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Research Article

Integrated generation and transmission line expansion planning considering reactive power in the presence of uncertainty of wind farms and FACTS devices

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Extended Abstract:
The ongoing transformation of power systems, characterized by the integration of renewable energy sources, the rise of distributed generation, and the increasing complexity of grid operations, demands a fundamental rethinking of traditional planning methodologies. A critical challenge in this context is the coordinated expansion of both generation and transmission infrastructure—a problem known as Generation and Transmission Expansion Planning (G&TEP). Historically, these two domains have often been planned in isolation, leading to suboptimal, inefficient, and potentially infeasible solutions that fail to account for the intricate interdependencies between where power is generated and how it is delivered. This research paper directly addresses this gap by proposing a novel, integrated G&TEP framework that explicitly considers reactive power management, the integration of Flexible AC Transmission Systems (FACTS) devices, the inherent uncertainty of wind power generation, and the growing imperative of environmental sustainability through pollution constraints.
The core objective of the proposed model is to maximize the expected profit for investors operating in both the generation and transmission sectors within a competitive electricity market framework. This is a significant departure from conventional models that typically aim to minimize total system cost, as it reflects a more realistic market-driven investment perspective. The investor's revenue is derived from two primary streams: generation investors earn income from selling active power based on the Locational Marginal Price (LMP) at their bus, while transmission investors (or a Transmission System Operator acting in an investment capacity) generate revenue from the provision of transmission services, valued by a newly defined Flow-based Marginal Price (FMP). This dual-revenue structure creates a natural economic incentive for the synergistic expansion of both assets. The total cost for the investor includes the capital expenditure for building new conventional generation units and transmission lines, the investment in FACTS devices, and the operational costs of running the conventional generators. By formulating the problem as a profit maximization exercise, the model inherently balances the trade-off between the upfront investment and the long-term operational revenue.
The physical and operational realism of the model is ensured through a comprehensive set of constraints. Most notably, the paper employs a full AC power flow model for the system equations, which accurately captures the complex relationship between active and reactive power, voltage magnitudes, and phase angles. This is a crucial advancement over many existing G&TEP studies that rely on the simplified, lossless DC power flow approximation, which ignores voltage stability and reactive power requirements—two critical aspects in modern, highly stressed grids. The model explicitly incorporates the dynamic behavior of wind farms, whose power output is modeled as a function of wind speed following a Weibull probability distribution. This stochastic treatment of wind

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speed transforms the problem into a probabilistic one, where the planning decisions must be robust against a range of possible future wind generation scenarios, thereby accounting for its inherent uncertainty. Furthermore, the model includes the installation of FACTS devices, such as STATCOMs, SVCs, TCSCs, and UPFCs, which can be deployed at candidate locations to actively control reactive power injection, line impedance, and power flow. These devices serve as a powerful, dynamic alternative to building new physical transmission lines or generators, offering a more flexible and often more economical solution to congestion and voltage stability issues. Finally, the framework integrates a hard constraint on total system pollution, limiting the amount of harmful emissions (e.g., CO_2) from conventional thermal generators. This ensures that the expansion plan is not only economically viable but also environmentally responsible, aligning with global decarbonization goals.

However, the proposed integrated model presents a formidable mathematical challenge. By combining integer decision variables (for the binary "build or not" choices of generators, lines, and FACTS devices) with the continuous, highly nonlinear, and non-convex AC power flow equations, the problem is formulated as a Mixed-Integer Nonlinear Programming (MINLP) problem. Such problems are notoriously difficult to solve, often requiring excessive computational time, and are prone to converging to local optima rather than a globally optimal solution, especially for larger test systems.

To overcome these significant computational barriers and make the model tractable for practical applications, the paper's key methodological contribution is the development of a Mixed-Integer Linear Programming (MILP) equivalent. This is achieved through a series of well-established linearization techniques. The nonlinear AC power flow equations are reformulated using a linearized AC model, which approximates the original equations with sufficient accuracy for planning purposes. The circular constraints that define the apparent power limits on transmission lines and generators are linearized by inscribing them within a regular polygon, converting the nonlinear boundary into a set of linear inequalities. Finally, the bilinear terms in the objective function (which arise from the multiplication of price and power flow variables in the revenue calculation) are replaced with equivalent linear expressions that preserve the location of the optimal solution.

The performance of both the original MINLP and the proposed MILP models is rigorously evaluated on the well-known 6-bus IEEE test system using the GAMS optimization platform with BONMIN and CPLEX solvers, respectively. The results are highly compelling. For various levels of system load, both models consistently select the same optimal set of new generation units, transmission lines, and FACTS devices, demonstrating that the linearization does not compromise the quality of the investment decisions. The most significant advantage of the MILP model is observed in its computational performance: it solves to a global optimum in a fraction of the time required by the MINLP model, which often gets stuck in a local optimum or fails to converge for higher load levels. This dramatic improvement in speed and solution reliability is a major practical contribution, making the sophisticated integrated planning framework accessible for real-world, large-scale system studies.

The numerical results also provide valuable insights into the value of the different components of the model. The analysis shows that the strategic deployment of FACTS devices can effectively eliminate the need for building new transmission lines in the test case, as they can manage power flows and voltage profiles more economically. Furthermore, the optimal location for a wind farm is shown to have a significant impact on the overall project profitability, with a more centrally located or load-proximate site yielding higher profits due to reduced congestion and lower transmission losses. The integration of an environmental pollution constraint is found to be aligned with cost-minimization objectives, as the most efficient (and thus lowest-cost) generators are often also the cleanest.

In conclusion, this research presents a comprehensive, integrated, and market-oriented G&TEP framework that successfully bridges the gap between theoretical rigor and practical applicability. By simultaneously addressing the challenges of renewable uncertainty, reactive power management, environmental limits, and nonlinear AC physics, and then providing a highly efficient MILP solution method, the paper offers a powerful new tool for power system planners. This tool can guide the development of future grids that are not only more resilient and efficient but also cleaner and more economically sound.

Keywords: Generation and Transmission Expansion Planning, linear AC power flow, wind unit, FACTS devices.

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