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A Review Paper on Battery Energy Storage System to Stabilize Transient Voltage and Frequency and Enhance Power Export Capability

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Abstract-

The increasing penetration of power export corridors and renewable generation has intensified concerns related to transient voltage and frequency stability in large-scale interconnected power systems. To address these challenges, extensive research has been reported on the application of Battery Energy Storage Systems (BESS) and Flexible AC Transmission System (FACTS) devices such as Static Synchronous Compensators (STATCOM). This paper presents a comprehensive review of existing studies focusing on the role of BESS and STATCOM in improving transient stability performance and enhancing power transfer capability between interconnected transmission networks. Particular emphasis is placed on control strategies adopted for BESS, including proportional–integral (PI), PI-lead, and lead–lag controllers, and their effectiveness in maintaining voltage and frequency regulation within permissible battery state-of-charge limits. Reported investigations based on benchmark transmission networks, including equivalent large-scale grids, are analyzed in the context of grid code compliance under various temporary and permanent fault conditions. Additionally, the impact of sequential disturbance events and increased power export levels on system stability is discussed. The comparative assessment highlights that BESS can provide effective support during severe disturbances, especially under scenarios involving reduced availability of reactive power compensation devices such as STATCOM. Furthermore, literature indicates that advanced control schemes for BESS exhibit superior transient response characteristics compared to conventional control approaches. The review identifies key research gaps and motivates further detailed simulation-based investigations for coordinated stability enhancement in modern power systems.

Key Words: optics, photonics, light, lasers, stencils, journals

1.INTRODUCTION

The operation of contemporary power transmission systems has become increasingly challenging due to the continuous growth in electricity demand and the large-scale integration of renewable energy sources. The transition from traditional vertically integrated utilities to deregulated and market-driven power systems has significantly altered power flow patterns, introducing additional complexity in system planning and real-time operation. Modern transmission networks are larger, more interconnected, and subject to frequent operating condition changes, making the maintenance of stability and reliability a critical concern for system operators.

Power systems are routinely exposed to a wide range of disturbances, including small-signal variations as well as severe transient events caused by faults or equipment outages. In deregulated electricity markets, market-based dispatch and cross-border power exchanges often lead to unpredictable power flow directions and magnitudes. Such unplanned transfers can result in transmission line congestion and heightened vulnerability to instability, particularly during faulty operating conditions.

The geographical separation between renewable energy generation sites and major load centers further exacerbates these challenges. Large-scale wind and solar installations are typically located in remote areas due to land availability and resource potential, necessitating long-distance bulk power transmission. Consequently, ensuring compliance with reliability standards such as the (N–1) contingency criterion while maximizing utilization of existing transmission assets has become a primary objective for transmission system operators.

System disturbances, whether temporary or permanent, inevitably induce oscillatory behavior in generator rotor angles, voltage magnitudes, and system frequency. Flexible AC Transmission System (FACTS) devices have been widely reported in the literature as effective tools for enhancing transient stability and improving controllability of power flows in stressed transmission networks. Among various FACTS technologies, the Static Synchronous Compensator (STATCOM) has received considerable attention due to its fast dynamic response, superior reactive power support capability, and effectiveness in mitigating voltage dips during fault events. Numerous studies highlight the ability of STATCOMs to improve voltage recovery, increase power transfer capability, and damp inter-area oscillations more efficiently than conventional reactive compensation devices.

In parallel, Battery Energy Storage Systems (BESS) have emerged as a versatile solution for addressing frequency regulation challenges associated with high renewable penetration. Unlike STATCOMs, which primarily provide reactive power support, BESS can actively exchange real power with the grid, enabling effective frequency stabilization, smoothing renewable power fluctuations, and enhancement of transient stability. Prior investigations have demonstrated that BESS-based control schemes can outperform conventional power system stabilizers and, in certain applications, offer superior damping characteristics compared to purely reactive compensation devices. Coordinated operation of BESS with STATCOMs or other energy storage technologies has also been reported to further improve system performance under dynamic operating conditions.

Despite extensive research on transient stability improvement and oscillation damping using BESS, its role in enhancing power transfer capability across interconnected transmission systems remains relatively underexplored. Recent studies suggest that energy storage can contribute to congestion mitigation, defer transmission expansion, and support stable power export during severe disturbances. However, many existing works focus primarily on either voltage or frequency regulation, without addressing their simultaneous control in large, interconnected networks.

