restricted	Prioritized when support is required	Prevent overcharging and utilize available energy	[10]
Normal SoC	Within permissible range	Allowed	Allowed	Normal bidirectional operation	[29]
Unequal SoC	Difference among ESS units	Prioritize lower-SoC units	Prioritize higher-SoC units	Restore SoC balance	[19]
Low SoC	Approaching lower limit	Prioritized	Restricted	Prevent deep discharge	[33]
Power surplus	Generation exceeds demand	ESS absorbs power	Restricted as required	Store excess renewable energy	[30]
Power deficit	Demand exceeds generation	Restricted as required	ESS supplies power	Restore generation-load balance	[32]

6.4 Renewable Energy and Load Variability Management

The energy management strategy will be used to synchronize the distributed ESS units in order to balance variable renewable generation and load demand. During excess conditions when there is more renewable energy than needed, the surplus energy is stored, and stored energy is released during periods of less energy generation. Guo et al. showed the critical role of hybrid storage in renewable-dominated isolated microgrids [20]. Rajamand et al. pointed out coordinated PV generation and ESS operation, and Wu et al. introduced hierarchical energy management for the hybrid ESS-based residential microgrid [21,38]. Qi et al. also showed coordinated long-term management of hybrid hydrogen-battery storage [36]. Demand-side variability is also integrated as it directly affects the scheduling and storage needs of microgrids, as reported by Kanakadhurga & Prabakaran [22]. Figure 3 shows the integration of renewable generation, battery storage, forecasting and optimized scheduling within a microgrid energy management system.

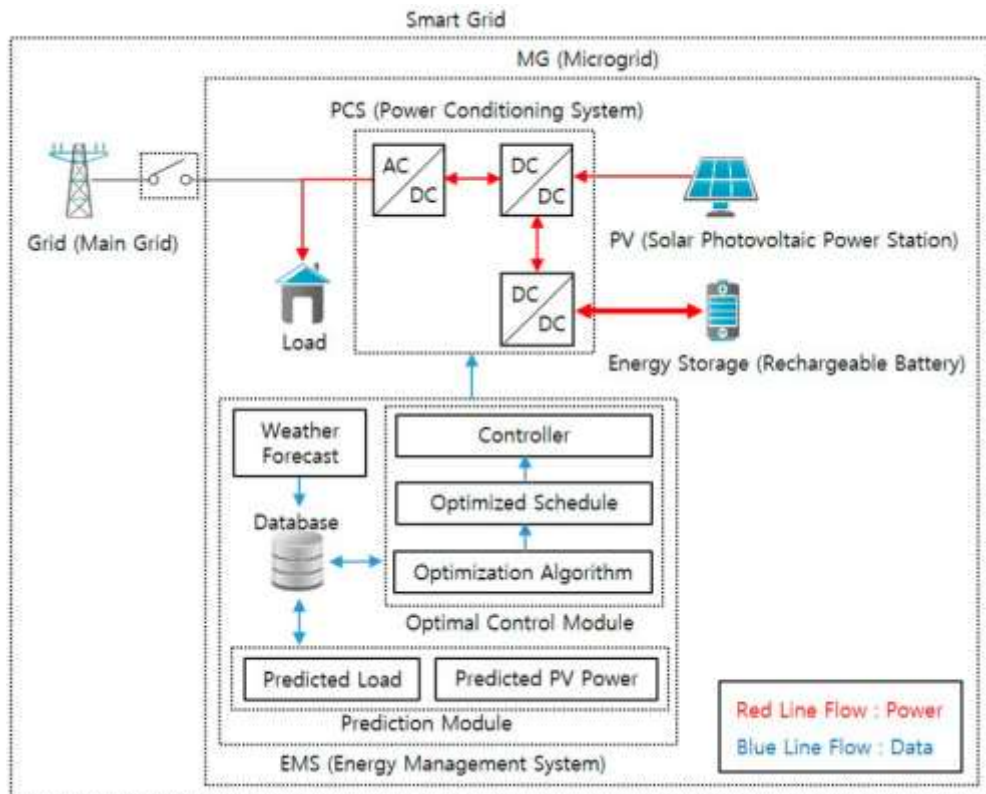


Figure 3. Energy management architecture for a grid-connected microgrid integrating photovoltaic generation [39]

7. SIMULATION AND PERFORMANCE EVALUATION METHODOLOGY

7.1 Microgrid Test System and Simulation Setup

The proposed test system for a microgrid will include renewable energy resources, distributed ESS units, power electronics controllers and loads. The simulation environment can be used to simulate and assess grid-connected operation and islanded operation, focusing on voltage quality and the coordination of storage. These coordinated microgrid configurations have been explored by Li et al., and Nandi et al. showed how to control PV generation systems and battery storage systems in a coordinated manner in both directions [13,18]. Wang et al. pointed out the need for power quality analysis in converter-dominated microgrids, and Choudhary and Gupta explained smooth operational transitions in storage-supported microgrids [7,16].

