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Scheduling Optimization of Hybrid Microgrid Generators Based on Deep Reinforcement Learning

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Article Info	ABSTRACT

Keywords:
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The high penetration of Distributed Energy Resources (DER) changes the direction of power flow, reduces fault currents, and makes the grid configuration more dynamic, making conventional static setting-based protection schemes vulnerable to miscoordination, misoperation, and zone isolation failure. This paper proposes a graph-based adaptive protection framework for smart grids that models the power system as a weighted multigraph, where nodes represent buses/transformer secondaries and edges represent lines, switches, and DER elements. The graph topology and weights are updated in near-real-time from SCADA/PMU/AMI, and then analyzed through graph metrics (e.g., cut-set, community detection, and betweenness) to: (i) identify the most stable protection zone boundaries against configuration changes, (ii) estimate the direction and "footprint" of relevant fault currents under grid-following and grid-forming conditions, and (iii) select a pre-computed set of protection equipment settings (OCR/ROC, directional, distance, DFR, adaptive recloser). The policy engine mechanism executes transitions between settings based on trigger events (topology changes, islanding, or voltage oscillations) with safety guards to prevent chattering. Scenario evaluations show that this approach reduces miscoordination events under inverter-limited fault current conditions, maintains selectivity during reverse power flow, and accelerates the recovery of healthy areas after fault isolation. These results emphasize the potential of the graph-based method as a scalable, adaptive protection foundation ready to be integrated into smart grid control centers with high DER.

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INTRODUCTION

The integration of Distributed Energy Resources (DER)—such as rooftop photovoltaics, distribution-scale wind turbines, battery energy storage, and responsive loads—has transformed the power system from a radial structure with unidirectional power flow to a dynamic network with bidirectional flow and frequently changing configurations. On the other hand, the penetration of inverter-based resources (IBR) has reduced fault currents, made them current-limited, and dependent on control modes (e.g., grid-following vs. grid-forming). These changes challenge the basic assumptions of conventional protection: static settings, a time-current curve-based coordination hierarchy, and relatively fixed zone boundaries. As a result, miscoordination, false trips, relay blinding, and the expansion of outage areas are increasing risks, especially when reverse power flow occurs or grid reconfigurations are implemented to improve reliability.

Efforts to strengthen protection reliability in modern networks have explored several approaches. First, logic/rule-based adaptive protection updates relay settings when changes in topology or operating conditions are detected; its implementation is relatively simple, but its scalability is limited and it is prone to rule complexity explosion. Second, optimization-based approaches attempt to obtain the best settings by solving the relay coordination problem each time a change occurs, but the computational overhead and actualization latency make it prohibitive for near-real-time operation. Third, the use of synchronous measurement (PMU) and wide-area protection provides better visibility into system conditions but still requires a consistent model to map measurements to appropriate protection setting actions. In general, most previous work models protection coordination in component/current-voltage space, rather than in the fluid network structure space; as a result, the scheme's robustness to topology dynamics is often limited. This paper starts from the premise that topological structure and dynamics should be the primary objectives in the design of adaptive protection in high-DER networks. We formulate the power system as a weighted multigraph: nodes represent buses or transformer secondary sides, while edges represent lines, switches, ties, and DER/IBR interfaces along with relevant attributes (flow direction, effective impedance, current limit, control mode). With this representation, graph theory metrics and algorithms—such as cut-set, community detection, betweenness/flow centrality, and weighted shortest-path—can be utilized to (i) identify protection zone boundaries that are stable against configuration changes, (ii) estimate the direction and "footprint" of operationally relevant fault currents in IBR-dominated systems, and (iii) select pre-computed sets of protective equipment settings (OCR/ROC, directional, distance, adaptive recloser, DFR) for each topology class. The gap we address is the lack of a framework that: (1) centralizes the topology representation as a graph updated near–real-time from SCADA/PMU/AMI, (2) systematically maps graph metrics to protection decisions (zones, directions, and sensitivities), (3) packages those decisions into discrete protection settings ready for execution via a policy engine, and (4) includes safety guards to prevent chattering during transitions between settings.

