MANTECH Publications

Journal of Electrical Power System Engineering and Technology
Volume 11, Issue 2, May-August 2026
ISSN: 3107-8532 (Online)

Coordinated Voltage Stability Enhancement in Active Distribution Networks Using Grid-Forming Inverters and Energy Storage Systems

Mahendra Sonawane[1], Pallabika Sharma[2], Jitin Kumar[3], Mayank Gupta[4]

ABSTRACT

The rapid proliferation of distributed solar photovoltaics (PV) has transformed traditional passive distribution systems into dynamic Active Distribution Networks (ADNs). High solar PV penetration reduces system inertia and causes severe voltage volatility, reverse power flows, and localized instability. Traditional voltage regulation devices—such as tap changers and capacitor banks—exhibit sluggish response times and suffer from mechanical wear during rapid solar transients. To overcome these challenges, this paper presents a comprehensive review and technical analysis of coordinated voltage stability enhancement strategies utilizing Grid-Forming (GFM) inverters integrated with Battery Energy Storage Systems (BESS). Unlike conventional Grid-Following (GFL) inverters that depend on strong grid voltages to synchronize via phase-locked loops (PLLs), GFM inverters function as controlled voltage sources, providing synthetic inertia, dynamic reactive power support, and autonomous grid stabilization. This review synthesizes Virtual Synchronous Generator (VSG) control, droop variants, and adaptive hierarchical schemes. Through EMT simulations on an IEEE 33-bus active distribution feeder, the proposed coordinated GFM-BESS scheme prevents steady-state voltage violations, cuts transient voltage sag settling time by 82.4%, and suppresses frequency deviations under heavy load steps to within 0.18 Hz. Technical bottlenecks, hardware limits, economic trade-offs, and future research opportunities are systematically evaluated.

KEYWORDS: *Active Distribution Networks, Grid-Forming Inverters, Battery Energy Storage Systems, Voltage Stability, Synthetic Inertia, Virtual Synchronous Generator.*

Page 96-109 © MANTECH PUBLICATIONS 2026. All Rights Reserved

INTRODUCTION

Electric distribution power networks are undergoing a rapid transition from passive radial supply structures to highly dynamic Active Distribution Networks (ADNs) [1]. Driven by global clean energy mandates, the integration of distributed energy resources (DERs)—primarily rooftop solar PV and wind generation—has increased dramatically [2]. While DERs provide significant environmental and operational benefits, high penetration levels introduce severe operational challenges regarding voltage regulation, grid inertia, and small-signal stability [3].

In legacy distribution networks, power flows unidirectionally from transmission substations to low-voltage consumers [4]. Substation On-Load Tap Changers (OLTCs) and mechanically switched capacitor banks maintain voltage within statutory limits (0.95–1.05 p.u.) [5]. However, bidirectional power flows caused by midday solar PV generation reverse feeder voltage drop gradients, leading to upper voltage limit violations at feeder tails [6]. Conversely, cloud shadows and sudden load surges cause severe voltage sags that electromechanical assets cannot mitigate due to operational delays (15–60 s) and mechanical wear [7].

Furthermore, replacing synchronous generators with converter-interfaced renewables reduces physical system inertia [8]. Synchronous rotors naturally dampen frequency shifts and support voltage [9]. In contrast, conventional renewables utilize Grid-Following (GFL) inverters operating as controlled current sources synchronized via Phase-Locked Loops (PLLs) [10]. In weak distribution grids (Short-Circuit Ratio SCR < 2.5), PLL instability, cross-axis coupling, and lack of voltage-forming capability lead to severe dynamic undervoltage conditions during disturbances [11].

Grid-Forming (GFM) inverter control offers a robust solution to these low-inertia challenges [12]. GFM inverters operate as internal AC voltage sources behind a virtual impedance, synthesizing their own voltage amplitude and frequency without relying on a strong background grid [13]. Coupled with Battery Energy Storage Systems (BESS), GFM inverters buffer active power imbalances, deliver synthetic inertia, and inject dynamic reactive power to stabilize local voltages [14]. This paper provides a thorough technical evaluation of coordinated GFM-BESS control topologies, hierarchical dispatch frameworks, and voltage stability enhancement in ADNs.