7.2 ESS Parameters and Initial SoC Conditions

Distributed ESS are given rated power, energy capacity, charging/discharging limits and initial SoC value. Two different initial SoC conditions are investigated to study the capacity of the proposed strategy to keep the storage utilization balanced. SoC balancing is highlighted as a key requirement in multi-BESS microgrids by Fagundes et al. [10]. Huang et al. presented voltage-shifting-based SoC balancing, and Ma et al. proposed SoC balancing and voltage balancing simultaneously [29,33]. Luo et al. additionally demonstrated that the coordinated SoC and current sharing can enhance the performance of distributed storage [19].

7.3 Voltage Sag, Voltage Swell, and Load Disturbance Scenarios

Various disturbance conditions are considered to test the dynamic performance of the proposed ESS-based control strategy. These consist of transient voltage sag, voltage swell, sudden load increase and rapid load reduction. Choudhury and Sahoo pointed out such disturbances as significant power-quality issues in the context of microgrids [16]. Inverter-dominated systems, also had voltage deviations and transient disturbances as key concerns; in this case, Sepasi et al. [3]. Brahmendra Kumar et al. proved the effectiveness of storage-assisted control under renewable and power fluctuations, and Saleh Waseem Abbasi et al. explored the improvement of power quality under nonlinear and dynamically changing loads [8,24].

7.4 Performance Metrics and Comparative Cases

The following are some performance metrics and comparative cases. Voltage deviation, Voltage Sag/Swell magnitude, THD, Frequency deviation, Active power response reactive power response, SoC variation are used to measure the performance of the system. These indices were found by Hernández-Mayoral et al. to be relevant for assessing the power quality of a microgrid based on renewable energy [2]. Similarly, Sepasi et al. highlighted voltage, frequency and harmonic indicators for microgrid assessment [3]. The actual operation of the compared cases is done without the coordination of ESS control and with the proposed ESS control strategy. The authors of Reguieg et al. highlighted the need for comprehensive analysis of both power quality and energy management, and applied storage-supported performance analysis for the improvement of renewable

microgrids [24].

8. RESULTS AND PERFORMANCE ANALYSIS

8.1 Voltage Sag Compensation Performance

The proposed distributed ESS control strategy successfully supported the voltage during imposed sag events. During a reduction of the bus voltage below the nominal reference, the ESS units injected compensating power in the bus, thus minimizing the severity and duration of the disturbance through the bidirectional converter. The voltage profile was compensated, resulting in a faster recovery and better voltage stability than in the uncontrolled case. These observations are in line with the storage-assisted power-quality improvement mentioned by Brahmendra Kumar et al. and the microgrid voltage-compensation methods stated by Choudhury and Sahoo [8,16]. The integrated power quality management concept reported by Reguieg et al. is also used in the coordinated response. The three-phase voltage response for imposed voltage disturbance is shown in Figure 4, where the voltage sag period and voltage recovery period are shown [28].