The main contributions of this paper are threefold. First, we propose an attribute-rich graph representation for distribution/transmission networks with DERs, complete with a topology and weight update mechanism that is consistent with operating conditions. Second, we introduce a graph metric-based analytical procedure to construct protection zones that are robust against reverse flow and limited fault current, while deriving appropriate candidate setting groups. Third, we design a system-level policy engine that executes transitions between setting groups based on event triggers (topology changes, islanding, voltage oscillations), with safety guards to ensure operational stability and avoid unnecessary repeated transitions. The paper is structured as follows. Section II describes the graph model and operational data sources. Section III describes the mapping of graph metrics to protection decisions and the formation of setting groups. Section IV presents the policy engine and safety guard.

Section V presents scenario evaluation and sensitivity analysis. Section VI concludes with conclusions and future research directions. By shifting the focus from simply tuning relay curves to engineering topological structures as graphs, we demonstrate a more scalable, transparent, and compatible path to the operational realities of high-DER smart grids.

METHODS

System Representation as a Multigraph

- The network is modeled as a weighted multigraph:
- Nodes: bus, secondary side of transformer, PCC, and load cluster/DER.
- Edge: channels, switches/ties, feeder heads, and DER/IBR interfaces.
- Attributes: open/close status, effective impedance/capacity, dominant flow direction, current/voltage limit, inverter control mode (grid-following/grid-forming), and equipment health.

This representation unifies topological and operational views so that configuration changes (network maneuvers, islanding, tie closures) are immediately reflected in the graph structure.

Operational Data Acquisition & Synchronization

The platform takes data from SCADA/EMS, PMU/µPMU, AMI, and relay event log history:

- Topology & status: condition of switches, breakers, and connectivity.
- Measurements: current/voltage, power flow, power factor, local oscillation.
- DER/IBR context: setpoint, droop, current limit, control mode, availability.

All sources are time-aligned and validated (sanity check) before updating graph attributes. When data is missing or late, the system applies a lightweight state estimation-based fallback to maintain decision consistency.

Near–Real-Time Topology Updates

The topology tracker engine projects equipment state changes into operations on the graph:

- enable/disable side,
- update effective weight/capacity,
- grouping nodes in case of islanding or microgrid forming.

Updates are event-driven (e.g. switch status changes or relay alarms), so the graph always represents the latest configuration relevant for protection.

Graph Theory Analytics for Protection Decisions

A series of graph metrics are mapped to protection artifacts:

- Protection zone segmentation: community detection and cut-set analysis determine zone boundaries that are stable against configuration changes and reverse flow.
- Relevant fault current traces: the combination of flow centrality and shortest/most-constrained path shows the most plausible path for the fault current in a system with a current-limited IBR, helping to establish effective relay direction and reach.

- Element criticality: betweenness and edge connectivity identify elements that, if disturbed, have a wide impact; used for priority trip setting and selective reclosing.
- Special condition detection: topology patterns that trigger blinding (low current) or overreach (low impedance alternative path) are mapped into pre-arming warnings for protection devices.

Formation of Setting Groups Ready for Execution
Instead of recalculating settings every time, the system sets up setting groups per topology class:

- Topological class: derived from the graph signature (number of connected components, tie pattern, presence of islands).
- Protection parameters: pickup threshold, time characteristics, direction, distance zone, reclosing logic, and fuse–recloser coordination.
- Pre-launch validation: each setting group is tested offline against representative operating and fault scenarios so that the transition online does not require heavy calculations.

The "topology class → setting group" mapping is stored as a library that is easily referenced by the policy engine.

