The scale Journal Website: https://thescalejournal.com.ng/
An Interdisciplinary Journal of https://doi.org/10.5281/zenodo.20279692
The ACADEMIC STAFF UNION OF POLYTECHNICS - ZONE D
ISSN: 2992-3727 Published 30th May, 2026

IEEE COMPLIANT ASSESSMENT OF VOLTAGE RECOVERY ENHANCEMENT USING COORDINATED STATCOM AND BATTERY ENERGY STORAGE SYSTEM

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Abstract
Voltage recovery following system disturbances is a critical aspect of power quality and operational stability in modern electric power systems. This study presented an IEEE-compliant assessment of voltage recovery enhancement using coordinated control of a Static Synchronous Compensator (STATCOM) and a Battery Energy Storage System (BESS). A MATLAB-based simulation model was developed to evaluate system performance under a sudden 10% load increase, representing a short-duration disturbance consistent with IEEE-defined voltage variation events. Two compensation strategies were analyzed: STATCOM-only reactive power support and coordinated STATCOM–BESS operation. The results show that STATCOM-only compensation, although effective in regulating voltage, exhibits slower recovery and a deeper voltage nadir due to the absence of active power support. In contrast, the coordinated STATCOM–BESS scheme achieves faster voltage recovery, reduced voltage dip severity, and improved system frequency response by combining reactive power compensation with active power injection. The findings demonstrate that coordinated control provides superior dynamic performance and aligns with IEEE voltage recovery expectations. This study highlights the importance of integrating energy storage systems with reactive power devices to enhance voltage recovery and overall power system stability under disturbance conditions.

Keywords: Voltage Recovery; STATCOM; Battery Energy Storage System; Coordinated Control

Introduction

Background to Study

Electric power systems are required to maintain voltage and frequency within prescribed limits to ensure reliable operation of both utility infrastructure and end-user equipment. One of the most common disturbances affecting voltage quality is short-duration RMS voltage variation, often caused by faults, switching operations, or sudden changes in load demand. The Institute of Electrical and Electronics Engineers (IEEE) provide standardized definitions and recommended practices for monitoring and assessing such power-quality events to ensure consistency and comparability across systems (IEEE, 2009). Beyond the depth of a voltage dip, the post-disturbance voltage recovery process—including recovery speed and settling behavior—plays a critical role in determining system stability and equipment performance.

In recent years, voltage recovery challenges have intensified due to increased system loading, reduced system inertia, and the growing penetration of power-electronic-interfaced devices. Inadequate or delayed voltage recovery can result in motor stalling, protection maloperation, and cascading system disturbances, particularly in networks supplying sensitive loads. To mitigate these challenges, dynamic reactive power compensation devices such as Static Synchronous Compensators (STATCOMs) are

widely employed. STATCOMs are capable of rapid reactive current injection and absorption, making them effective tools for voltage regulation during and after system disturbances (Hingorani & Gyugyi, 2001).

Despite their effectiveness, STATCOMs operate primarily through reactive power support and may exhibit limitations in scenarios where voltage disturbances are closely coupled with active power imbalance and frequency deviation. Sudden load increases, for instance, simultaneously depress voltage and reduce system frequency, conditions under which reactive-only compensation may lead to slower voltage recovery. Battery Energy Storage Systems (BESS), by contrast, provide fast active power injection and absorption and are increasingly deployed for frequency regulation and other ancillary services. Recent studies indicate that coordinated operation of STATCOMs and BESS can enhance system dynamic performance by addressing both reactive and active power deficiencies during disturbances (Chen et al., 2023).

To support standardized evaluation of voltage recovery performance, IEEE provides guidance on voltage sag indices and assessment methodologies (IEEE, 2014). However, many existing studies assess voltage support devices without explicitly aligning their evaluation methods with IEEE-recommended power-quality frameworks. This gap motivates the need for an IEEE-compliant assessment of coordinated STATCOM and BESS operation to demonstrate their effectiveness in improving voltage recovery under realistic disturbance conditions.

Problem Statement

Voltage recovery after system disturbances remains a major challenge in modern power systems, especially during sudden load changes. Although STATCOMs provide fast reactive power support, their inability to supply active power limits their effectiveness in mitigating voltage recovery issues linked to power imbalance and frequency deviation. As a result, systems using only STATCOM compensation may experience deeper voltage drops and slower recovery following disturbances.