A critical limitation identified in the literature is the frequent assumption of constant battery state of charge (SOC), which does not reflect realistic operational constraints. Several studies rely on simple proportional–integral (PI) control strategies and neglect SOC management or deadband implementation, potentially leading to excessive battery cycling and reduced system robustness. Investigations involving active or reactive power prioritization are often limited to isolated or small-scale systems, while comprehensive analyses for large, interconnected grids remain scarce. Furthermore, comparative assessments between STATCOM and BESS under identical operating conditions, particularly during permanent faults involving coupled voltage and frequency stability issues, are limited.

Based on these observations, existing literature reveals notable gaps in coordinated voltage–frequency regulation, SOC-aware BESS control, and systematic comparison of STATCOM and BESS for enhancing power transfer capability between interconnected regions. Addressing these gaps is essential for developing reliable control strategies suitable for future power systems with high renewable penetration.

Accordingly, this paper presents a critical review and comparative assessment of STATCOM and BESS applications for improving transient stability and power export capability in interconnected transmission networks. The review examines reported studies considering various disturbance scenarios, including temporary and permanent faults as well as line outages, within the framework of established grid code requirements. Attention is given to control strategies capable of maintaining voltage and frequency stability simultaneously while respecting operational constraints of energy storage systems.

The key contributions highlighted in the reviewed literature include comparative evaluation of STATCOM and BESS for stability enhancement, investigation of advanced BESS control approaches beyond conventional PI regulation, and assessment of system resilience under closely spaced disturbance events. These aspects provide valuable insights into preventing cascading failures and enhancing operational security in large-scale power systems.

2.LITERATURE REVIEW

Zhai & Bu (2024) – ICEPET Conference

Haoran Zhai and Jing Bu, Proceedings of the 3rd International Conference on Energy, Power and Electrical Technology (ICEPET 2024), Chengdu, China.

The authors investigated power control challenges in echelon Battery Energy Storage Systems (BESS) arising from heterogeneous response times of second-life battery modules. To overcome delayed power dispatch during frequency regulation in wind–storage systems, they proposed an Adaptive Variational Mode Decomposition (AVMD)-based strategy. The grid power command is decomposed into intrinsic mode functions and reassigned according to module dynamics, allowing faster modules to respond to high-frequency components. Simulation results demonstrated improved frequency regulation performance and reduced response lag, indicating the feasibility of utilizing retired EV batteries in grid-support applications.

Liu et al. (2024) – IEEE EI2 Conference

Xianzhuo Liu, Jiale Liu, Bo Peng, and Hao Chen, Proceedings of the IEEE 8th Conference on Energy Internet and Energy System Integration (EI2 2024), Shenyang, China.

This study focused on interoperability issues in large-scale BESS by applying IEC 61850 object-oriented information modeling. The authors analyzed BESS architecture and battery management system hierarchies to identify essential monitoring and control parameters. Using IEC 61850, a standardized information model was developed to enable seamless data exchange across heterogeneous platforms. Implementation on a representative BESS showed enhanced communication consistency, simplified system integration, and improved operational reliability, highlighting the importance of standardized modeling for future smart grids.

Bonatto et al. (2024) – IEEE URUCON

Alexa B. Bonatto, Benedito D. Bonatto, Gabriel F. Torrezan, Ubiratan F. Castellano, Luiz C. P. Da Silva, and Antonio C. Z. De Souza,

Proceedings of IEEE URUCON 2024, Montevideo, Uruguay.

The authors presented a real-world case study on integrating photovoltaic generation with a BESS at the UNIFEI university campus in Brazil. Using HOMER software, the system was optimized under a time-of-use tariff structure to reduce electricity costs through energy shifting. The study demonstrated that charging batteries during low-cost periods using solar energy and discharging during peak demand significantly reduced energy expenses and demand charges. The work highlights the economic and environmental benefits of PV-BESS systems for institutional energy sustainability.