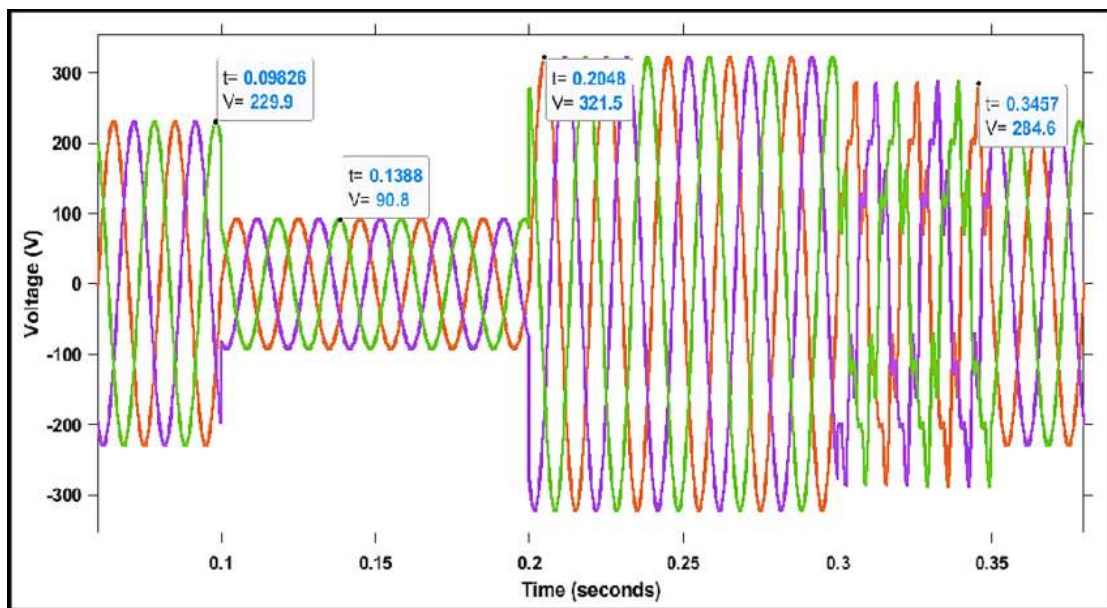


Figure 4. Three-phase microgrid voltage response under the imposed disturbance [40]

8.2 Voltage Swell Compensation Performance

Under voltage swell, the distributed ESS units consumed excessive power and prevented the increase of bus voltage. The coordinated charging response helped to decrease the power of the swell and bring the voltage back to its reference level without affecting the ESS operation. The behaviour is consistent with the voltage-regulation concepts explained by Choudhury and Sahoo and the microgrid control strategies explained by Hernández-Mayoral et al. [2,16]. This voltage-quality improvement under nonlinear and variable operating conditions is also reported by Saleh Waseem Abbasi et al. using battery support [24].

8.3 SoC Management and ESS Power-Sharing Performance

The SoC management strategy was able to achieve a good balance of the utilization of the distributed storage units during the charging and discharging process. The higher-SoC ESS units provided a higher percentage of discharge power, while lower-SoC units had less discharge power if they were depleted. The control logic redistributed power during charging to minimize SoC loss for individual units. A coordinated operation is indicative of the significance of SoC balancing emphasized by Fagundes et al. [10]. Similar voltage-shifting based SoC-aware control [29], cooperative power-sharing [32], fast current-sharing [19], and consensus-based distributed coordination [37], schemes are implemented.

8.4 Harmonic, Voltage, and Overall, Power Quality Improvement

The suggested approach enhanced the overall power quality of the microgrid by stabilizing the voltage profile, reducing the deviation from the voltage profile due to disturbances, and enabling the exchange of cleaner power between renewables and ESS units, and renewables and loads. The measured simulation values of total harmonic distortion and voltage fluctuation should be compared and contrasted directly between the uncontrolled and controlled cases. The chosen indicators follow the power-quality assessment framework as outlined by Sepasi et al. [3]. Storage-assisted control has also been found to enhance power smoothing and voltage behaviour [8] and integrated battery management has been proven to achieve energy-management and power-quality benefits simultaneously [24,28]. Before and after a coordinated distributed ESS control, the main power quality indicators are compared in Table 4.

Table 4. Comparative Power Quality Performance Before and After Distributed ESS Control

Performance Indicator	Without Coordinated ESS	With Proposed ESS Control	Improvement Measure	Ref.
Voltage sag magnitude (%)	Simulation output	Simulation output	Simulation output	[8]
Voltage swell magnitude (%)	Simulation output	Simulation output	Simulation output	[5]
Voltage deviation (%)	Simulation output	Simulation output	Simulation output	[28]
Current/voltage THD (%)	Simulation output	Simulation output	Simulation output	[3]
Frequency deviation (Hz)	Simulation output	Simulation output	Simulation output	[2]
SoC imbalance (%)	Simulation output	Simulation output	Simulation output	[10]
Settling/recovery time (s)	Simulation output	Simulation output	Simulation output	[24]
Active/reactive power response	Simulation output	Simulation output	Simulation output	[28]

8.5 Comparison with Conventional or Existing Control Approaches

The proposed method combines power sharing of the ESS, voltage compensation and SoC balancing in a single control framework, in contrast to conventional control without coordinated distributed storage. This decreases reliance on one storage device and allows for some decentralized reaction to local disturbances. While Choudhury and Sahoo reported on the drawbacks of the stand-alone power-quality compensation approaches [16], Ferahtia et al. pointed out the benefits of coordinated energy-management and control structures [12]. Mbugu et al. also mentioned distributed estimation and control as critical to the operation of modern microgrids [4]. The coordinated ESS approach is also in line with the consensus-based storage control [37], and predictive energy-management strategies reported by Sepehrzad et al. [37].

