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# Analysis and Evaluation of Distribution Network Structure Based on Artificial Intelligence

**Gao Fengxi, He Xin, Wu Zhuohang, Liang Yi, Han Zhentao, Sun Mingze, Liu Hao**

*Power Electric Research Institute, State Grid Liaoning Electric Power Co., Ltd, Shenyang, 110015, China*

***Abstract:*** *The planning of distribution network framework is an important component of power system planning and urban planning. Reasonable distribution network planning is a prerequisite for achieving the economic and safety of future urban distribution networks, which can achieve significant economic and social benefits; On the contrary, errors in distribution network planning can cause irreparable losses to the country's economic development and people's lives. We use the current distribution network structure and existing installation information of secondary equipment such as protection and automation, we analyze the distribution characteristics of terminal types, terminal functions, and terminal communication methods on different feeders, main lines, and branch lines, and summarize and extract the characteristics of terminal coverage range and distribution density. Based on the distribution of terminals, a comprehensive evaluation of standard automated feeders is conducted to identify the missing distribution points and repeated installations of secondary equipment in distribution lines.*

***Keywords:*** *Twin monitoring; Primary structure of grid structure; Secondary equipment of distribution network*

## 1. Introduction

The critical backbone infrastructure for ensuring safe and resilient operation of modern power systems is a robust, optimally configured distribution network. This sophisticated infrastructure component substantially enhances power supply stability and reliability through scientifically optimized resource allocation methodologies leveraging graph theory and linear programming, significantly reduces distribution line failure rates through predictive maintenance strategies informed by IoT sensor networks and failure mode analysis, and elevates service quality through AI-driven load balancing techniques incorporating real-time demand forecasting. Comprehensive planning of this framework represents an indispensable element within both broader power system strategic development initiatives and metropolitan infrastructure master planning, serving as the foundational cornerstone for sustainable urban energy ecosystems capable of supporting smart city transformations. When executed with technical precision and strategic foresight incorporating lifecycle cost analysis and risk-based planning principles, distribution network planning delivers substantial socioeconomic benefits by ensuring future grids achieve optimal economic viability through asset utilization optimization while maintaining uncompromised operational safety through N-2 redundancy standards; conversely, planning deficiencies risk severe macroeconomic consequences including industrial productivity losses quantified at national GDP percentages, supply chain disruptions cascading across economic sectors, and profound public welfare implications through extended service interruptions exacerbating healthcare vulnerabilities and educational disruptions [1]. Contemporary distribution networks exhibit increasingly complex topologies characterized by heterogeneous equipment configurations spanning multiple technological generations, aging infrastructure components exceeding design lifespans, and dynamic load patterns reflecting urbanization megatrends - collectively presenting two primary planning challenges: significant difficulties in compiling comprehensive negative lists due to inadequate technical capabilities for holistic grid evaluation incorporating graph centrality metrics and betweenness analysis, forcing management professionals across organizational hierarchies to manually analyze, identify, and document deficiencies using fragmented fault histories and partial automation requirements - a labor-intensive process consuming thousands of person-hours annually while revealing urgent needs for enhanced analytical precision through digital twin implementations; and critically insufficient planning quality/efficiency stemming from experience-based renovation

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approaches that fail to achieve globally optimized equipment-line coordination through multi-objective optimization algorithms. When multiple renovation alternatives exist - as commonly occurs in metropolitan grid retrofits - the absence of robust technical methodologies for evaluating lifecycle economic viability through net present value calculations, operational usability metrics via human factors engineering, and post-implementation effectiveness through reliability-centered maintenance principles fundamentally prevents optimal solution identification. These scientific and rational planning deficiencies ultimately compromise long-term grid operational efficiency through increased system losses, stability parameters through voltage fluctuation incidents, and resilience thresholds through cascading failure vulnerabilities, potentially triggering systemic blackouts. Regulatory mandates from authoritative bodies including China's National Development and Reform Commission and National Energy Administration explicitly require power enterprises to prioritize safety and reliability while advancing grid construction through structural optimization incorporating modular design principles and predictive maintenance protocols aligned with Industry 4.0 standards [2]. Addressing these imperatives necessitates adopting innovative digital paradigms and emerging technologies like artificial intelligence neural networks, blockchain-secured IoT sensor networks, and quantum computing-accelerated simulation platforms to deliver integrated analytical solutions for distribution network evaluation, thereby fundamentally transforming planning quality and operational efficiency through data-driven decision-making frameworks that incorporate real-time phasor measurement unit monitoring, predictive analytics leveraging federated learning, and automated optimization algorithms using genetic programming to future-proof energy infrastructure against evolving demand patterns, climate change impacts, and cybersecurity threats while enabling seamless integration of distributed renewable generation and electric vehicle charging ecosystems through adaptive protection schemes.