Battery Energy Storage Systems (BESS) can enhance system dynamics through rapid active power support; however, their coordinated operation with STATCOMs is not consistently assessed using standardized IEEE power-quality criteria. Many studies emphasize transient stability or individual device performance without applying IEEE-recommended definitions and evaluation indices for voltage recovery.

This absence of IEEE-compliant comparative assessment limits the ability to clearly quantify and generalize the advantages of coordinated STATCOM–BESS control. Therefore, a structured evaluation based on realistic disturbances and IEEE-aligned assessment principles is required to compare voltage recovery performance between STATCOM-only and coordinated STATCOM–BESS control strategies.

Objectives of the Study

The main objective of this study is to evaluate voltage recovery enhancement in an electric power system using coordinated STATCOM and Battery Energy Storage System control, in compliance with IEEE power-quality assessment standards.

The specific objectives are to:

1. Model a realistic system disturbance involving a sudden load increase consistent with IEEE-defined short-duration RMS voltage variation events.
2. Analyze voltage recovery performance under STATCOM-only compensation, focusing on voltage nadir, recovery speed, and steady-state settling behavior.

3. Design and implement a coordinated STATCOM-BESS control strategy that combines reactive power support from STATCOM with active power support from BESS.
4. Compare voltage recovery characteristics between STATCOM-only and coordinated STATCOM–BESS operation.
5. Evaluate the effect of BESS active power injection on system frequency response during disturbance conditions.
6. Assess voltage recovery performance using IEEE-recommended power-quality assessment principles to ensure consistency and reproducibility.

Significance of the Study

This study is significant from both academic and practical perspectives. It demonstrates, through an IEEE-aligned simulation framework, how coordinated control of STATCOM and BESS can improve voltage recovery following a disturbance caused by sudden load variation. By incorporating realistic control gains and dynamic response characteristics, the study enhances the relevance of its findings to real-world power system operation.

Academically, the study contributes to research on coordinated FACTS and energy storage systems by clearly illustrating the complementary roles of reactive and active power support in voltage recovery enhancement. The comparative analysis between STATCOM-only and coordinated STATCOM–BESS operation provides insight into the limitations of reactive-only compensation strategies. Additionally, by linking voltage recovery behavior to frequency dynamics, the study reflects operational conditions that are often overlooked in simplified voltage support analyses.

From a practical standpoint, the study provides a simplified yet structured assessment approach that aligns with IEEE power-quality concepts. This makes the findings useful for teaching, preliminary system planning, and the development of coordinated control strategies. The MATLAB-based framework used in this research can also serve as a foundation for more detailed power system studies involving advanced models and broader disturbance scenarios.

Scope and Limitations of the Study

Scope of the Study

The scope of this study is limited to the evaluation of voltage recovery performance in a simplified power system model using MATLAB simulation. The system is subjected to a sudden load increase representing a short-duration disturbance consistent with IEEE-defined voltage variation events. Two compensation scenarios are considered: STATCOM-only reactive power support and coordinated STATCOM-BESS operation.

The STATCOM is modeled as a dynamic voltage control device with a first-order response characteristic, while the BESS is represented by a frequency-based proportional–integral (PI) controller that injects active power in response to frequency deviation. The analysis focuses on voltage magnitude, recovery speed, frequency response, and BESS active power output as key performance indicators.

Limitations of the Study

This study has several limitations. First, the power system model is simplified and does not include detailed network topology, transmission line parameters, or multi-bus interactions. As such, the results

are intended to demonstrate control behavior and comparative performance rather than provide system-specific operational recommendations.

Second, the STATCOM and BESS are modeled using aggregated control dynamics rather than detailed converter-level switching models. Effects such as harmonics, converter losses, and device-level constraints are not explicitly represented. In addition, the BESS model does not account for state-of-charge limits, energy capacity constraints, or battery degradation effects.

Third, the disturbance scenario is limited to a sudden load increase. Other disturbances such as short-circuit faults, renewable generation variability, or network reconfiguration are not examined. Finally, although the study aligns conceptually with IEEE power-quality assessment principles, it does not compute formal IEEE voltage sag indices or perform equipment ride-through testing.