Okafor et al. (2025) – SAUPEC Conference

Chukwuemeka E. Okafor, Azeez O. Olasoji, Komla Folly, and D.T.O. Oyedokun,

Proceedings of the 33rd Southern African Universities Power Engineering Conference (SAUPEC 2025), Pretoria, South Africa.

This paper examined the role of BESS in improving voltage stability in power systems with high renewable penetration. By injecting both active and reactive power at critical buses, the BESS enhanced voltage profiles and increased load margins across the network. Simulation results showed voltage improvement at more than 90% of buses, validating BESS as an effective voltage support device beyond traditional energy arbitrage applications.

Sun et al. (2024) – IEEE IPEMC-ECCE Asia

Sun, Jiao, and Li, IEEE 10th International Power Electronics and Motion Control Conference (IPEMC-ECCE Asia 2024), Chengdu, China.

The authors analyzed frequency-domain characteristics of modular multilevel converters integrated with BESS using Harmonic State-Space modeling. Their impedance-based analysis revealed improved harmonic suppression and system stability when energy storage is embedded within MMC structures. The study provides valuable insights for designing MMC-BESS systems in HVDC and renewable-rich power networks.

Yang et al. (2018) – Protection and Control of Modern Power Systems

Yang, Li, Li, and Chen, Protection and Control of Modern Power Systems, Springer.

This work proposed a hierarchical distributed control strategy for decentralized BESS in DC microgrids. A two-layer control framework combined local power regulation with a consensus-based secondary control to achieve state-of-charge balancing and coordinated power sharing. Simulation results confirmed improved reliability, scalability, and autonomy without reliance on a central controller.

Tang et al. (2023) – IEEE ICUS Conference
Tang, An, Zhang, Sun, Lu, and Feng, Proceedings of the IEEE International Conference on Unmanned Systems (ICUS 2023).
The authors introduced a fixed-time distributed secondary control strategy for BESS in DC microgrids. The method ensured rapid convergence of voltage and energy coordination using fixed-time consensus theory validated through Lyapunov stability analysis. The decentralized approach improved robustness and suitability for time-critical applications such as autonomous and mission-critical power systems.

Abdulrahman et al. (2024) – ICAEE Conference
Ali Abdulrahman, Yacine Chama, Zakaria Chama, Mahdi Ben Ghanem, Abderrahim Sadik, and Mustafa Boussaboun, Proceedings of the International Conference on Advanced Electrical Engineering (ICAEE 2024).
This study evaluated the integration of a hybrid PV–BESS system into a low-voltage grid using MATLAB/Simulink. The authors demonstrated that BESS enhances voltage and frequency stability, supports peak shaving, and ensures reliable operation during islanding conditions. The results emphasize the importance of hybrid PV-BESS systems in improving energy resilience in decentralized networks.

3.ADVANTAGES

The deployment of Battery Energy Storage Systems (BESS) within modern power networks offers multiple technical and operational benefits. One of the primary advantages is the rapid response capability to transient disturbances, which helps maintain system voltage and frequency within prescribed limits. This contributes to enhanced reliability and minimizes the likelihood of interruptions or cascading failures.
BESS also supports increased power transfer capacity, enabling more stable and efficient delivery of electricity, particularly from variable renewable energy sources such as solar photovoltaic and wind generation. Additionally, BESS contributes to improved power quality by mitigating harmonic distortions, reducing voltage flicker, and damping oscillations.
From a strategic perspective, the integration of energy storage can defer or reduce the need for traditional grid infrastructure upgrades, providing a cost-effective and environmentally sustainable alternative. The modularity of BESS systems further allows for scalable deployment, ensuring flexibility in meeting application-specific energy and power requirements. Overall, these capabilities make BESS a critical tool in enhancing grid stability, reliability, and renewable energy integration.

4.HARDWARE & SOFTWARE REQUIREMENTS

Hardware's-
1) Processor: Intel Core i5 or AMD Ryzen 5 (or equivalent)
2) Memory: 8 GB RAM
3) Graphics: NVIDIA GeForce GTX 1660 or higher, or equivalent GPU with CUDA support
4) Storage: 256 GB SSD or larger for high-speed data access

Software's-
1) Operating System: Windows 10 or 11
2) Simulation Environment: MATLAB & Simulink
3) Required Toolboxes: Simulink, Simscape

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