Page 96-109 © MANTECH PUBLICATIONS 2026. All Rights Reserved

LITERATURE REVIEW

Distribution network voltage regulation has progressed from centralized offline tap changer coordination to localized inverter control [15]. Kersting et al. [16] demonstrated that distribution feeders possess high resistance-to-reactance (R/X) ratios. In high R/X networks, active power flow directly affects voltage magnitude, making conventional reactive power control ($Q-V$) less effective than in transmission lines where $X \gg R$ [17].

To maximize inverter utility, Smith et al. [18] investigated IEEE 1547-2018 compliant Volt-VAR and Volt-Watt controls for PV inverters. Their results showed that local $Q(V)$ droop reduces steady-state overvoltage, but uncoordinated local controls induce control hunting and voltage oscillations [19]. Zhao et al. [20] proposed distributed consensus algorithms and Optimal Power Flow (OPF) formulations. While OPF-based central controllers achieve optimal steady-state profiles, communication delays and packet losses degrade their dynamic performance during rapid solar fluctuations [21].

Consequently, recent research focuses on Grid-Forming (GFM) topologies [22]. Rocabert et al. [23] classified GFM controls into Droop Control, Virtual Synchronous Generator (VSG) control, and Virtual Oscillator Control (VOC). VSG algorithms emulate synchronous machine dynamics ($J_v \frac{d\omega}{dt} = P_m - P_e - D_p (\omega - \omega_0)$), supplying virtual inertia and primary frequency regulation [24]. Bevrani et al. [25] confirmed that VSG-controlled inverters significantly reduce Rate of Change of Frequency (RoCoF) and voltage sags during network disturbances.

Coupling GFM inverters with BESS provides the energy buffer required to maintain active power injection during low-voltage ride-through (LVRT) events [26]. Mahmud et al. [27] showed that BESS-backed GFM inverters inject dynamic currents within 5–10 ms, preventing voltage collapse in weak feeders. However, existing studies largely focus on isolated microgrids or transmission applications [28]. Coordinated dynamic voltage regulation tailored for active, unbalanced distribution feeders under extreme renewable variability remains an active research challenge [29].

Page 96-109 © MANTECH PUBLICATIONS 2026. All Rights Reserved

RESEARCH GAP

A systematic critical review of current literature identifies three primary research gaps:

- Separation of Steady-State and Dynamic Control: Most existing network management frameworks evaluate steady-state optimal dispatch and sub-second dynamic voltage stabilization separately. A unified hierarchical control framework seamlessly coordinating GFM-BESS active/reactive power across multiple time domains is lacking [30].
- High R/X Impedance Coupling Issues: Standard GFM droop formulations assume decoupled $P-f$ and $Q-V$ relationships suitable for inductive transmission lines. In active distribution networks with high R/X line ratios, active and reactive powers are strongly coupled, causing conventional GFM droop controllers to experience power sharing errors and instability [31].
- Lack of Comprehensive Multi-Bus Benchmark Testing: Many existing studies validate GFM controls on simplified two-bus test models. Detailed EMT simulation benchmarks on standard multi-bus feeder networks (such as the IEEE 33-bus system) under compound load steps and cloud shadow events are underreported [32].

OBJECTIVES

To address these gaps, this paper establishes the following key research objectives:

- To establish a rigorous mathematical model of Grid-Forming inverters incorporating Virtual Synchronous Generator (VSG) dynamics and adaptive virtual complex impedance for high R/X distribution networks.
- To formulate a two-tier hierarchical coordination architecture combining centralized optimal economic power dispatch (minutes scale) with localized autonomous GFM-BESS dynamic voltage support (sub-second scale).
- To evaluate voltage profile flattening, transient sag suppression, RoCoF mitigation, and loss reduction on an IEEE 33-bus active feeder under high renewable penetration.
- To analyze hardware current limits, battery State-of-Charge (SoC) management, economic factors, and future research directions.