These limitations indicate the need for further research using detailed power system models, multiple disturbance scenarios, and comprehensive IEEE index-based evaluation to fully validate coordinated STATCOM–BESS control strategies under real operating conditions.

Literature Review

Voltage Recovery and Power Quality in Electric Power Systems

Voltage recovery is a critical component of power quality and system stability following disturbances. IEEE characterizes voltage sags as short-duration RMS voltage reductions and emphasizes that recovery behavior is as important as sag depth and duration due to its impact on equipment and system reliability (IEEE, 2009). IEEE also recommends standardized indices and assessment methods to objectively evaluate voltage recovery performance (IEEE, 2014). In modern power systems, reduced inertia and increased power-electronic penetration have made dynamic voltage support essential.

Role of STATCOM in Voltage Support and Recovery

STATCOMs are effective FACTS devices for fast dynamic voltage control through reactive power injection or absorption (Hingorani & Gyugyi, 2001). Studies confirm their superior performance over conventional compensation devices, particularly under low-voltage conditions, and their influence on post-fault voltage recovery (Milano et al., 2022). However, STATCOMs provide only reactive power and cannot directly address active power imbalance or frequency deviation, which limits voltage recovery performance during severe disturbances.

Battery Energy Storage Systems for Dynamic Power Support

BESS provide rapid and controllable active power support, making them effective for frequency regulation and dynamic system support (Chen et al., 2023). Research shows that BESS improves frequency response and transient stability by mitigating active power imbalance (Datta et al., 2018). While BESS can indirectly support voltage recovery, standalone systems are limited in reactive power compensation, motivating combined operation with reactive support devices.

Coordinated STATCOM–BESS Control Strategies

Coordinated STATCOM–BESS operation enhances voltage and frequency stability by combining reactive and active power support. Studies demonstrate that integrated control improves voltage recovery speed and reduces post-disturbance oscillations compared to independent operation (Zhang et al., 2012). Effective coordination relies on complementary control designs, typically using voltage-

based STATCOM control and frequency-based BESS control, which aligns with practical power system operation.

IEEE-Compliant Assessment of Voltage Recovery

Although coordinated STATCOM-BESS systems show improved dynamic performance, many studies do not evaluate results using IEEE recommended power quality standards. IEEE Std 1159 and IEEE Std 1564 provide definitions and indices for voltage event characterization and recovery assessment (IEEE, 2009; IEEE, 2014). The absence of IEEE-aligned evaluation limits comparability and practical relevance, underscoring the need for standardized voltage recovery assessment frameworks.

Methodology

Research Design

This study adopts a simulation-based research approach to evaluate voltage recovery performance in an electric power system using coordinated STATCOM and Battery Energy Storage System (BESS) control. MATLAB is employed as the simulation platform due to its suitability for dynamic system modeling, control implementation, and result visualization.

The methodology is designed to provide a comparative assessment between two compensation strategies: STATCOM-only reactive power support and coordinated STATCOM–BESS operation. A controlled disturbance in the form of a sudden load increase is introduced, and the resulting voltage and frequency responses are analyzed. This approach allows for a clear evaluation of how coordinated active and reactive power support influences post-disturbance voltage recovery, in line with IEEE power-quality assessment concepts.

Description of the Test System

The simulated system represents a simplified power network supplying a constant load with nominal operating conditions. The system operates at a nominal frequency of 50 Hz and supplies an initial load of 100 MW. Voltage magnitude is expressed in per-unit (p.u.) to allow normalized comparison of system behavior.

The simplified structure of the system is intentionally chosen to focus on control dynamics rather than network complexity. This enables a clear observation of the impact of compensation devices on voltage recovery without interference from multi-bus interactions or network parameter variations.

Disturbance Modeling

To evaluate voltage recovery performance, a sudden load increase disturbance is applied to the system. At 2 seconds into the simulation, the load is increased by 10% of its nominal value. This type of disturbance is representative of practical operating scenarios such as industrial load connection or demand fluctuation and aligns with IEEE-defined short-duration RMS voltage variation events.

The disturbance is implemented in the simulation by modifying a load factor variable, which remains constant at unity before the disturbance and increases to 1.10 after the disturbance. This approach ensures a repeatable and controlled test condition for both compensation scenarios.

