Journal of **N**ovel **R**esearches on **S**mart **P**ower **S**ystems - Vol. 13 - No. 4 – Winter 2025
P-ISSN: 2322-2468, E-ISSN: 2981-0272, https://jeps.dezful.iau.ir/

Research Article

Multi-Objective Energy Management Optimization in Smart Distribution Networks Using a Hybrid Fuzzy-Genetic Algorithm in the Presence of Renewable Energy Sources, Electric Vehicles, and Energy Storage Systems

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Extended Abstract:
The modern power distribution grid is undergoing a profound and irreversible transformation, driven by the large-scale integration of Distributed Energy Resources (DERs) such as solar photovoltaic (PV) and wind generation, the proliferation of Electric Vehicles (EVs), and the deployment of Battery Energy Storage Systems (BESS). While these technologies offer immense opportunities for enhancing energy efficiency, reducing carbon emissions, and empowering consumers, they simultaneously introduce significant new layers of operational complexity. The inherent intermittency of renewable sources, the variable and mobile nature of EV charging loads, and the dynamic control requirements of storage systems create a highly non-linear, time-dependent, and multi-objective optimization problem that traditional grid management strategies are ill-equipped to handle. This research directly confronts this critical challenge by proposing a novel, intelligent, and comprehensive framework for multi-objective energy management in smart distribution networks. The core of this framework is a hybrid Fuzzy-Genetic Algorithm (FGA) that synergistically combines the human-like reasoning capabilities of fuzzy logic with the powerful global search and optimization prowess of a Genetic Algorithm (GA) to simultaneously minimize operational costs, reduce system losses, improve voltage profiles, and mitigate environmental pollution.
The proposed optimization model is meticulously designed to capture the full spectrum of modern grid dynamics within a 24-hour scheduling horizon. It integrates a diverse portfolio of assets: dispatchable Distributed Generation (DG) units (such as natural gas microturbines), intermittent renewable sources (PV and wind), stationary BESS, mobile EV fleets, On-Load Tap Changer (OLTC) transformers, and voltage regulators. Critically, the model treats the EVs not merely as an unpredictable load but as a flexible grid resource, modeling their availability for charging and discharging based on user mobility patterns—a key innovation that unlocks a new dimension of grid flexibility. The problem is formulated as a complex mixed-integer non-linear program (MINLP) with five primary, and often competing, objective functions that are normalized and combined into a single weighted objective for the optimization engine. These objectives are: (1) minimizing active power losses across all network feeders, a direct measure of technical efficiency; (2) minimizing the total cost of purchasing energy from the upstream transmission grid, which is subject to time-varying tariff structures; (3) managing the operational costs associated with the charging and discharging cycles of both BESS and EVs; (4) minimizing the total voltage deviation across all network buses to ensure high power quality and

