A Review on Voltage Sag Assessment and Mitigation in Distribution Systems

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Abstract: The increasing incorporation of DERs (Distributed Energy Resources) in Radial Distribution Networks (RDNs) has raised power quality issues, especially voltage sag, swell, and harmonic distortion. The effectiveness of conventional voltage regulation equipment has been proven to be limited in addressing rapid and random voltage fluctuations in DER-dominated systems. Although the Dynamic Voltage Restorer (DVR) has been proven to provide better performance in voltage regulation through better series compensation, its effectiveness is still limited by its energy storage and static control system capabilities. Although various researchers have explored and discussed DVR and BESS technology in isolation, there has been a lack of a coordinated and multi-objective framework. In this regard, this thesis has proposed an integrated framework of DVR and BESS (Battery Energy Storage System) for voltage stability improvement in radial distribution systems through the development of two metaheuristic optimization algorithms: Self-Adaptive Learning Osprey Optimization Algorithm and Hybrid Golden Jackal-Hippopotamus Algorithm. In addition, the Self-Adaptive Learning Osprey Optimization Algorithm (S-OOA) has been applied for real-time tuning of the proportional and integral parameters of the DVR through real-time simulations using MATLAB-Simulink on a 14-bus radial distribution feeder system, achieving voltage stability improvement on the load side and achieving voltage values of 0.95-1.05 per unit according to the IEEE 1159 standard within half a cycle. In addition, the power quality index was achieved at 0.95, outperforming other algorithms such as Coati, Crayfish, Pelican, and Osprey Optimization Algorithm. Furthermore, the effectiveness of the proposed system has been proven through comparative analysis of recent literature on voltage stability improvement and harmonic distortion mitigation. The proposed system has been proven to provide better performance in power quality management in modern power systems dominated by renewable energy sources and variability.

Keywords: *Dynamic Voltage Restorer; Battery Energy Storage System; Radial Distribution Network; Metaheuristic Optimization; Power Quality.*

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I. INTRODUCTION

The increasing penetration of Distributed Energy Resources (DERs) in modern power distribution systems has introduced significant power quality challenges, particularly voltage sag in radial distribution networks. Conventional voltage regulation methods are often inadequate for mitigating fast and dynamic disturbances, necessitating the use of advanced compensation techniques.

The Dynamic Voltage Restorer (DVR) has emerged as an effective solution for voltage sag and swell mitigation; however, its performance is limited by control strategies and energy storage constraints. Integrating Battery Energy Storage Systems (BESS) with DVR enhances its capability to provide sustained and reliable voltage support under varying operating conditions.

In addition, the application of metaheuristic optimization techniques enables efficient controller tuning and optimal system design in complex, multi-objective environments. This paper presents a comprehensive review of voltage sag assessment and mitigation strategies, highlighting existing limitations and proposing an integrated DVR-BESS framework optimized using advanced algorithms to improve voltage stability and overall power quality in distribution systems.

II. EARLY ANALYTICAL AND SENSITIVITY-BASED APPROACHES

The foundational works of Schmill (1965) and Bae (1978) are constrained by simplified load models that assume uniform or known distribution, and by their restriction to steady-state, single-objective analysis. Both studies were designed for single-objective loss minimisation without

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provision for dynamic load variation, discrete capacitor sizing, or economic multi-period analysis. Similarly, Grainger and Lee (1982) improved capacitor modelling accuracy but was limited to radial feeders with fixed load configurations and did not address distributed generation or real-time operational constraints. Bunch et al. (1982) proposed integrated reactive power and voltage control but predated the computational resources needed for large-scale simulation, leaving the framework largely conceptual with limited practical validation at the time. These works collectively lack the ability to model harmonics, unbalanced loads, inverter-based DERs, or the stochastic nature of modern distribution systems.

III. AI AND METAHEURISTIC OPTIMISATION FOR CAPACITOR PLACEMENT

While Boone and Chiang (1993) pioneered genetic algorithm application to capacitor placement, the study was limited to small radial test systems and did not account for multi-phase unbalance, harmonics, or DER interaction. Venkatesh and Ranjan (2006) addressed uncertainties through fuzzy-evolutionary programming but assumed deterministic load profiles and excluded voltage stability indices from the objective function. Huang et al. (2008) and Pires (2009) introduced multi-objective treatment but validated their methods primarily on simplified IEEE standard feeders, without dynamic load profiles or renewable penetration. Studies by El-Fergany and Abdelaziz (2014), Abdelaziz (2016), and Injeti (2015) focused on shunt capacitor optimisation in isolation, without co-optimisation of distributed generation placement or active compensation devices such as DVRs and BESS. Furthermore, Rajendran and Narayanan (2018) and Jayabarathi et al. (2022) addressed joint DG and capacitor placement but did not consider power quality under fault-induced voltage disturbances, the primary design scenario of the present thesis.

