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Research Article

Simultaneous Optimization of Energy Entropy and Structural Resilience in Power Transmission Networks Using a Hierarchical Metaheuristic Algorithm

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Abstract:

Modern power transmission networks face unprecedented operational pressures driven by the rapid integration of variable renewable generation, evolving load patterns, and increasing exposure to high-impact, low-probability (HILP) disruptions—ranging from extreme weather events to coordinated cyber-physical attacks. Traditional optimization frameworks, which predominantly prioritize economic dispatch and loss minimization, often overlook two critical dimensions of system health: **spatial power flow uniformity** and **structural robustness against cascading failures**. This paper addresses this gap by proposing a novel, **multi-objective optimization framework** that **simultaneously minimizes total operational cost, reduces energy losses, maximizes structural resilience, and enhances the uniformity of power flow distribution**—quantified through the **energy entropy index**.

The core innovation of this work lies in the formulation of a **composite objective function** that, for the first time, integrates **energy entropy** as a formal metric of network load-balancing alongside a **weighted structural resilience index**. Energy entropy, derived from information theory, provides a rigorous, quantitative measure of the evenness of power distribution across transmission lines. A higher entropy signifies a more uniform utilization of the network, thereby reducing congestion hotspots, mitigating the risk of thermal overloads, and inherently enhancing system robustness. Concurrently, the structural resilience index is defined as the sum of weighted, operational lines in the network, where each line’s weight reflects its criticality to maintaining network connectivity and loop structure under a defined set of disruption scenarios.

The optimization model is subject to a comprehensive set of constraints that ensure physical feasibility and operational security:

- **AC power balance** at every bus;
- **Thermal limits** on all transmission lines, which are dynamically enforced even during simulated outages;
- **Generator output limits**, reflecting technical and contractual constraints;
- **Scenario-based disruption constraints**, where the number of simultaneously failed lines is capped (e.g., up to three lines), mimicking plausible N-k contingency events.

To solve this complex, non-convex, and mixed-variable (continuous power flows and binary line status) problem, the paper introduces a **novel Hybrid Hierarchical Metaheuristic Algorithm (HHMA)**. This algorithm is built upon the NSGA-II framework but incorporates three key enhancements to overcome the limitations of conventional metaheuristics in high-dimensional, multi-objective spaces:

1. **Stratified (Hierarchical) Selection**: The population is divided into performance tiers, and parent selection is biased toward top tiers while still preserving a controlled influx of genetic material from lower tiers to maintain solution diversity and avoid premature convergence.
2. **Entropy-Driven Mutation**: A targeted mutation operator is applied to the power flow variables. It deliberately redistributes power from heavily loaded lines to underutilized ones in a manner that provably increases the system’s energy entropy, thus directly steering the search toward more balanced network states.
3. **Controlled Binary Perturbation**: The binary variables representing line status (healthy vs. failed) are subjected to a low-probability, constraint-aware flipping mechanism to explore the space of potential network configurations and enhance resilience.

The proposed framework is rigorously validated on two standard IEEE test systems: a **14-bus network** and a **39-bus network**, under four distinct operational scenarios: a base case (no contingencies) and three increasingly severe contingency cases (1, 2, and 3 line outages). The performance of the HHMA is benchmarked against a standard Genetic Algorithm (GA).

The simulation results are compelling and demonstrate the efficacy of the proposed approach:

- In the **14-bus system**, the HHMA achieves a **14% increase in energy entropy** compared to conventional methods, indicating a significantly more uniform power flow distribution. Simultaneously, the **structural resilience index improves by 18%**, and the **total operational cost is reduced from 880 to 850 monetary units**.
- In the more complex **39-bus system**, the benefits are even more pronounced from an operational standpoint: **transmission losses are reduced from 18.4 MW to 14 MW**, and the **total generation cost drops from 3400 to 3100 units**. This demonstrates that the framework's focus on system-wide balance (via entropy) naturally leads to substantial economic and physical efficiency gains.
- When directly compared with a standard GA in the 14-bus, two-outage scenario, the HHMA outperforms it on all metrics: it achieves a **lower total cost (28,500 vs. 29,550)**, a **higher energy entropy (2.95 vs. 2.70)**, and a **superior resilience index (12.8 vs. 11.3)**, all while requiring **significantly less computational time (42.1 s vs. 60.4 s)**. This highlights the algorithm's superior convergence speed and solution quality.

The practical implications of this work are profound. By explicitly optimizing for energy entropy, system operators can proactively manage the network to prevent the formation of critical congestion pathways that are often the precursors to cascading failures. The integration of a scenario-based resilience index ensures that the resulting dispatch and network configuration are not only efficient under normal conditions but are also inherently more robust to credible disruptive events. The HHMA's ability to handle this multi-faceted problem efficiently makes it a viable candidate for both offline planning studies and, with further refinement, for near-real-time operational decision support.

In conclusion, this paper presents a paradigm shift in transmission network optimization by unifying economic, physical, and resilience objectives into a single, coherent framework. The introduction of energy entropy as a formal control objective, coupled with the development of a purpose-built hierarchical metaheuristic, provides a powerful new toolkit for enhancing the **sustainability, efficiency, and security** of future power grids. Future work will extend this framework to incorporate dynamic stability constraints, multi-period operational planning, and the integration of machine learning for predictive resilience assessment.

Keywords: Transmission Network Optimization, Energy Entropy, Hierarchical Metaheuristic Algorithm, Energy Losses.

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