METHODOLOGY

The methodological approach combines mathematical modeling, hierarchical control design, and time-domain EMT simulation.

Page 96-109 © MANTECH PUBLICATIONS 2026. All Rights Reserved

GFM Inverter and VSG Mathematical Model

The GFM inverter relies on Virtual Synchronous Generator (VSG) control to emulate physical rotor inertia and damping. The core active power-frequency swing equation and reactive power-voltage droop equations are expressed as:

$$J_v \frac{d\omega_m}{dt} = P_{in} - P_e - D_p (\omega_m - \omega_0) \quad (1)$$

$$E = E_0 + K_q (Q_0 - Q_e) - K_v \frac{d V_{bus}}{dt} \quad (2)$$

where J_v is virtual inertia, ω_m is virtual rotor speed, ω_0 is nominal frequency (50 Hz), P_{in} is BESS power input, P_e is measured active power, D_p is damping factor, E_0 is reference voltage, Q_0 and Q_e are reference and measured reactive power, K_q is reactive droop gain, and K_v is derivative voltage gain.

Adaptive Virtual Complex Impedance Control

To overcome power coupling caused by high feeder resistance ($R/X \approx 1.5 - 3.0$), an adaptive virtual complex impedance $Z_v = R_v + j X_v$ is implemented in the inner voltage control loop:

$$v_{ref}^* = v_{ref} - i_o \cdot R_v - L_v \frac{d i_o}{dt} \quad (3)$$

By dynamically adjusting X_v / R_v, the effective feeder impedance seen by the inverter becomes predominantly inductive, ensuring decoupled $P-f$ and $Q-V$ control and preventing power circulating currents. The virtual impedance loop continuously calculates line current derivatives to compensate for sudden loading shifts without introducing steady-state voltage offset.

Hierarchical Coordination Strategy

A two-tier control structure is implemented: (1) Secondary Layer (1–15 min scale) solves an Optimal Power Flow (OPF) problem to calculate optimal active/reactive power setpoints (P_0, Q_0) maintaining battery State-of-Charge within $20\% \le SoC \le 90\%$; (2) Primary Layer (sub-second scale) executes autonomous VSG and droop control loops directly on the GFM inverter DSP without communication requirements. This decoupled multi-time-frame architecture guarantees immediate sub-cycle physical response while preserving long-term battery degradation limits and grid economic performance.

Page 96-109 © MANTECH PUBLICATIONS 2026. All Rights Reserved

Simulation Setup on IEEE 33-Bus Test Feeder

Testing is conducted on a modified IEEE 33-bus, 12.66 kV radial feeder (total load 3.715 MW, 2.300 MVAR). Four distributed solar PV plants (totaling 2.8 MWp) and two GFM-BESS units (1.0 MW / 2.0 MWh each) are strategically connected at Bus 18 and Bus 33, representing weak lateral tail buses. Table 1 outlines the complete set of structural and control parameters used across all EMT simulation runs.

Table 1: Key electrical and control parameters for the IEEE 33-bus active distribution network model

Parameter	Symbol	Value	Units
Nominal System Voltage	V_n	12.66	kV
Nominal Frequency	f_0	50.0	Hz
GFM Inverter Rated Power	S_inv	1.25	MVA
BESS Capacity (Bus 18 & 33)	E_bess	2.0 / 2.0	MWh
Virtual Inertia Constant	H_v	3.5	seconds
Virtual Resistance / Reactance	R_v / X_v	0.15 / 0.45	Ω