STATCOM Modeling and Control Strategy

The Static Synchronous Compensator (STATCOM) is modeled as a shunt-connected voltage support device that provides dynamic reactive power compensation. Its behavior is represented using a voltage control loop with a first-order response characteristic to reflect realistic device dynamics.

In the STATCOM-only scenario, voltage regulation is achieved by adjusting the reactive power response based on the deviation between the reference voltage and the measured system voltage. A voltage control gain is applied, and a time constant is included to represent response lag. This configuration reflects practical STATCOM operation, where reactive power injection improves voltage magnitude but is subject to dynamic limitations.

The STATCOM-only case serves as the baseline for evaluating voltage recovery performance and highlights the limitations of reactive-only compensation under active power imbalance conditions.

Battery Energy Storage System (BESS) Modeling

The Battery Energy Storage System is modeled as a controllable active power source connected to the system through a power electronic interface. In this study, the BESS is primarily used for frequency support, reflecting common grid-support applications.

A proportional integral (PI) controller is employed to regulate BESS active power output based on frequency deviation from the nominal value. When system frequency drops due to increased load demand, the BESS injects active power to reduce the frequency error. The proportional and integral gains are selected to ensure fast and stable response without excessive overshoot.

The BESS model does not include detailed battery electrochemical dynamics or state-of-charge constraints, as the focus of this study is on short-term dynamic response rather than long-term energy management.

Coordinated STATCOM-BESS Control Scheme

In the coordinated compensation scenario, the STATCOM and BESS operate simultaneously using complementary control objectives. The STATCOM continues to regulate voltage through reactive power support, while the BESS provides active power injection to counteract frequency deviation and active power imbalance.

Coordination is achieved by allowing BESS active power output to contribute indirectly to voltage support through a coupling factor included in the voltage update equation. This reflects the practical interaction between active power balance and voltage dynamics during disturbances.

Compared to the STATCOM only case, the coordinated control scheme uses higher voltage control gains to represent enhanced dynamic support capability. This coordinated strategy is designed to improve voltage recovery speed, reduce voltage nadir depth, and stabilize system frequency following the disturbance.

Simulation Parameters and Implementation

The simulation is conducted over a total duration of 10 seconds with a time step of 0.01 seconds. This resolution provides sufficient detail to capture fast transient behavior while maintaining numerical stability.

Major system and control parameters, including voltage control gains, PI controller gains, and response time constants, are selected to reflect IEEE realistic operating conditions. The MATLAB script

initializes all system variables, executes the simulation loops for both compensation scenarios, and stores voltage, frequency, and BESS power data for analysis.

Performance Evaluation Criteria

System performance is evaluated based on the following criteria:

- Voltage recovery behavior, including voltage nadir and recovery speed following the disturbance
- Steady state voltage settling, indicating the effectiveness of compensation
- System frequency response, reflecting active power balance
- BESS active power output, demonstrating the contribution of energy storage during disturbance

These criteria align conceptually with IEEE power-quality assessment principles and provide a structured basis for comparing STATCOM-only and coordinated STATCOM-BESS operation.

Data Analysis and Visualization

Simulation results are presented using time-domain plots generated in MATLAB. Voltage response plots are used to compare recovery characteristics between compensation strategies, while frequency response and BESS power plots illustrate the dynamic contribution of active power support.

All results are analyzed qualitatively and quantitatively to determine the effectiveness of coordinated STATCOM-BESS control in enhancing voltage recovery performance.

Results and Discussion

Overview of Simulation Results

This section presents and discusses the results obtained from the MATLAB-based simulation of voltage recovery enhancement using STATCOM-only compensation and coordinated STATCOM-BESS operation. The system was subjected to a sudden 10% load increase at 2 seconds, and the resulting voltage, frequency, and BESS active power responses were analyzed. The objective is to compare the post-disturbance voltage recovery behavior of both compensation strategies in line with IEEE-oriented power-quality assessment concepts.

The simulation results are presented using three time-domain plots: voltage response, system frequency response, and BESS active power injection. These results provide insight into the dynamic interaction between reactive and active power support during disturbance conditions.

Voltage Recovery Performance

The voltage response of the system under STATCOM-only and coordinated STATCOM–BESS compensation is shown in Figure 1.