IV. DVR CONTROL AND COMPENSATION STRATEGIES

Despite significant advances in DVR control design, several key limitations persist across the existing literature. Early studies on DVR deployment were often restricted to specific industrial or test installations, limiting the generalisability of their findings to broader network topologies. Fitzer et al. (2004) addressed voltage sag detection but did not evaluate detection performance under multi-disturbance conditions including simultaneous harmonics and unbalance. Haghifam and Malik (2007) and Kanjiya et al. (2013) advanced intelligent planning and SRF control respectively, but neither integrated energy storage or addressed the problem of sustained compensation during deep sags lasting multiple cycles. Khalghani et al. (2014) used bi-objective PSO for DVR tuning but validated the approach on a simplified single-phase model and did not extend to three-phase unbalanced network scenarios. Khooban and Javidan (2016) proposed the OBSEL emotional learning controller but focused exclusively on DVR performance without considering the BESS sizing and placement problem. Naidu et al. (2020, 2021) and Metwally et al. (2022) demonstrated robust optimisation-based DVR control but treated the DVR in isolation, without energy storage integration, optimal placement analysis, or radial feeder multi-bus assessment. Rawa et al. (2023), Goud et al. (2023), and Arya et al. (2024) represent the current state-of-the-art in DVR control optimisation, but none simultaneously optimises the DVR controller and the storage subsystem under realistic network conditions using a purpose-designed hybrid algorithm.

V. BATTERY ENERGY STORAGE SYSTEM MODELLING AND PLACEMENT

Studies on BESS placement and modelling face limitations at both the modelling fidelity and optimisation application layers. Padhee et al. (2020) developed accurate technology-specific BESS models but targeted large-scale transmission networks, leaving distribution-level application under-explored. Zhu et al. (2019) applied the Cross-Entropy method to BESS placement for transient voltage stability on a transmission benchmark, but the approach was not applied to distribution feeders where DVR-BESS interaction is the operative concern. Gui et al. (2019) introduced degradation-aware modelling but focused on wind farm dispatch rather than reactive power or voltage compensation. Cassano et al. (2024) refined BESS scheduling via SOC-dependent dynamic power constraints but concentrated on hydro-BESS hybrid scheduling, with limited direct relevance to DVR energy support in distribution networks. Habib et al. (2018) identified BESS as a valuable communication-failure contingency resource but provided only a conceptual framework without quantitative placement optimisation.

VI. VOLTAGE STABILITY ANALYSIS AND DISTRIBUTED COMPENSATION

Voltage stability indices proposed by Chakravorty and Das (2001) and the three-phase unbalanced models of Carpinelli et al. (2005) offer valuable analytical tools but were formulated for offline planning, lacking the real-time update capability required for dynamic DVR placement in actively managed networks. Zeinalzadeh et al. (2019) addressed combined DSTATCOM and capacitor placement using MOPSO but did not account for time-varying DER generation profiles or harmonic interaction. Kamel et al. (2019) proposed a simple analytical approach to capacitor sizing but acknowledged its limitation to well-characterised loading scenarios, making it unsuitable for systems with high renewable penetration and stochastic load dynamics.

VII. SMART GRID DISTRIBUTED AND DECENTRALISED VOLTAGE CONTROL

A recurring limitation in the distributed voltage control literature is the assumption of reliable, low-latency communication. Farag and El-Saadany (2013) assumed always-available communication for the cooperative DER protocol, which is unrealistic in many distribution environments. Bolognani et al. (2015) and Qu and Li (2020) provided formal convergence guarantees but relied on idealised network models and did not address the impact of communication failures or cyber events. Dall'Anese et al. (2013) and Maknouninejad and Qu (2014) developed

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distributed OPF frameworks for microgrids but assumed synchronous agent updates and full knowledge of network topology, conditions rarely met in large distribution networks. Liu et al. (2017) proposed a hybrid local-distributed voltage control strategy but acknowledged scalability constraints when communication is intermittent. Magnússon et al. (2020) and Ortmann et al. (2020) advanced communication-resilient distributed control methods but focused on reactive power-based voltage regulation, without provision for series compensation devices such as DVRs. Sarker et al. (2022) highlighted cyber-event vulnerabilities in distributed active power curtailment strategies, while Vosughi et al. (2022) identified broader cyber-physical threats to DER-integrated systems, limitations that underscore the practical advantage of the locally autonomous DVR-BESS compensation approach in this thesis.