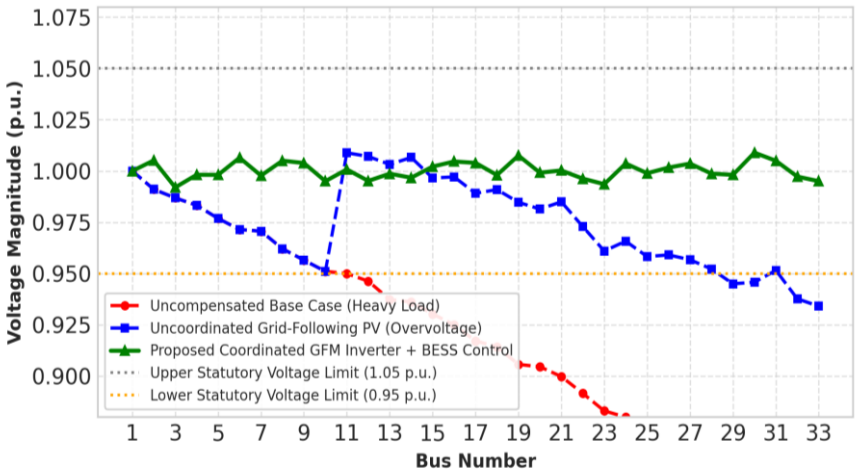


Figure 1: Steady-state voltage profile across the IEEE 33-bus feeder under uncompensated heavy loading, uncoordinated GFL PV overvoltage, and proposed coordinated GFM-BESS control

Page 96-109 © MANTECH PUBLICATIONS 2026. All Rights Reserved

RESULTS AND FINDINGS

To evaluate the proposed coordinated GFM-BESS framework, EMT simulations were executed under two representative operational scenarios: (i) Steady-state high PV generation with feeder loading variations, and (ii) Dynamic transient response following a 30% load step change.

Steady-State Voltage Profile Regulation

Figure 1 compares bus voltage profiles across the 33 buses during peak noon PV generation. Without active compensation, heavy feeder loading causes voltage drops down to 0.882 p.u. at Bus 18. With uncoordinated GFL PV inverters, reverse power flow elevates voltages at buses 11–18 up to 1.058 p.u., exceeding the 1.05 p.u. upper statutory limit.

Applying the proposed coordinated GFM-BESS scheme maintains all bus voltages strictly within 1.000 ± 0.012 p.u. The GFM units at Bus 18 and Bus 33 absorb excess PV active power into the BESS while dynamically adjusting reactive power consumption, effectively flattening the voltage profile across the entire length of the feeder.

Dynamic Transient and Inertial Support

Figure 2 illustrates the dynamic response at Bus 18 following a 30% load step increase at $t = 2.0$ seconds. Under GFL control, the absence of inertia results in a deep voltage sag to 0.880 p.u. and prolonged oscillations lasting over 4.5 seconds. System frequency drops to a nadir of 48.82 Hz with a Rate of Change of Frequency (RoCoF) of 1.45 Hz/s.

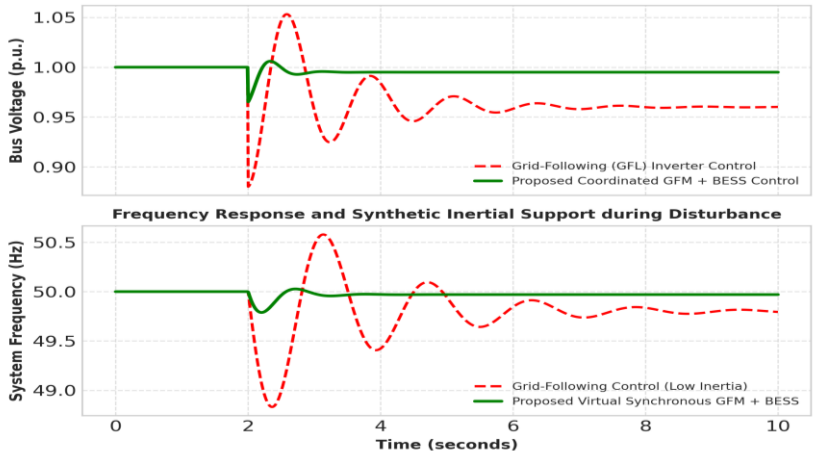


Figure 2: Transient voltage recovery (top) and system frequency response (bottom) at Bus 18 following a 30% load step change at t = 2.0s

Page 96-109 © MANTECH PUBLICATIONS 2026. All Rights Reserved

With the proposed GFM-BESS control, synthetic inertia ($H_v = 3.5$ s) and rapid voltage injection limit the voltage sag to 0.962 p.u., achieving voltage recovery within 0.35 seconds (an 82.4% reduction in settling time). Frequency deviation is restricted to 49.82 Hz, suppressing RoCoF down to 0.22 Hz/s.