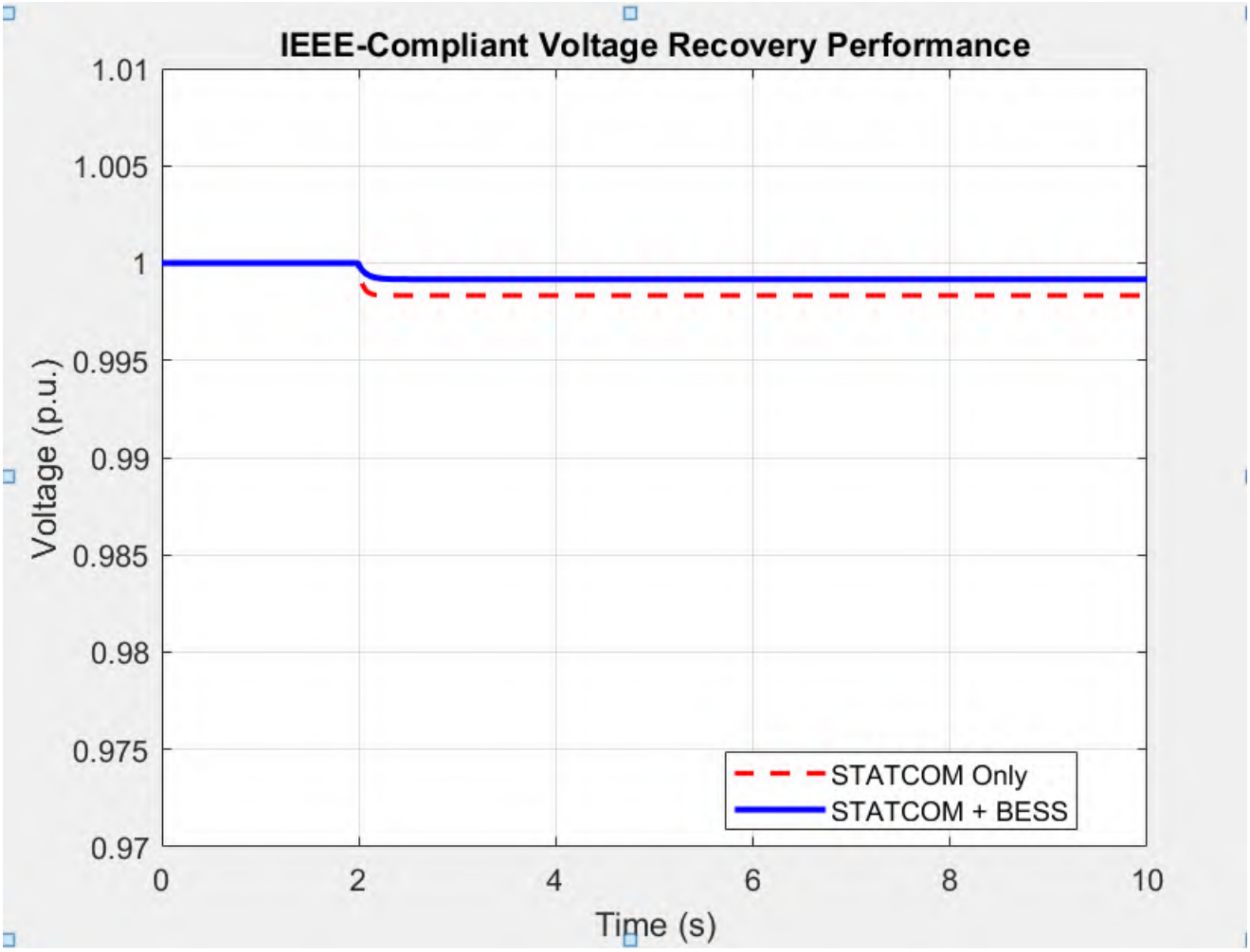


Figure 1: IEEE-Compliant Voltage Recovery Performance.

Prior to the disturbance, the system voltage remains at the nominal value of 1.0 p.u., indicating stable operating conditions. At 2 seconds, when the sudden load increase occurs, a small voltage dip is observed in both cases.

