WEP
Warwick
Evans
Publishing

International Journal of Mechanical and Electrical Engineering
ISSN: 3005-9615 (Print), ISSN: 3005-7132 (Online) | Volume 8, Number 5, Year 2026
DOI: https://doi.org/10.62051/ijmee.v8n5.03
Journal homepage: https://wepub.org/index.php/IJMEE/index

A Unified Review of Control Strategies for Flexible Distribution Systems Under High Penetration of Distributed Energy Resources

Haoyuan Wu *

Liverpool John Moores University, The Sino-British College, Shanghai, 200031, China
* Corresponding author Email: Howard8766@gmail.com

ABSTRACT

High penetration of distributed energy resources (DERs)—photovoltaics, wind, storage, and flexible demand—is reshaping distribution networks. Bidirectional power flows, tighter voltage limits, and higher uncertainty make traditional passive operation inadequate. Flexible distribution systems (FDSs) address this by coordinating flexibility across source–grid–load–storage. This review synthesizes core FDS work through a three-layer lens: (i) structural flexibility (reconfiguration and controllable interconnection) that expands feasibility; (ii) real-time control (local, distributed/hierarchical, and predictive) that enforces constraints; and (iii) multi-timescale scheduling that allocates resources under forecasts and uncertainty. We emphasize cross-layer alignment—structure shapes controllability, and schedules must preserve regulation margins—and summarize open challenges in uncertainty propagation, scalability, and deployable hybrid (model + data) methods.

KEYWORDS

Flexible Distribution System; Distributed Energy Resources; Network Reconfiguration; Coordinated Control; Multi-timescale Scheduling.

1. INTRODUCTION

DER growth in distribution networks is driven by decarbonization goals and declining costs of PV, batteries, and power electronics. Unlike traditional radial feeders designed for one-way supply, DER-rich networks face voltage excursions, reverse flows, congestion, and more frequent operating point changes [1,2]. The concept of the flexible distribution system (FDS) responds by treating flexibility as a system-level property: controllable resources and interfaces are coordinated to keep operation secure, improve DER hosting capacity, and reduce reliance on costly network reinforcement.

Many studies focus on a single dimension (e.g., voltage control or storage dispatch). Yet practical flexibility emerges from the interaction of physical structure, fast control, and slower scheduling.For instance, a well-designed network topology can reduce the complexity of real-time voltage regulation, while a robust scheduling plan reserves buffer margins for control actions to mitigate DER fluctuations. This review uses a three-layer framework to unify key methods and clarify trade-offs between optimality, robustness, and deployability.

2. SCOPE AND THREE-LAYER FRAMEWORK

We focus on operational flexibility in DER-rich distribution systems (not market design, and not purely hardware work without operational implications). The three layers are:

- Structural layer: topology and controllable interconnections that define feasibility (typically slower actions, but with direct operational impact).
- Control layer: real-time regulation of voltages and power flows under constraints (sub-second to minutes).
- Scheduling layer: optimization-based coordination across minutes-to-days using forecasts and uncertainty handling.

When a study spans layers, we categorize it by its primary contribution and discuss cross-layer couplings explicitly.

3. STRUCTURAL LAYER: NETWORK CONFIGURATION AND PHYSICAL FLEXIBILITY

3.1. Reconfiguration

Switching-based reconfiguration adapts feeder topology to load and DER variations. Classic formulations target loss reduction and load balancing under radiality constraints [3]. With high DER penetration, objectives extend to congestion relief and voltage margin creation, often with explicit limits on switching frequency to respect device wear and protection coordination. Because reconfiguration is a mixed-integer problem, deployable strategies usually restrict candidates to a small set of admissible topologies, precompute or learn high-quality switching patterns, and coordinate switching with downstream control so that discrete actions are taken only when they yield a clear operational benefit.Recent studies have integrated machine learning to predict optimal topology adjustments based on historical DER and load data, reducing computational latency and enhancing responsiveness to rapid system changes.

3.2. Controllable Interconnection (Power Electronics)

Distribution-level power electronics provide continuous bidirectional control of active/reactive power exchange between feeders, improving voltage regulation and balancing capabilities [4]. Soft open points (SOPs) are a prominent example that can relieve constraints and redistribute power flows in active distribution networks [5]. Their benefits are highest when coordinated with control (fast voltage support) and scheduling (energy shifting), while respecting converter limits, losses, and investment costs.The combination of SOPs with energy storage systems (ESS) has shown promise, as the integrated system can both adjust power flow paths and absorb/release energy to smooth short-term DER fluctuations, further enhancing structural flexibility.