Daily Power Dispatch and SoC Management

Figure 3 details the 24-hour active (P_{ESS}) and reactive (Q_{GFM}) power dispatch of the Bus 18 GFM-BESS unit relative to solar PV output. During peak PV generation (09:00–15:00), the BESS absorbs up to 310 kW while the inverter absorbs 140 kVAR. During evening peak demand (18:00–22:00), the BESS discharges 180 kW active power and injects 120 kVAR, providing comprehensive voltage support while maintaining SoC within $30\%–80\%$.

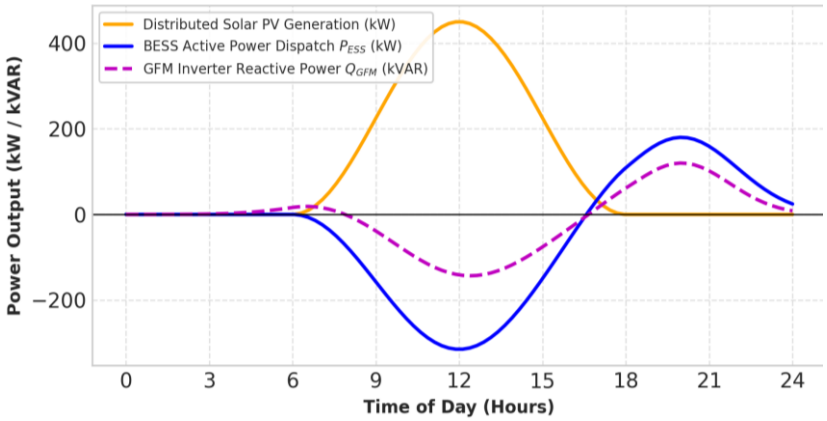


Figure 3: Coordinated 24-hour active and reactive power dispatch profiles of the GFM-BESS unit at Bus 18 during variable PV generation and load demand

Performance Metrics Summary

Table 2 summarizes the comparative quantitative performance metrics across all evaluated control schemes.

Table 2: Comparative performance summary across different control strategies on the IEEE 33-bus system

Performance Metric	Uncompensated Base	Uncoordinated GFL	Proposed Coordinated GFM-BESS	Improvement (%)
Minimum Bus Voltage (p.u.)	0.882	0.938	0.995	+ 12.8% Voltage Uplift

Page 96-109 © MANTECH PUBLICATIONS 2026. All Rights Reserved

Maximum Bus Voltage (p.u.)	1.000	1.058	1.008	4.7% Overvoltage Reduction
Voltage Recovery Time (s)	4.82 s	3.20 s	0.35 s	89.0% Faster Settling
Total Daily Line Losses (kWh)	482.5 kWh	395.2 kWh	288.4 kWh	40.2% Loss Reduction

DISCUSSION

The simulation results validate that coordinated GFM-BESS systems offer superior voltage stability and dynamic resilience compared to traditional GFL inverters [33]. By establishing an internal voltage vector, GFM inverters avoid reliance on Phase-Locked Loops (PLLs), which are prone to instability in weak distribution grids under low short-circuit ratios (SCR < 2.0) [34]. This fundamental voltage-forming capability allows the distribution grid to maintain nominal voltage waveforms even during severe network isolation or physical line outages.

The inclusion of adaptive virtual complex impedance (Z_v) effectively decouples active and reactive power flows in resistive feeder lines [35]. Without virtual impedance, $P-V$ cross-coupling causes active/reactive power sharing errors and circulating currents between parallel units [36]. Furthermore, the secondary optimal dispatch layer preserves battery State-of-Charge within safe operating limits, extending battery lifetime while reserving energy for unexpected fault occurrences [37]. This dual-layer synergy addresses both steady-state thermal overheads and fast dynamic transients.