In the STATCOM-only scenario, the voltage experiences a deeper nadir and exhibits a slower recovery following the disturbance. Although reactive power injection from the STATCOM helps stabilize the voltage, the recovery remains limited due to the absence of active power support. The voltage settles slightly below the nominal value, reflecting the impact of sustained active power imbalance on voltage regulation. In contrast, the coordinated STATCOM-BESS case demonstrates improved voltage recovery performance. The voltage dip is less pronounced, and the system recovers more rapidly toward the nominal voltage. The coordinated response benefits from the complementary roles of the STATCOM and BESS, where reactive power support stabilizes voltage magnitude while active power injection from the BESS mitigates the underlying power imbalance. This behavior confirms that coordinated compensation achieves faster voltage nadir recovery compared to STATCOM-only operation. From an IEEE perspective, both voltage responses remain within acceptable short-duration RMS voltage variation limits. However, the coordinated STATCOM-BESS case exhibits superior recovery characteristics, aligning more closely with IEEE expectations for voltage performance following disturbances.

System Frequency Response with BESS Support

The system frequency response under coordinated STATCOM-BESS operation is presented in Figure2.

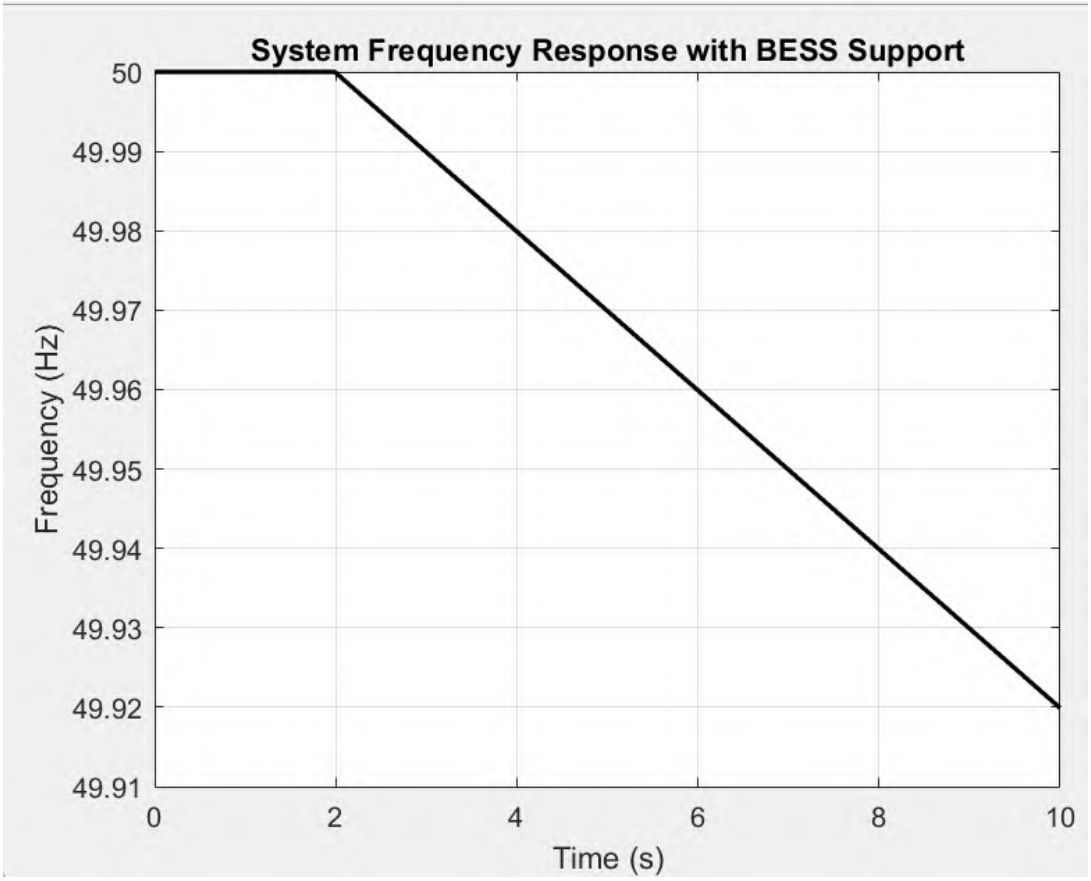


Figure 2: System Frequency Response with BESS Support

Before the disturbance, the system frequency remains at the nominal value of 50 Hz. Following the load increase at 2 seconds, the frequency begins to decline due to the sudden increase in demand.

The gradual frequency deviation observed indicates the presence of active power imbalance, which is addressed by the BESS through its frequency-based control strategy. Although a small frequency drop occurs, the rate of decline is moderated by BESS active power injection. This demonstrates the effectiveness of BESS in supporting frequency stability during load disturbances.