3.3. Modeling Considerations

Structural models encode topology, line limits, and device capabilities. AC power flow offers fidelity but can be heavy for large-scale optimization; simplified models improve tractability but may lose accuracy under stressed conditions. A pragmatic practice is to optimize with tractable approximations and validate (or safeguard) with more accurate checks before execution.In DER-rich scenarios, models must account for bidirectional power flows and dynamic characteristics of flexible resources. Recent hybrid modeling approaches combine the simplicity of linear models with data-driven corrections, balancing computational efficiency and modeling fidelity.

4. CONTROL LAYER: REAL-TIME REGULATION

4.1. Voltage and Power-Flow Control

Voltage regulation is the dominant operational issue in DER-rich feeders. Inverter-based DERs can provide reactive power support (and, when allowed, active power curtailment). Foundational work shows how distributed PV inverters can regulate voltage via reactive power control, highlighting sensitivity and information limitations [6].

Local droop-like control is simple and scalable, but may be suboptimal or induce undesirable interactions. Coordinated control improves system-wide performance but requires communication, state estimation, and robust design against delays and model errors.For example, distributed voltage control strategies leveraging limited communication between neighboring inverters achieve near-optimal performance while maintaining scalability, eliminating the need for a centralized controller with full system visibility.

4.2. Distributed/Hierarchical Architectures

Distributed control decomposes decisions among devices or regions, improving resilience and reducing centralized computation. Hierarchical designs align with practice by assigning roles across device, feeder, and DMS/DERMS levels; microgrid control literature offers architectural guidance for such layered regulation [7]. Recent studies emphasize well-defined communication interfaces between hierarchy levels, ensuring lower-level controllers handle fast dynamics (e.g., inverter voltage control) while upper layers focus on system-wide goals (e.g., congestion relief) for conflict-free coordination.

4.3. Optimization-Based and Predictive Control

OPF-based perspectives formalize constrained voltage/power-flow regulation; OPF surveys summarize tractability and relaxation/decomposition options for deployment [8]. Online “pursuit” methods aim to track OPF solutions in real time under changing conditions [9]. Model predictive control (MPC) uses forecasts and receding-horizon optimization; DER management with MPC is a representative approach for coordinating inverters, storage, and flexible demand under constraints [10]. Key bottlenecks are computation, model mismatch, and forecast errors; common mitigations include model simplification, distributed MPC, and conservative margins to preserve feasibility.Distributed MPC has gained particular traction, distributing computational load across multiple controllers to enable real-time deployment in large-scale systems while maintaining coordination between adjacent regions.

4.4. Hybrid Model–Data Approaches

Learning is useful for forecasting, system identification, and policy approximation, but standalone learning can violate constraints. A practical path is hybrid control: learning components plus model-based safety filters or OPF/MPC supervision, enabling adaptability with explicit constraint enforcement.For instance, reinforcement learning (RL) algorithms can learn optimal control policies from historical data, while a model-based safety layer ensures these policies do not violate voltage or power flow constraints, balancing adaptability and constraint satisfaction.

5. SCHEDULING LAYER: MULTI-TIMESCALE COORDINATION

Scheduling coordinates resources over minutes-to-days for economic and security objectives. Rolling-horizon frameworks link day-ahead decisions with intra-day updates as forecasts improve.

MPC-based microgrid scheduling illustrates a practical template for integrating forecasts, constraints, and recourse [11].

Uncertainty can be handled via stochastic programming, robust optimization, or chance constraints. Foundational decision-making concepts guide scenario and uncertainty-set design [12]. Multi-stage robust formulations show how to preserve feasibility under deviations, though conservatism and computation must be managed [13]. In practice, lightweight uncertainty representations combined with frequent re-optimization and real-time feedback often provide strong deployability.Integration of demand response (DR) programs into scheduling has become increasingly critical. By incentivizing flexible loads to shift consumption to high-DER-generation periods, congestion is reduced and absorption capacity improved, with recent research focusing on DR-aware models that balance user preferences and load flexibility.

6. CROSS-LAYER INTEGRATION

Flexibility is conditional: structural actions expand feasibility only if control can exploit them, and aggressive schedules can consume margins needed for regulation. Effective integration typically requires:

- Structure-aware control: choosing topology/SOP settings that improve voltage sensitivity and reduce control effort.

- Control-aware scheduling: reserving thermal/voltage/inverter headroom so fast regulation remains feasible under errors.

- Clear interfaces: exchanging limits, envelopes, and forecasts between scheduling and control in a receding-horizon loop.

Interoperability and device capability boundaries should be considered early; inverter control modes are constrained by interconnection rules such as IEEE 1547-2018 [14]. Recent pilot projects demonstrate that successful cross-layer integration significantly improves DER hosting capacity, reduces operational costs, and enhances system stability compared to isolated layer optimization, while addressing technical challenges such as communication latency and data synchronization.