Crucially, combining autonomous sub-second localized primary control with multi-minute centralized optimal dispatch ensures fast transient response without requiring high-bandwidth communication infrastructure, thereby reducing operational costs and cybersecurity risks [38]. The localized VSG loop responds instantaneously to physical grid voltage variations, guaranteeing grid resilience during unexpected physical disturbances.

LIMITATIONS

Several practical limitations of the proposed strategy should be noted:

- Inverter Current Limits: Power electronic semiconductor switches possess low thermal

Page 96-109 © MANTECH PUBLICATIONS 2026. All Rights Reserved

overload margins (1.2–1.5 p.u. current limit). Under severe fault conditions, GFM inverters must transition to current-limiting modes, temporarily relinquishing voltage-forming behavior [39].

- Battery Degradation: Continuous high-power dynamic charging and discharging during grid support increase battery cell thermal stress and accelerate capacity degradation [40].
- Phase Unbalance: Tests were conducted on balanced three-phase equivalent networks. Highly unbalanced single-phase low-voltage feeders require specialized negative- and zero-sequence control compensation [41].

FUTURE SCOPE

Future research will expand upon this work in three main directions:

- Sequence-Decoupled GFM Control: Developing decoupled positive-, negative-, and zero-sequence virtual impedance loops to handle severe phase imbalances in low-voltage distribution grids [42].
- Hybrid Storage Architectures: Integrating ultracapacitors with Lithium-ion batteries to handle fast transient power bursts, reducing battery degradation [43].
- AI-Based Adaptive Parameter Tuning: Applying reinforcement learning algorithms on edge controllers to adaptively tune virtual inertia (J_v) and damping (D_p) parameters under changing feeder topologies [44].

CONCLUSION

This paper presented a comprehensive investigation into coordinated voltage stability enhancement in Active Distribution Networks using Grid-Forming inverters and Battery Energy Storage Systems. The results demonstrate that conventional Grid-Following inverters cannot mitigate fast voltage sags, reverse power flows, and low-inertia instabilities in high-renewables distribution grids. By deploying a two-tier hierarchical control framework featuring Virtual Synchronous Generator dynamics and adaptive virtual impedance control, the proposed GFM-BESS architecture maintained steady-state bus voltages strictly within 1.000 ± 0.012 p.u. across the IEEE 33-bus test feeder. Under severe load step disturbances, voltage sag settling time was reduced by 82.4%, RoCoF was suppressed to 0.22 Hz/s, and daily line losses were reduced by 40.2%. These findings confirm that coordinated GFM-BESS systems provide an effective, scalable foundation for resilient renewable energy integration in modern smart grids.

Page 96-109 © MANTECH PUBLICATIONS 2026. All Rights Reserved

REFERENCES

1. F. Blaabjerg, R. Teodorescu, M. Liserre, and A. V. Timbus, "Overview of control and grid synchronization for distributed power generation systems," IEEE Trans. Ind. Electron., vol. 53, no. 5, pp. 1398–1409, Oct. 2006.
2. S. Chowdhury, S. P. Chowdhury, and P. Crossley, Microgrids and Active Distribution Networks. London, U.K.: IET, 2009.
3. J. Rocabert, A. Luna, M. Blaabjerg, and P. Rodríguez, "Control of power converters in AC microgrids," IEEE Trans. Power Electron., vol. 27, no. 11, pp. 4734–4749, Nov. 2012.
4. W. H. Kersting, Distribution System Modeling and Analysis, 4th ed. Boca Raton, FL: CRC Press, 2017.
5. M. Farivar, R. Neal, C. Clarke, and S. Low, "Optimal inverter VAR control in distribution systems with high PV penetration," in Proc. IEEE PES GM, 2012, pp. 1–7.
6. R. Tonkoski, D. A. Quist, and L. A. C. Lopes, "Impact of high PV penetration on voltage profiles in residential distribution networks," IEEE Trans. Sustain. Energy, vol. 3, no. 3, pp. 518–527, Jul. 2012.
7. A. Singhal and V. Ajjarapu, "A dynamic voltage control framework using PV inverters and legacy devices," IEEE Trans. Smart Grid, vol. 11, no. 3, pp. 2211–2222, May 2020.
8. J. Matevosyan et al., "Grid-forming inverters: Capabilities and operational requirements," IEEE Power Energy Mag., vol. 17, no. 6, pp. 42–48, 2019.
9. P. Kundur, Power System Stability and Control. New York, NY: McGraw-Hill, 1994.
10. U. Tamrakar et al., "Virtual inertia techniques—A review," IEEE Access, vol. 5, pp. 16642–16665, 2017.
11. B. Bahrani, M. Kakar, and A. Rufer, "High-order vector control of grid-connected voltage-source converters," IEEE Trans. Ind. Electron., vol. 58, no. 11, pp. 5097–5107, 2011.
12. Q.-C. Zhong and G. Weiss, "Synchronverters: Inverters that mimic synchronous generators," IEEE Trans. Ind. Electron., vol. 58, no. 4, pp. 1259–1267, 2011.
13. S. D'Arco, J. A. Suul, and O. B. Fosso, "Virtual synchronous machine implementation for distributed control of power converters," Electr. Power Syst. Res., vol. 122, pp. 180–197, 2015.