## 2. Existing problems

The comprehensive analytical scope encompasses the entire lifecycle of distribution networks - spanning strategic planning horizons incorporating 30-year demand projections, detailed design specifications conforming to IEC 61850 standards, phased construction methodologies employing building information modeling, and continuous operational phases implementing condition-based maintenance - involving meticulous multi-criteria assessments of current grid conditions including load distribution patterns analyzed through kernel density estimation, equipment degradation metrics quantified through remaining useful life algorithms, and redundancy configurations evaluated via graph connectivity indices; sophisticated forecasting of future electricity demand patterns considering urbanization trajectories modeled through cellular automata, industrial expansion projections utilizing input-output matrices, and electric vehicle adoption curves calibrated against subsidy policies; predictive modeling of grid operating status under extreme weather scenarios incorporating climate model ensembles and contingency events simulating coordinated cyber-physical attacks; and formulation of economically viable renovation strategies employing mixed-integer linear programming to achieve overarching development goals including technological innovation leadership through cognitive automation deployment, advanced equipment modernization with autonomous self-healing capabilities utilizing multi-agent systems, and sustainable economic efficiency through circular economy principles while ensuring uninterrupted safe operation conforming to Safety Integrity Level 3 certifications and premium power quality standards maintaining THD below 1.5%. Current industry practices disproportionately emphasize discrete physical components such as substations analyzed in isolation, distribution lines modeled as independent segments, and individual equipment units cataloged without system context while critically neglecting the interconnected structural relationships and systemic interactions between distribution network elements that determine overall resilience through emergent properties - particularly the complex interplay between protection coordination settings, automation response times, and topological reconfiguration capabilities during fault conditions [3]. Continuous network expansion compounds these analytical deficiencies through proliferating structural configurations including mesh-topology business districts and radial residential feeders, escalating topological complexity exceeding computational tractability thresholds, and interoperability challenges between legacy electromechanical devices and digital substations, collectively manifesting as operational weaknesses including unbalanced load distributions creating thermal stress hotspots accelerating insulation degradation, insufficient power transfer capacities between network segments limiting operational flexibility during generator outages, and inadequate redundancy provisions reducing fault tolerance below NERC reliability standards. Simultaneously, emerging operational requirements for adaptive boundary switch control logic incorporating synchrophasor measurements, automated equipment placement strategies utilizing drone-LiDAR surveying with centimeter accuracy, and AI-optimized protection device installation protocols requiring impedance-based coordination demand grid-structure-informed allocation methodologies that account for dynamic load flows simulated through quasi-steady-state time-series analysis. However, prevailing equipment transformation approaches typically involve reactive, localized modifications addressing immediate failure points through emergency procurement rather than proactive, system-wide optimization guided by holistic structural improvement principles incorporating reliability-centered design - a limitation exacerbated by the current absence of robust technical frameworks for comprehensive structural analysis and evaluation incorporating digital twin simulations with hardware-in-loop validation [4]. Planning workflows suffer from severe data fragmentation requiring extensive manual input across incompatible software platforms including GIS databases, SCADA historians, and asset management systems, creating information silos that prevent unified optimization and resulting in convoluted processes with diminished efficiency evidenced by planning cycles exceeding 18 months and unverifiable solution viability. Implementing virtual-real iterative digital twin simulation systems could fundamentally restructure these workflows toward standardized analytical procedures, supporting resilient network development through predictive modeling of multiple what-if scenarios including hurricane landfall simulations and cyberattack penetration testing. Critical analytical domains requiring enhancement include: systematic weak point identification through grid-wide scanning using operational telemetry from PMUs for load pattern analysis employing Fourier transforms, transfer capacity evaluation under peak conditions using continuation power flow methods, feeder length optimization for voltage stability through impedance compensation techniques, automated boundary switch configuration for fault isolation utilizing graph partitioning algorithms, and N-1 compliance verification through Monte Carlo contingency testing with probabilistic reliability indices [5]; comprehensive secondary equipment assessment auditing protection/automation device deployment against international IEC 61850 standards to identify coverage gaps and redundancies through functional hierarchy analysis; automated negative listing synthesizing multidimensional deficiency reports (e.g., overloaded lines exceeding 80% capacity, non-N-1 segments violating redundancy standards, complex interconnections creating protection blindness) with geographic visualization in 3D cyber-physical models; optimized renovation planning deriving integrated equipment/layout solutions maximizing power transfer through conductor upsizing while minimizing outage impacts through strategic switch placement optimized via genetic algorithms; and rigorous solution validation simulating post-renovation performance under diverse operating conditions including electromagnetic pulse events and pandemic workforce restrictions to verify effectiveness and resilience through quantitative reliability indices including SAIDI, SAIFI, and CAIDI metrics benchmarked against international utilities.

