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

Optimizing Energy Infrastructure in Big Cities: A Case Study of Iran's Electricity Transmission Network

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Extended Abstract:

The rapid expansion of urban populations and the consequent surge in electricity demand, particularly in developing nations, have placed unprecedented stress on national power transmission infrastructures. This challenge is acutely felt in large-scale, complex grids like that of Iran, which must balance the dual imperatives of reliability and economic efficiency while navigating a future increasingly defined by variable renewable energy sources and dynamic load patterns. Traditional planning methodologies often struggle with the sheer computational complexity and inherent uncertainties of such systems, leading to suboptimal, costly, and potentially fragile expansion plans. To address this critical gap, the research by Khademi et al. presents a novel and highly effective framework for Transmission Network Expansion Planning (TNEP) that combines a sophisticated stochastic modeling approach with a state-of-the-art metaheuristic optimization algorithm—the Golf Optimization Algorithm (GOA). The primary objective of this work is to demonstrate that by leveraging advanced computational intelligence, it is possible to derive a robust, cost-effective, and highly efficient expansion strategy for a real-world, large-scale power grid.

The core of the proposed methodology is a comprehensive two-stage stochastic optimization model. The first stage deals with the strategic, long-term investment decisions, specifically the binary choice of whether to build new transmission lines from a pre-defined set of candidate corridors. The second stage addresses the operational response of the power system under various uncertain future scenarios. This two-stage structure is crucial because it explicitly accounts for the future operational costs and reliability implications of today's capital investment decisions. The model's objective function is meticulously designed to minimize the total system cost, which is a composite of several key components: the annualized capital investment cost for new transmission lines, the expected operational cost of running conventional generation units, and the costs associated with potential load shedding and generator start-up/shut-down cycles. By including load shedding as a cost, the model inherently prioritizes solutions that maintain system security and reliability. The problem is subject to a rigorous set of physical and operational constraints, including the AC power flow equations (which accurately model real and reactive power flows, line losses, and voltage angles), generator capacity limits, transmission line flow limits, voltage stability requirements, and a hard budget constraint on the total capital expenditure. This level of detail ensures that the resulting expansion plan is not only economically sound but also technically feasible and physically realistic.

The most significant innovation of this research lies in its choice of the optimization engine: the Golf Optimization Algorithm (GOA). The authors correctly identify that the large scale and non-convex, mixed-integer nature of the TNEP problem render it computationally intractable for conventional solvers, which often fail to converge or get trapped in poor local optima. The GOA, a recently developed nature-inspired metaheuristic, is presented as a powerful alternative. The paper provides a clear and instructive explanation of the GOA's mechanics, which are elegantly inspired by the strategic gameplay of golf. The algorithm operates in two distinct phases that mirror the game: an Exploration (Drive) Phase and an Exploitation (Putt) Phase. In the Drive phase, the algorithm performs a broad, global search of the solution space by simulating a powerful stroke toward the "hole," which represents the current best-known solution. This phase is designed to escape local optima and discover promising new regions of the search space. Conversely, the Putt phase focuses on a fine-grained, local search around a promising solution, simulating the short, precise strokes required to sink the ball into the hole. This dual-phase mechanism provides an excellent balance between exploration and exploitation, which is the key to the algorithm’s success in navigating the complex and rugged landscape of the TNEP problem. The paper details the mathematical formulation of these two phases, including the use of a penalty function to handle infeasible solutions that violate the problem’s physical constraints.

The validity and practical relevance of the proposed framework are rigorously demonstrated through its application to the Iranian national electricity transmission network—a non-trivial, real-world test case. The Iranian grid is an ideal benchmark due to its vast geographical scale, its complex mix of generation and load centers, and its ongoing challenges with congestion and reliability. The simulation results are both compelling and quantifiable. The GOA successfully converges to an optimal expansion plan that achieves the primary planning objectives with remarkable efficiency. The key performance metrics are as follows: the total minimized cost of the expansion and its operational implications is 212 million USD; the plan requires the construction of only 8 new transmission lines, with a total length of 326 kilometers; and critically, the solution results in zero load shedding across all considered scenarios, confirming its robustness and reliability. Perhaps most impressively, the algorithm achieves this high-quality solution in a mere 51 seconds of computational time on a standard high-performance workstation, showcasing its exceptional computational speed.

To further validate the superiority of the GOA, the study conducts a direct comparative analysis against four other well-established metaheuristic algorithms: Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Grey Wolf Optimizer (GWO), and JAYA. The results of this comparison are unequivocal. The GOA outperforms all its competitors across every single evaluation metric. It achieves the lowest total cost (212 million USD vs. 225, 221, 217, and 215 million USD for GA, PSO, GWO, and JAYA, respectively), requires the fewest new lines (8 vs. 11, 12, 11, and 9), and has the shortest total line length (326 km vs. 412, 420, 425, and 369 km). This demonstrates that the GOA does not just find a good solution; it finds a more economically and physically efficient solution. The most dramatic advantage, however, is in computational speed. The GOA solves the problem in 51 seconds, while the next fastest algorithm (GWO) takes 897 seconds, and the slowest (GA) requires 1,589 seconds—a difference of nearly half an hour. This speed advantage is not merely a technical curiosity; it is of immense practical significance for system planners who need to evaluate multiple scenarios and run extensive sensitivity analyses in a timely manner.

In conclusion, this research makes a substantial and timely contribution to the field of power system planning. It successfully bridges the gap between theoretical optimization and practical, large-scale application by proposing a novel integrated framework that is both sophisticated in its modeling and pragmatic in its execution. The use of a stochastic two-stage model ensures that the plan is resilient to an uncertain future, while the innovative application of the Golf Optimization Algorithm provides an exceptionally powerful and efficient tool to solve the resulting complex problem. The results on the Iranian grid provide concrete, quantitative evidence of the framework’s effectiveness, showing that it can deliver a secure, reliable, and significantly more cost-effective expansion plan than conventional approaches. This work not only offers a valuable blueprint for the modernization of Iran’s energy infrastructure but also serves as a compelling case study for other nations facing similar challenges in their quest to build a more robust, efficient, and sustainable power grid for the 21st century. The demonstrated speed, accuracy, and robustness of the GOA position it as a highly promising tool for a wide range of complex optimization problems beyond TNEP, including integrated generation and transmission planning, microgrid design, and energy hub optimization.

Keywords: Optimization algorithm, generation expansion planning, realworld studies, clean energy so urces.

Received: 21 Oct. 2024
Revised: 3 Jan. 2025
Accepted: 8 Jan. 2025

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Citation: V. Khademi, F. Barzgar, Sh. Jolaee, A. Ghaffari, “Optimizing Energy Infrastructure in Big Cities: A Case Study of Iran's Electricity Transmission Network”, Journal of Novel Researches on Smart Power Systems, vol. 13, no. 4, pp. 1-12, March 2025 (in Persian).