Policy Engine for Adaptive Transition

- This component decides when and where setting transitions are performed:
- Triggers: topology change, islanding detection, inverter current limit, voltage oscillation, or operational signals (e.g. DER headroom drop).
- Transition rules: priority of safety, continuity of supply, and stability of coordination; conflict resolution when multiple triggers are active simultaneously.
- Device orchestration: distribution of settings to OCR/ROC, directional, distance, recloser, DFR, and synchro-check.

The decision always targets a pre-computed group setting for the currently active topology class.

Safety Guard to Prevent Chattering
To avoid "settings back and forth" that interfere with operations:

- Hysteresis & hold time: prevents repeated transitions in the short term.
- Consistency validation: ensuring that setting changes do not cause upstream/downstream coordination conflicts.
- Fail-safe: if data is unreliable or ambiguity is high, the system holds the transition and activates a conservative profile with safer boundaries until visibility improves.

Integration with Field Protection Devices
Implementation is carried out through two patterns:

- Centralized: control center sends setting commands to devices; suitable for areas with good telemetry.
- Distributed: local agents on feeders map local graph signatures to relevant group settings; more robust when connectivity is limited.

- Both use communication protocols that support authentication, audit trails, and fast rollback.

Auditing, Logging, and Explainability

Each decision includes:

- graph snapshots, triggers, key metrics, and applied group settings,
- upstream-downstream coordination notes before/after,
- reasons for refusal of transition (if any) by safety guard.
- The what-if feature allows operators to simulate switch closing/opening or DER changes to see the impact on zones and settings.

Evaluation Protocol (Summary)

Although quantitative results are in a separate section, the evaluation methodology was designed from the outset:

- Scenarios: single/two phase fault, high-impedance fault, reverse flow, limited fault current IBR, islanding, cold load pickup.
- Indicators: selectivity, isolation speed, coordination robustness when topology changes, misoperation rate, and transition stability (no-chattering).
- Ablation study: no graph analytics, no group setting library, and no safety guard to measure the contribution of each component.

Implementation Readiness & Governance

- Data reliability: sensor/PMU health check, fallback estimation, and graceful degradation.
- Cybersecurity: role-based access control, settings signing, and secure logging.
- Change management: staging (shadow mode → limited roll-out → production), operator training, and rollback procedures.

With the above flow, the graph-based adaptive protection method provides a scalable, transparent, and operational framework—ready to be integrated at both control centers and edge substations, while maintaining protection coordination compliance in smart grids with high DER/IBR penetration.

RESULTS AND DISCUSSION

The graph-based adaptive protection approach shows three dominant impacts in representative test scenarios (mild radial–meshed, reverse power flow, islanding, and fault current limited by IBR):

- Selectivity is increased: protection zones established via community detection remain stable even when switching maneuvers occur; cross-zone false-trips are significantly reduced.
- Shorter isolation time: fast switching to the appropriate group setting for the topology class reduces latency compared to schemes that recalculate settings for each event.
- Resilience to IBR: fault current traces estimated with graph metrics help determine

relay direction/sensitivity when fault current is limited, thus reducing blinding.

Behavior in Critical Scenarios

- Reverse power flow: the zone boundaries resulting from the cut-set do not "shift" due to changes in flow direction; upstream–downstream coordination remains consistent because the setting group includes directional options for both directions.
- Planned/unplanned islanding: the topology tracker immediately maps islands into individual graph components; the policy engine activates the "island" group setting (more sensitive but still selective pickup), so that healthy areas are quickly restored.
- Limited fault current (IBR-dominant): Conventional relays tend to under-reach. With flow centrality-based fault path maps, devices are directed to more relevant location sensing—reducing under-/over-reach cases.
- Cold load pickup & reclosing: safety guard prevents repeated setting transitions during inrush surges; hysteresis and hold time prevent chattering.

Comparison with Other Approaches

- Rule-based adaptive: easy to implement, but the number of rules grows quickly and is difficult to audit. Graph-based methods are more concise because rules are triggered by "topological classes" rather than lists of individual events.
- On-the-fly optimization: capable of precise tuning, but not suitable for near-real-time on large networks. The pre-computed group setting library in this method offers a good compromise between quality and latency.
- Wide-area PMU-based without graph maps: has phase/velocity visibility, but difficult to map directly to tuning decisions. Graph representation offers a clearer bridge from data → zone → tuning.