## 3. Implementation method

Advanced machine learning applications for sophisticated electricity theft detection encompass multiple methodological approaches requiring careful algorithmic selection through bias-variance tradeoff analysis and hyperparameter optimization via Bayesian techniques: decision trees classify consumption patterns through intuitive hierarchical structures based on usage characteristics including diurnal variations quantified through wavelet analysis, seasonal fluctuations modeled via SARIMA decomposition, and anomalous power factors detected through clustering outliers, though exhibiting overfitting vulnerabilities when excessively tailored to training datasets without proper cost-complexity pruning and cross-validation protocols; random forests integrate ensembles of decision trees through randomized sampling techniques including bootstrap aggregation with replacement and random subspace feature selection, substantially enhancing predictive stability and accuracy for complex theft patterns involving meter tampering and phase swapping while effectively mitigating overfitting risks through out-of-bag error estimation and committee-based decision mechanisms that outperform single-model approaches by 15-30% accuracy margins [6-9]; support vector machines identify optimal classification boundaries for nonlinear datasets through maximum-margin hyperplanes and kernel tricks (radial basis functions, polynomial transformations) but encounter computational scalability limitations with high-dimensional AMI data streams exceeding 10^6 features, necessitating approximation techniques like the kernel trick; neural networks implement multilayer architectures inspired by biological cognition to extract complex feature representations adaptively through backpropagation with Adam optimization and gradient descent with momentum, offering robust pattern recognition capabilities for non-technical losses albeit with extended training requirements measured in GPU-days, vanishing gradient challenges addressed through residual connections, and local optima convergence possibilities requiring advanced regularization including dropout layers and L2 penalties; and unsupervised clustering techniques (e.g., K-Means with silhouette scoring, DBSCAN with density reachability, hierarchical clustering with Ward's method) group consumers by behavioral similarity

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using Mahalanobis distance metrics to identify statistical anomalies through isolation forest algorithms, though effectiveness diminishes with irregular data distributions common in industrial consumers exhibiting multimodal consumption patterns. Deep learning extensions significantly expand detection capabilities through representation learning architectures: convolutional neural networks (CNNs) process spatially structured data (e.g., power quality waveforms captured at 128 samples/cycle, meter images from automated inspection drones) through convolutional filtering with ReLU activations, max-pooling operations for translational invariance, and fully-connected layers for precise anomaly identification in voltage harmonics and consumption signatures using transfer learning from ImageNet; recurrent neural networks (RNNs) model temporal consumption sequences through gated recurrent units (GRUs) with attention mechanisms for behavioral trend analysis and deviation-based theft detection, employing sequence-to-sequence architectures to address gradient challenges while processing irregular time series; deep belief networks (DBNs) integrate unsupervised feature pre-training with stacked restricted Boltzmann machines and supervised fine-tuning with contrastive divergence for hierarchical representation learning of non-linear correlations; and generative adversarial networks (GANs) implement Wasserstein GAN frameworks with gradient penalty regularization to enhance anomaly detection robustness through synthetic data augmentation, though requiring careful hyperparameter tuning via grid search and spectral normalization for training stability against mode collapse. Key enabling technologies feature: scientifically architected database infrastructures (e.g., PostgreSQL with TimescaleDB extension for time-series compression, Oracle Exadata for in-memory processing) securely managing petabyte-scale data through sharding and multi-master replication, including consumer profiles with demographic segmentation, smart meter records at 1-minute granularity with lossless compression, equipment status telemetry with OPC UA integration, and theft incident documentation with blockchain-verified chain-of-custody; intuitive graphical user interfaces with dashboard customization using Grafana and Kibana enabling real-time consumption monitoring with geospatial heatmap visualization, granular historical data queries with SQL-like syntax and export functionality to Parquet formats, and role-based system configuration with OAuth 2.0 authentication and audit trails compliant with NIST standards; distributed real-time monitoring systems with Apache Kafka pipelines and Spark Streaming triggering multi-channel alert protocols (SMS/email/REST API/webhooks) for immediate response workflows upon anomaly detection thresholds exceeding 3-sigma deviations; comprehensive digital twin implementations integrating equipment inventories with RFID/QR tagging, geospatial load profiles from LiDAR surveys, topological models with Neo4j graph databases, and operational metrics for immersive 3D asset/negative list visualization in Unity Engine environments; automated structural diagnostics employing graph algorithms (Dijkstra for shortest path, PageRank for critical node identification) to quantify nodal relationships and vulnerability hotspots across multiple dimensions; secondary system audits evaluating terminal device distribution characteristics (RTU types, IED functions, IEC 61850 communication protocols) against automation standards through conformance testing; negative list synthesis engines generating interactive deficiency reports with drill-down OLAP capabilities and ARIMA-based trend forecasting; multi-objective optimization workflows employing constraint programming with Choco solver and genetic algorithms with NSGA-II selection to derive Pareto-optimal equipment solutions balancing competing goals (SAIDI minimization below 90 minutes, fault isolation within 3 cycles, CAPEX/OPEX tradeoffs with 15% IRR thresholds); and rigorous validation protocols simulating post-renovation grid dynamics under stochastic failure scenarios using Monte Carlo methods with 10^6 iterations to verify solution resilience through probabilistic reliability modeling yielding EENS and LOLE metrics.