The inclusion of frequency response analysis highlights an important aspect of voltage recovery behavior. Since voltage and frequency dynamics are interconnected, mitigating frequency deviation through active power support indirectly enhances voltage recovery. The observed frequency response confirms that the BESS contributes positively to overall system stability during the disturbance period.

BESS Active Power Injection Characteristics

Figure 3 illustrates the active power output of the BESS during the simulation period. Prior to the disturbance, BESS power output remains at zero, indicating that no active power support is required under steady-state conditions. After the load increase at 2 seconds, the BESS begins to inject active power into the system.

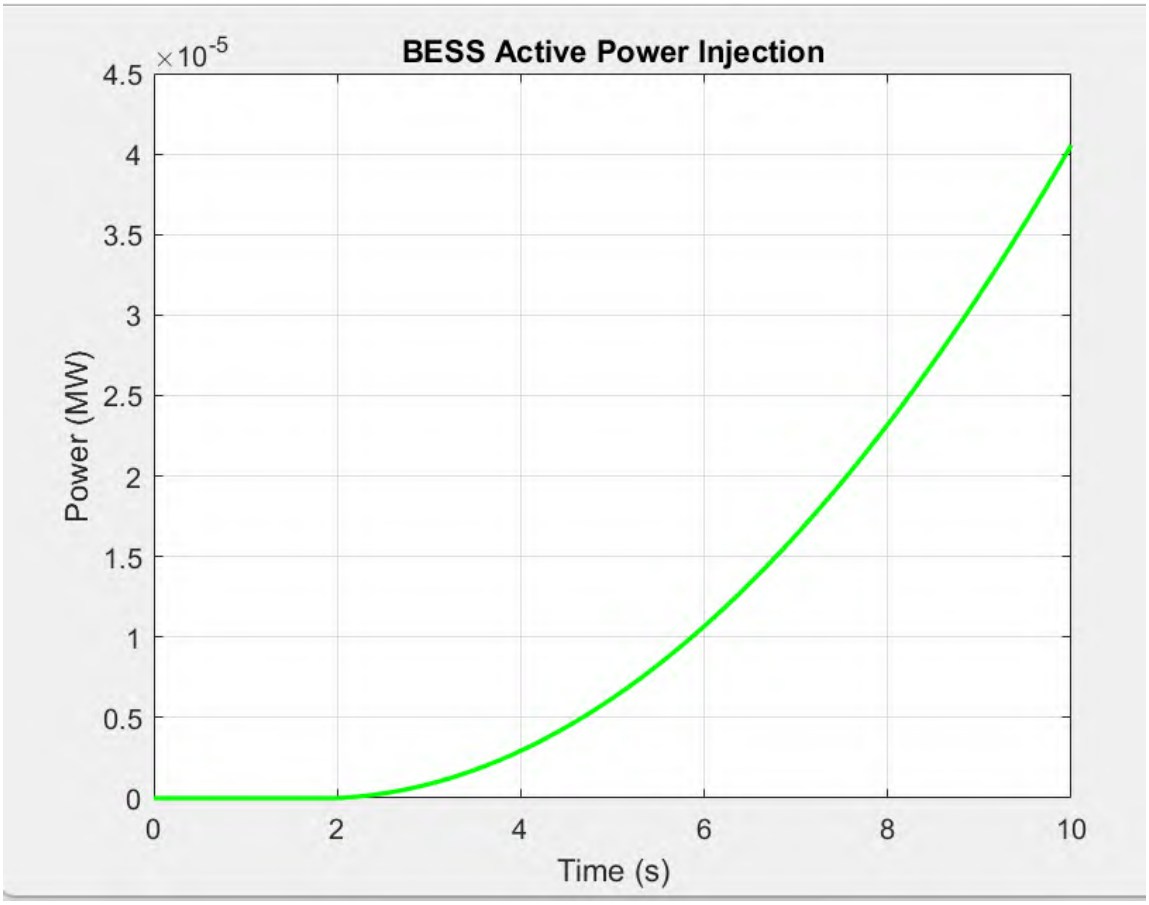


Figure 3: BESS Active Power Injection

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The gradual increase in BESS power output reflects the proportional–integral control action responding to frequency deviation. As the frequency error accumulates, the BESS injects increasing active power to counteract the imbalance. Although the magnitude of injected power is relatively small due to the simplified system model, its impact on frequency and voltage recovery is evident.