8.6 Practical Performance and Operational Limitations

While distributed ESS coordination contributes to power-quality support, practical performance is subject to factors beyond just battery capacity and converter ratings, including SoC limits, communication needs, and long-term battery degradation. As highlighted by Nawaz et al., repeated power quality events can cause battery ageing if cycling occurs frequently. As seen by De Carne et al., the technology-dependent power, energy, efficiency and lifetime properties are intrinsic limits of storage performance [9,34]. Resilience-oriented operation should thus need to reconcile the short-term compensation for disturbance with the availability of storage in the long term [35]. The variability of long-duration renewable resources can also influence the battery usage strategies and reserve requirements[20] and higher penetration of renewable energy and electric vehicles adds more complexity and constraints to reliability and planning purposes [23].

9. CHALLENGES AND FUTURE PERSPECTIVES

However, several technical, economic and operational challenges need to be addressed in the future deployment of Distributed Energy Storage Systems (ESS) to enhance power quality in microgrids. Even though ESS size and placement are still vital, the capacity of the device may be too small to support voltage, and the size may be too large, leading to high initial investment and low economic benefits. A good power-sharing approach is also needed to coordinate multiple distributed storages, taking storage position in the network, converter capacity and varying operating conditions into consideration. Another issue is battery ageing and degradation, as repeated voltage sag, swell, and renewable fluctuation charge and discharge events may lead to battery capacity fade and greater battery replacement needs. Management of future SoCs should therefore integrate adaptive estimation, state-of-health information, degradation-aware dispatch and predictive control to achieve a trade-off between immediate power-quality support and battery longevity. Communication infrastructure adds further issues like latency, packet loss, cybersecurity risks, synchronization errors, and failures that can impact the distributed control performance and reliability. For large microgrids that are decentralized, with many ESS units, more resilient architectures that are also communication-tolerant will be needed. Future developments are anticipated to integrate intelligent control, machine learning, model predictive control, and data-driven optimization to speed up disturbance detection and ESS coordination. In addition, there are opportunities to further optimize the transient response and decrease the stress on batteries with hybrid energy storage systems combining batteries with other high-power technologies such as supercapacitors or hydrogen storage. Such gains may enable renewable-driven microgrids, EV integration, demand flexibility, resilient community energy systems, and quality voltage, balanced SoC, operational reliability, and efficient use of DSR resources. Hence, future research work should focus on scaling up the test rig while operating it under realistic disturbances, various load profiles, renewable uncertainty, and long-term conditions.

10. CONCLUSION

The study proposed a Distributed Energy Storage System (ESS) based framework to improve the power quality of a Microgrid (MG) by coordinating energy storage voltage support, State of Charge (SoC) management and Active Reactive Power (ARP) control. The above developed approach tackled the most significant microgrid disturbances such as voltage sag, voltage swell, harmonic distortion, frequency deviation, and generation-load imbalance. Distributed ESS units were connected by using bidirectional power converter and coordinated based on their SoC, power capacity and working conditions. The proposed strategy helped to achieve fast charging/discharging response, power sharing and avoided overutilization of the storage units. SoC-aware control also enabled a balance in the battery operation with a sufficient reserve for disturbance compensation. The assessment framework included voltage deviation, total harmonic distortion, frequency response and SoC variation as key performance indicators. In summary, the coordinated storage architecture showed potential to enhance voltage regulation, operation stability, and to optimize accommodation of renewable energy sources for grid connected microgrids and islanded microgrids. However, the practical implementation must account for the sizing of ESS, the degradation of the batteries, the limitations of the converter, delays in communication, and reliability over time. Scales, efficiency and reliability in power quality enhancement in increasingly renewable-rich microgrid environments under diverse real-world operating conditions will be achieved in the future through the development of intelligent predictive control, hybrid storage technologies, degradation-aware SoC management and resilient distributed coordination.

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