## 4. Conclusion

The systematic deduction of distribution network optimization schemes facilitates structured task management grounded in comprehensive negative list analytics and predictive simulation outcomes, establishing a paradigm shift from reactive maintenance to prescriptive grid modernization through model-based systems engineering. By computationally processing multiple competing objectives through advanced multi-criteria decision analysis incorporating AHP weighting and TOPSIS ranking - including maximizing inter-sector power transfer capacity through strategic tie-line reinforcement with high-temperature superconductors, minimizing outage impacts from mainline faults through intelligent segmentation using solid-state circuit breakers and intentional islanding with microgrid formation, and ensuring consumer-level faults remain isolated through adaptive protection coordination schemes employing peer-to-peer communication - this methodology generates integrated improvement plans for primary and secondary equipment deployment across the grid architecture with quantified performance guarantees documented in service-level agreements. Subsequent multidimensional evaluation matrices

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incorporating economic efficiency metrics (NPV discounted at 8%, IRR exceeding 12%, payback periods under 7 years), operational availability indices (SAIDI < 80 minutes, SAIFI < 1.2 interruptions), and resilience scoring mechanisms (TREI > 0.95) enable rigorous comparison through weighted scoring models with sensitivity analysis to identify Pareto-optimal solutions balancing technical performance and financial feasibility across the 30-year asset lifecycle. Establishing formalized review governance processes with stakeholder collaboration platforms like IBM Engineering Lifecycle Management allows predictive deduction of post-renovation grid structures and operational states through high-fidelity digital twin simulations incorporating climate change projections from CMIP6 models and technology adoption curves following Bass diffusion parameters, enabling comprehensive assessment of transformation quality through gap analysis, operational effectiveness through virtual commissioning, and long-term sustainability through carbon footprint accounting prior to capital deployment. This integrated, model-based approach ensures reliable, data-validated decision-making for distribution network construction planning, fundamentally supporting the development of resilient, high-efficiency power infrastructure capable of meeting evolving energy demands exceeding 5% CAGR while maintaining operational stability through wide-area monitoring systems and premium service continuity through self-healing capabilities employing multi-agent systems and predictive maintenance integration with CBM 4.0 methodologies. The systematic computational validation of proposed solutions through stochastic scenario testing including coordinated cyber-physical attacks simulated via MITRE ATT&CK framework, extreme weather events modeled through WRF climate simulations, and demand shock scenarios incorporating behavioral economics further strengthens confidence in planning outcomes, optimizes resource allocation through multi-scenario sensitivity analysis, and provides auditable justification for infrastructure investments through regulatory-grade reporting compliant with FERC standards, ultimately contributing to national energy security and sustainable urban development through technologically advanced grid modernization initiatives that balance reliability, efficiency, and economic feasibility across the entire power system lifecycle from conceptual planning through decommissioning and recycling, while establishing scalable frameworks for integrating distributed energy resources exceeding 30% penetration and transitioning toward carbon-neutral energy ecosystems through adaptive infrastructure design principles employing modular transformers, dynamic line rating systems, and AI-optimized VAR compensation that collectively form the technological foundation for achieving UN Sustainable Development Goal 7 through digitalized, decarbonized, and democratized energy systems resilient to twenty-first century challenges.

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