VIII. POWER QUALITY SURVEYS AND RENEWABLE INTEGRATION STUDIES

Review and survey papers such as Mahela and Shaik (2016), Gandoman et al. (2018), Sun et al. (2019), and Antoniadou-Plytaria et al. (2017) provide excellent taxonomic and conceptual frameworks but are inherently restricted by their survey nature, they synthesise existing knowledge without contributing new computational tools, experimental results, or validated system designs. Howell et al. (2017) proposed holonic multi-agent architectures for DER management but remained at the conceptual level without field implementation or controlled simulation study. Sarinuthu et al. (2016) reviewed OLTC-based voltage management for RES integration but noted the inherent mechanical wear and limited switching frequency of OLTCs as a fundamental constraint, one that DVR-based compensation elegantly circumvents. Benali et al. (2018) validated DVR-based compensation for hybrid wind–solar systems but stopped short of comprehensive multi-disturbance testing and did not address the BESS sizing and placement problem. Dudi and Sharma (2024) provided detailed DG and ESS integration analysis for RDNs but focused on economic and reliability metrics rather than transient power quality compensation performance.

IX. ADAPTIVE PROTECTION AND RELAY COORDINATION STUDIES

Protection studies such as those by Chaitusaney and Yokoyama (2008), Rajaei et al. (2014), Zhan et al. (2016), and Fani et al. (2018) address DG-induced miscoordination comprehensively but treat protection in isolation from voltage quality. The power quality and protection interaction is rarely modelled simultaneously, creating a conceptual gap that the combined DVR-BESS system in the present thesis begins to bridge by providing voltage support that itself reduces fault current escalation. Barra et al. (2020), Lin et al. (2019), and Strezoski et al. (2020) proposed adaptive protection methods but their validation was largely simulation-based on small test systems, and they did not evaluate the effect of DVR or BESS presence on relay coordination. Reiz and Leite (2022) and Bisheh et al. (2023) advanced DER-inclusive protection frameworks but their scope remained restricted to coordination optimisation without co-consideration of power quality enhancement devices.

X. HYBRID COMPENSATION AND MULTI-DEVICE COORDINATION

Studies on advanced UPQC configurations by Thentral et al. (2022), Heenkenda et al. (2023), and Khosravi et al. (2022) demonstrate the technical superiority of integrated shunt-series compensation but are constrained by the cost and complexity of full UPQC hardware. DVR-only systems remain more practical for targeted voltage sag and swell compensation in industrial and commercial settings. Balasundar et al. (2023) advanced adaptive LMS-based control for DSTATCOM but focused on EV charging station applications, which differ significantly in disturbance profile from the general distribution network scenario of this thesis. Rao et al. (2023) combined SPV and passive filter placement using ARO on the IEEE 33-bus system, achieving significant THD reduction and loss improvement, but did not address voltage sag and swell compensation, the primary mandate of DVR systems. Salimon et al. (2023) presented DG penetration analysis with novel voltage stability indices but did not include active compensation devices, leaving voltage disturbance mitigation unaddressed. Mattar et al. (2024) validated a JFS-tuned PI-controlled DVR under industrial nonlinear load conditions but reported results only for single-bus scenarios without multi-bus network analysis or BESS integration.

XI. CONCLUSION

Across the reviewed literature, a consistent cluster of limitations emerges that defines the research gap addressed by the present thesis: (a) most DVR studies treat the compensator in isolation from energy storage, leaving the sustained and energy-buffered compensation problem unsolved; (b) BESS placement research rarely considers the specific operational requirements of DVR energy support, focusing instead on frequency regulation, economic dispatch, or generalised stability improvement; (c) metaheuristic optimisation has been applied to either controller tuning or device placement, but rarely to both in an integrated co-optimisation framework; (d) multi-disturbance, multi-phase simulation testing under realistic polluted grid conditions remains uncommon; and (e) the convergence speed and algorithmic novelty of the chosen optimisers have often been secondary considerations. The present thesis is designed specifically to address each of these gaps, providing a validated, integrated DVR-BESS system with novel algorithm-based control optimisation and placement, tested comprehensively under the full spectrum of power quality disturbances found in modern radial distribution networks.

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