reliability; and (5) minimizing the environmental pollution, specifically CO_2 emissions, associated with the operation of fossil-fuel-based DG units.
The true novelty and power of this work lie in its hybrid optimization strategy. The process begins with a fuzzy inference system that acts as an intelligent pre-processor and guide. This system takes key real-time or forecasted operational indicators—such as bus voltage deviations, line loading, and the state of charge (SoC) of storage systems—and uses a set of expert-defined, human-readable rules to assess the "criticality" of different network segments. The output of this fuzzy logic system is a set of priority scores that are then used to intelligently bias the initial population generation in the subsequent GA phase. This ensures that the GA starts its search in the most promising regions of the vast and complex solution space, thereby significantly accelerating convergence and avoiding the computational inefficiency of a purely random initial search. The GA then takes over, encoding potential solutions as chromosomes that represent the complete operational state of the network over the 24-hour period, including the on/off status of network reconfiguration switches, the power output of all generation units, the charging/discharging schedules for BESS and EVs, and the tap positions for OLTCs and voltage regulators. Through iterative processes of selection, crossover, and mutation, the GA evolves this population toward an optimal or near-optimal solution that best satisfies the composite objective function while strictly adhering to all physical and operational constraints, including power balance equations, voltage limits, line capacity limits, storage SoC dynamics, and the fundamental radiality constraint of the distribution network.
The performance of the proposed framework is rigorously validated through extensive simulations on the standard IEEE 33-bus test system, a widely accepted benchmark in the field of distribution system analysis. The results are presented through a series of carefully designed scenarios that isolate and evaluate the contribution of each key technology. In the base scenario, which includes only conventional DG units and loads, the system suffers from high losses (154.9 kWh), a low average voltage (0.957 p.u.), high operational costs ($14,420), and significant CO_2 emissions (1,845 kg). The sequential activation of advanced technologies demonstrates a clear and cumulative benefit: network reconfiguration alone reduces losses by 14.5%; the addition of BESS further reduces them by 7.5%; and the inclusion of EVs as flexible resources provides an additional 5.2% reduction. In the final, fully integrated "proposed" scenario, where all components (reconfiguration, BESS, EVs, OLTC, and voltage regulators) are managed by the FGA, the improvements are dramatic and holistic. Total energy losses are reduced by 29% to 109.8 kWh, the average bus voltage is improved to an excellent 0.981 p.u., total operational costs are slashed by 22.9% to $11,120, and CO_2 emissions are lowered by 23.5% to 1,410 kg. These results unequivocally demonstrate the synergistic value of a coordinated, holistic management strategy.
Furthermore, the proposed FGA is benchmarked against three other well-established optimization methods: a classical Genetic Algorithm (GA), a Particle Swarm Optimization (PSO) algorithm, and a Disjunctive Convex Hull Relaxation (DCHR) method. The FGA outperforms all of them across the board. It achieves the lowest energy loss (109.8 kWh vs. 112.9–118.8 kWh), the lowest operational cost ($11,120 vs. $11,380–$11,920), the highest average voltage (0.981 p.u. vs. 0.976–0.979 p.u.), and, remarkably, does so in the shortest computational time (96 seconds vs. 105–134 seconds). This superior performance highlights the efficiency of the fuzzy logic pre-processing, which effectively directs the GA's search and prevents it from wasting computational resources on unpromising areas of the solution space. A sensitivity analysis further confirms the model's robustness, showing that the deactivation of any single component (e.g., removing BESS or disabling the OLTC) leads to a significant degradation in overall performance, underscoring the interdependence and necessity of the full suite of smart grid technologies within the proposed framework.
In conclusion, this research presents a significant and practical contribution to the field of smart grid energy management. By developing and validating a comprehensive, multi-objective optimization model driven by a novel hybrid Fuzzy-Genetic Algorithm, the authors provide a powerful and flexible tool for distribution system operators. This framework not only addresses the core technical challenges of modern grids—intermittency, flexibility, and voltage control—but also delivers tangible economic and environmental benefits. Its demonstrated ability to outperform conventional optimization methods in both solution quality and computational speed makes it a highly promising candidate for real-world implementation. The study offers a clear pathway toward a more efficient, reliable, sustainable, and

economically viable future for distribution networks, where diverse and dynamic energy resources are managed in a fully coordinated and intelligent manner. The modular and scalable nature of the proposed approach also suggests its potential applicability to larger, more complex networks and its adaptability to incorporate emerging grid-edge technologies in the future.

Keywords: Energy Management, Smart Grid, Fuzzy Algorithm, Renewable Energy Sources.

Received: 16 Dec. 2024
Revised: 14 Jan. 2025
Accepted: 18 Feb. 2025

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Citation: H. Tavalaei, M. Samiei Moghaddam, M. Vahedi, N. Salehi, M. Hoseini Abardeh, “Multi-Objective Energy Management Optimization in Smart Distribution Networks Using a Hybrid Fuzzy-Genetic Algorithm in the Presence of Renewable Energy Sources, Electric Vehicles, and Energy Storage Systems”, Journal of Novel Researches on Smart Power Systems, vol. 13, no. 4, pp. 37-50, Ferbruary 2025 (in Persian).