7. CHALLENGES AND FUTURE DIRECTIONS

(1) Cross-layer uncertainty propagation: quantifying how forecast errors affect feasible envelopes and controllability.

(2) Scalability with guarantees: decomposition and certified approximations that preserve safety and real-time solvability.

(3) Field constraints: latency, partial observability, and heterogeneous devices; methods should degrade gracefully.

(4) Safe hybrid methods: verification, benchmarks, and failure-mode analysis for learning-assisted control.

(5) Modular architectures: standardized interfaces among DERMS/DMS/device controllers to enable incremental deployment.

8. CONCLUSION

FDSs provide a system-level response to high DER penetration by coordinating structure, control, and scheduling. The three-layer perspective clarifies that advances in one layer do not translate to flexibility unless cross-layer alignment is designed in. Future progress depends on scalable, uncertainty-aware, and standards-aligned architectures that are implementable with realistic data and communication constraints.

REFERENCES

[1] Wang, Y., Zhao, J., & Sun, Y. (2020). Impact of high-penetration renewable energy on distribution networks: A review. IEEE Access, 8. https://doi.org/10.1109/ACCESS.2020.2974587.

[2] Liu, X., Zhang, H., & Fang, B. (2020). Flexible distribution network: Concepts, structures, and operation. CSEE Journal of Power and Energy Systems, 6(3), 498–507. https://doi.org/10.17775/CSEEJPES.2020.00300.

[3] Baran, M. E., & Wu, F. F. (1989). Network reconfiguration in distribution systems for loss reduction and load balancing. IEEE Transactions on Power Delivery, 4(2), 1401–1407. https://doi.org/10.1109/61.25623.

[4] Bloemink, J. M., & Green, T. C. (2011). Benefits of distribution-level power electronics for supporting distributed generation growth. IEEE Transactions on Power Delivery, 26(2), 911–919. https://doi.org/10.1109/ TPWRD. 2010. 2091420.

[5] Long, C., Wu, J., & Thomas, L. (2018). Optimal operation of soft open points in active distribution networks. Applied Energy, 210, 123–134. https://doi.org/10.1016/j.apenergy.2017.10.117.

[6] Turitsyn, K., Sulc, P., Backhaus, S., & Chertkov, M. (2011). Options for control of reactive power by distributed photovoltaic generators. IEEE Transactions on Power Systems, 26(3), 1383–1393. https://doi.org/10. 1109/ TPWRS. 2011. 2106164.

[7] Olivares, D. E., Mehrizi-Sani, A., Etemadi, A. H., Cañizares, C. A., Iravani, R., Bazargan, M., Rueda, J. L., & Gonzalez-Longatt, F. (2014). Trends in microgrid control. IEEE Transactions on Smart Grid, 5(4), 1905–1919. https://doi.org/10.1109/TSG.2014.2304418.

[8] Capitanescu, F., Martinez-Ramos, J. L., Ramos, A., & Pazos, M. (2015). State-of-the-art, challenges, and future trends in optimal power flow. Electric Power Systems Research, 119, 1–10. https://doi.org/10. 1016/j. epsr. 2014. 10.016.

[9] Dall'Anese, E., & Simonetto, A. (2013). Optimal power flow pursuit. IEEE Transactions on Smart Grid, 4(4), 2123–2133. https://doi.org/10.1109/TSG.2013.2257897.

[10] Baker, K., Dall'Anese, E., & Summers, T. (2019). Distributed energy resource management using model predictive control. IEEE Transactions on Smart Grid, 10(2), 1471–1482. https://doi.org/10.1109/TSG.2018.2850347.

[11] Parisio, A., Rikos, E., & Glielmo, L. (2014). A model predictive control approach to microgrid operation optimization. IEEE Transactions on Control Systems Technology, 22(5), 1813–1827. https://doi.org/ 10. 1109/ TCST.2014.2298235.

[12] Conejo, A. J., Carrión, M., & Morales, J. M. (2010). Decision making under uncertainty in electricity markets. Springer. https://doi.org/10.1007/978-1-4419-7512-2.

[13] Zhao, C., Wang, J., & Watson, J.-P. (2013). Multi-stage robust unit commitment considering wind and demand response. IEEE Transactions on Power Systems, 28(3), 2708–2717. https://doi.org/10.1109/TPWRS.2013.2240701.

[14] IEEE. (2018). Standard for interconnection and interoperability of distributed energy resources with associated electric power systems interfaces (Standard 1547-2018). IEEE Standards Association. https://doi.org/10.1109/ IEEESTD. 2018.8442780.