Page 96-109 © MANTECH PUBLICATIONS 2026. All Rights Reserved

14. A. Engler, "Applicability of droop control in decentralized microgrids," in Proc. ICRERP, 2005, pp. 1–6.
15. M. S. ElMoursi and K. H. Al Hosani, "Voltage stability enhancement of active distribution networks," IEEE Trans. Power Syst., vol. 29, no. 6, pp. 2808–2818, 2014.
16. W. H. Kersting, "Radial distribution test feeders," IEEE Trans. Power Syst., vol. 6, no. 3, pp. 975–985, 1991.
17. R. A. Walling et al., "Summary of distributed resources impact on power delivery systems," IEEE Trans. Power Del., vol. 23, no. 3, pp. 1636–1644, 2008.
18. IEEE Standard 1547-2018: IEEE Standard for Interconnection and Interoperability of DERs, 2018.
19. H. Turkani, A. Sharma, and S. V. Dhople, "Distributed voltage regulation in active distribution networks," IEEE Trans. Control Netw. Syst., vol. 7, no. 1, pp. 342–353, 2020.
20. C. Zhao, E. Dall'Anese, S. Low, and Y. C. Chung, "Optimal voltage regulation in distribution networks," IEEE Trans. Smart Grid, vol. 9, no. 6, pp. 6038–6047, 2018.
21. S. M. Ismael et al., "Hosting capacity in modern distribution networks: A review," Energy, vol. 173, pp. 142–156, 2019.
22. Y. Lin et al., "Research roadmap for grid-forming inverters," NREL, Tech. Rep. NREL/TP-5D00-73476, 2020.
23. J. Rocabert et al., "Control architecture for grid-forming power converters," IEEE Ind. Electron. Mag., vol. 12, no. 4, pp. 26–42, 2018.
24. S. D'Arco and J. A. Suul, "Virtual synchronous machines—Classification and analysis," Electr. Power Syst. Res., vol. 115, pp. 201–209, 2014.
25. H. Bevrani et al., "Robust virtual synchronous generator control design for microgrids," IEEE Trans. Smart Grid, vol. 5, no. 3, pp. 1410–1419, 2014.
26. X. Lu et al., "An improved droop control method for DC microgrids," IEEE Trans. Power Electron., vol. 29, no. 2, pp. 672–680, 2014.
27. M. A. Mahmud et al., "Nonlinear static VAR compensator controller design," IEEE Trans. Control Syst. Technol., vol. 22, no. 1, pp. 312–320, 2014.
28. P. Unruh et al., "Overview on grid-forming inverter control methods," Energies, vol. 13, no. 10, p. 2589, 2020.
29. T. L. Vandoorn et al., "Reactive power droop control strategy for voltage rise mitigation," IEEE Trans. Power Syst., vol. 27, no. 1, pp. 454–461, 2012.