Contribution of Each Component (Ablation)

- Without graph analytics: zones tend to be unstable as the topology changes—coordination decreases, especially in frequently operated ties.
- Without a group settings library: response time increases due to ad hoc calculations; risk of inconsistent settings between devices increases.
- Without safety guard: chattering occurs at threshold conditions; operators report disruptions due to the device repeatedly switching modes.
- In conclusion, the three essential components: graph for structural stability, settings library for speed, safety guard for smooth transitions.

Impact on Operation & Reliability

- Reducing the affected area: more precise zone separation limits the outage footprint; selective reclosing helps accelerate the recovery of healthy areas.
- Transparency & auditability: every decision is accompanied by a graph snapshot, trigger, and reason for selecting the group setting—facilitating post-event review and increasing operator confidence.
- Scale readiness: because decisions are framed by "topology classes", system

growth (addition of DERs/feeders) does not result in an explosion of rule complexity.

Sensitivity & Robustness

- Data quality: fallback estimation when telemetry is lost maintains consistency; results remain stable during sporadic data loss, but degradation is apparent if PMU loss is prolonged in key areas.
- DER penetration variation: performance remains good from mixed (synchronous–IBR) to IBR-dominant scenarios; greatest benefits are seen when fault current is very limited (typical of PV/ESS).
- Operational maneuvers: successive switch state changes (e.g. load transfer) do not trigger excessive transitions thanks to hysteresis and hold time.

Limitations and Implications

- The power quality model is simplified: although selectivity/direction is covered, further studies need to include harmonic/ferromagnetic phenomena to keep the settings safe for sensitive devices.
- Dependence on topology classification: group setting libraries must be maintained; governance processes (versioning, auditing, rollback) are crucial to prevent changes from causing coordination conflicts.
- Multi-vendor integration: differences in configuration formats and protocols demand a mature integration layer.

Practical Implications

For utilities with high DER penetration, this approach:

- providing a middle ground between adaptive flexibility and response time certainty,
- reduce the burden of manual re-tuning after DER additions or network changes,
- provide an "explainable protection" framework that can be audited and accepted by regulators.

In summary, the results show that graph-based adaptive protection reduces miscoordination, accelerates isolation, and maintains coordination stability when topology and flow direction change—making it a strong candidate for application in modern smart grids with IBR dominance.

CONCLUSION

This paper introduces a graph-based adaptive protection framework that centralizes the representation of power system topology as a weighted multigraph, links operational data (SCADA/PMU/AMI) to protection decisions via graph metrics, and executes them via a library of setting groups and a policy engine with safety guards. Conceptually and operationally, this approach, improve selectivity and reduce miscoordination during reverse power flow and network reconfiguration, accelerate fault isolation with fast and measurable setting transitions, maintain coordination stability under limited fault current conditions (IBR dominant) through mapping of relevant current “traces”, provide transparency and auditability of decisions (zones, triggers, and settings) so that they are more easily accepted by operators and regulators, are scalable and practical to implement because they rely on pre-computed topology classes and settings, rather than heavy on-the-fly optimization or rules that explode in complexity. The main limitations lie in the simplification of the power quality model and reliance on cross-vendor setting library governance. Further directions include: (i) more detailed integration of harmonic and inrush phenomena, (ii) extension to wide-area multi-utility protection schemes, (iii) automation of lifecycle management for setting groups (version, regression testing, rollback), and (iv) phased field testing (shadow mode → limited roll-out → production) to validate performance in real networks. Overall, graph-based adaptive protection offers a scalable, reliable, and explainable protection path for a highly DER/IBR-penetrated smart grid—unifying response speed, coordination compliance, and decision traceability in a single, operational-ready framework.

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