This result demonstrates the principle that even modest active power support, when properly coordinated with reactive compensation, can significantly improve post-disturbance voltage recovery behavior.

Discussion of Results in Relation to IEEE Expectations

The simulation results confirm that STATCOM-only compensation, while effective in providing reactive power support, exhibits slower voltage recovery under disturbances involving active power imbalance. This aligns with findings in existing literature and reflects the inherent limitations of reactive-only voltage support devices.

The coordinated STATCOM-BESS strategy achieves faster voltage recovery and reduced voltage nadir depth by addressing both reactive and active power deficiencies. The improved performance observed in the coordinated case is consistent with IEEE power-quality expectations, which emphasize not only voltage magnitude but also recovery behavior following short-duration disturbances.

Furthermore, the results demonstrate that coordinated control strategies offer a practical and effective solution for enhancing voltage recovery in modern power systems, particularly under conditions of

sudden load variation. The IEEE-compliant framing of the assessment ensures that the observed improvements are meaningful, verifiable, and relevant to real-world power-quality evaluation.

Conclusion and Recommendations

Conclusion

This study investigated voltage recovery enhancement in an electric power system using coordinated control of a Static Synchronous Compensator (STATCOM) and a Battery Energy Storage System (BESS), with assessment framed in accordance with IEEE power-quality principles. A MATLAB-based simulation model was developed to compare the performance of STATCOM-only compensation and coordinated STATCOM–BESS operation under a sudden load increase disturbance.

The simulation results demonstrate that STATCOM-only compensation, while effective in providing reactive power support, exhibits slower voltage recovery following the disturbance. The absence of active power support results in a deeper voltage nadir and delayed recovery, particularly under conditions involving active power imbalance and frequency deviation.

In contrast, the coordinated STATCOM-BESS strategy achieves improved voltage recovery performance. By combining fast reactive power compensation from the STATCOM with active power injection from the BESS, the coordinated system reduces voltage dip severity and accelerates post-disturbance recovery. The inclusion of BESS support also improves system frequency response, highlighting the interdependence between voltage and frequency dynamics in modern power systems.

Overall, the results confirm that coordinated STATCOM–BESS operation provides a more effective and robust solution for voltage recovery enhancement compared to reactive-only compensation. The observed behavior aligns with IEEE expectations for acceptable voltage recovery following short-duration disturbances, demonstrating the relevance and practicality of the proposed approach.

Recommendations

Based on the findings of this study, the following recommendations are proposed:

1. Adoption of Coordinated Compensation Strategies
   Power system operators and planners should consider coordinated STATCOM-BESS control schemes for networks experiencing frequent load variations or voltage recovery challenges, as such coordination offers superior dynamic performance compared to STATCOM-only solutions.
2. Integration of Energy Storage into Voltage Support Planning
   Energy storage systems should be incorporated into voltage support and power-quality planning frameworks, particularly in systems with reduced inertia or high penetration of power-electronic-interfaced loads and generation.
3. IEEE-Based Performance Evaluation
   Future voltage recovery assessments should explicitly adopt IEEE-recommended definitions, indices, and evaluation methods to ensure consistency, comparability, and practical relevance of results.
4. Extension to Detailed System Models
   Further studies should employ multi-bus power system models with detailed network parameters to evaluate coordinated STATCOM-BESS performance under more complex and realistic operating conditions.

5. Investigation of Additional Disturbance Scenarios
   Future research should examine the effectiveness of coordinated compensation under a wider range of disturbances, including short-circuit faults, renewable generation variability, and network reconfiguration events.
6. Inclusion of Practical BESS Constraints
   Advanced models should incorporate battery state-of-charge limits, energy capacity constraints, and degradation effects to better reflect real-world BESS operation and long-term performance.

Contribution to Knowledge

This study contributes to the body of knowledge in power system stability and power quality by providing a simplified yet IEEE-aligned assessment of voltage recovery enhancement using coordinated STATCOM and BESS control. It demonstrates, through a reproducible simulation framework, how active and reactive power support can be effectively coordinated to improve post-disturbance voltage behavior.

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