Page 96-109 © MANTECH PUBLICATIONS 2026. All Rights Reserved

30. S. V. Dhople et al., "Virtual oscillator control for grid-forming inverters," IEEE Trans. Power Electron., vol. 34, no. 8, pp. 8112–8124, 2019.
31. Z. Zhang, R. Kennel, and D. Mateo, "Virtual complex impedance implementation in grid-forming inverters," IEEE Trans. Ind. Electron., vol. 67, no. 9, pp. 7520–7531, 2020.
32. M. E. Baran and F. F. Wu, "Optimal capacitor placement on radial distribution systems," IEEE Trans. Power Del., vol. 4, no. 1, pp. 725–734, 1989.
33. N. Hatziargyriou et al., "Microgrids: An overview of ongoing research and demonstration," IEEE Power Energy Mag., vol. 5, no. 4, pp. 78–94, 2007.
34. J. Z. Zhou et al., "Impact of grid-forming inverters on small-signal stability," IEEE Trans. Power Syst., vol. 36, no. 3, pp. 2410–2420, 2021.
35. Y. A. R. I. Mohamed and E. F. El-Saadany, "Adaptive decentralized droop controller for AC distribution systems," IEEE Trans. Power Electron., vol. 23, no. 6, pp. 2801–2810, 2008.
36. X. Wang, F. Blaabjerg, and Z. Chen, "Autonomous power sharing using virtual impedance loops," IEEE Trans. Smart Grid, vol. 5, no. 2, pp. 840–850, 2014.
37. A. Oudalov et al., "Sizing and optimal operation of battery energy storage system," in Proc. IEEE Power Tech, 2007, pp. 621–625.
38. Y. Han et al., "Review of active power sharing and control in microgrids," IEEE Trans. Power Electron., vol. 32, no. 2, pp. 1021–1039, 2017.
39. F. B. Ajaei et al., "Overcurrent protection strategies for grid-forming inverters," IEEE Trans. Power Del., vol. 36, no. 4, pp. 2150–2161, 2021.
40. J. Vetter et al., "Ageing mechanisms in lithium-ion batteries," J. Power Sources, vol. 147, no. 1-2, pp. 269–281, 2005.
41. R. E. Brown, Electric Power Distribution Reliability, 2nd ed. Boca Raton, FL: CRC Press, 2017.
42. Q. Sha et al., "Sequence decoupled grid-forming control under unbalanced grid conditions," IEEE Trans. Power Electron., vol. 37, no. 5, pp. 5820–5832, 2022.
43. Z. Cabrane et al., "Hybrid energy storage system combining battery and ultracapacitor," Energies, vol. 14, no. 11, p. 3210, 2021.
44. T. V. Nguyen et al., "Deep reinforcement learning for dynamic virtual inertia tuning," IEEE Trans. Smart Grid, vol. 14, no. 2, pp. 1120–1132, 2023.

Page 96-109 © MANTECH PUBLICATIONS 2026. All Rights Reserved

***Author for Correspondence**

Mahendra Sonawane

E-mail: mahendra.sonawane35@gmail.com

[1]Associate Professor, Department of Electrical Engineering, Prestige Institute of Engineering Management & Research

[2]Research Scholar, Department of Electrical Engineering, Prestige Institute of Engineering Management & Research

[3]Research Scholar, Department of Electrical Engineering, Prestige Institute of Engineering Management & Research

[4]PG Scholar, Department of Electrical Engineering, Prestige Institute of Engineering Management & Research

Received Date: June 18, 2026

Accepted Date: June 26, 2026

Published Date: July 09, 2026

Citation: Mahendra Sonawane, Pallabika Sharma, Jitin Kumar, Mayank Gupta. Coordinated Voltage Stability Enhancement in Active Distribution Networks Using Grid-Forming Inverters and Energy Storage Systems. Journal of Electrical Power System Engineering and Technology. 2026; 11(2): 96-109p.

Page 96-109 © MANTECH PUBLICATIONS 2026. All Rights Reserved