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# Multi-objective transmission expansion planning considering multiple generation scenarios

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ABSTRACT

This paper shows a methodology for solving the Transmission Expansion Planning (TEP) problem when Multiple Generation Scenarios (MGS) are considered. MGS are a result of the multiple load flow patterns caused by realistic operation of the network, such as market rules, availability of generators, weather conditions or fuel prices. The solution to this problem is carried out by using multiobjective evolutionary strategies for the optimization process, implementing a new hybrid modified NSGA-II/Chu–Beasley algorithm and taking into account variable demand and generation. The proposed methodology is validated using the 6-bus Garver system and the IEEE-24 bus system. The TEP is based on the DC model of the network and non-linear interior point method is used to initialize the population.

A set of Pareto optimal expansion plans with different levels of cost and load shedding is found for each system, showing the robustness of the proposed approach.



## 1. Introduction

The TEP consists on determining the required investment plan to reinforce the transmission network, in order to achieve minimum cost without load shedding. For finding an adequate plan, different aspects should be taken into consideration with the purpose of facing the new challenges that have arisen in the previous years.

Restructuring process in the electricity sector has led to a stronger interaction of technical and market aspects. Theoretically, these changes allow competition, promote higher quality and lead to better prices of the service. Planning and expansion in competitive markets should be characterized by low costs, quality, reliability and security, and accompanied by remuneration to equipment owners.

Planning also promotes network access for generators, as well as customers. The bridge to allow this access is the transmission network and all associated infrastructure, and consequently is the base for the electric market. In the case of the generation, the transmission network permits different dispatch scenarios and allows competition among the agents.

Under the previous premises, it becomes necessary to build a transmission network capable of taking advantage of future generation, supplying forecasted load, and avoiding potential congestion costs, which are at the end transferred to customers. The planning process and models must take into account investment and congestion costs, by analyzing possible dispatching scenarios resulting from market rules. The resulting power flow patterns become a test for planners, in order to model and find a suitable transmission system with plenty of capacity, and guaranteeing social welfare.

The mathematical model for planning the transmission system considers current system topology, the forecast of generation and demand, power balance equations, among others, and results in linear and non-linear algebraic expressions containing real and integer variables. Given the nature of model, it is considered as a Mixed-Integer Non-linear Programming (MINLP) problem.

### 1.1. Modeling and solving the TEP

The problem can be solved using a static approach [1–3] or a multistage model [4–8]. The Static approach considers only one generation-demand scenario, and the multistage or dynamic model takes into account several generation-demand periods of time.

Different mathematical representations have been proposed to solve the TEP. The main implemented models in order of complexity, are: transportation [9], hybrid [10], DC [4,11] and AC [12,13].

For solving the previous the mathematical models, different techniques and methods of solution have been used, such as linear

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**List of symbols**

| | |
|---|---|
| $c_{ij}$ | cost of circuit between buses $i-j$ |
| $f_{ij}$ | power flow between buses $i-j$ |
| $\gamma_{ij}$ | susceptance between buses $i-j$ |
| $n_{ij}$ | number of added circuits between buses $i-j$ |
| $n_{ij}^0$ | number of circuits in the base case between buses $i-j$ |
| $\bar{f}_{ij}$ | maximum power flow between buses $i-j$ |
| $\bar{n}_{ij}$ | maximum number of circuits between buses $i-j$ |
| $S$ | branch-node incidence matrix |
| $g$ | generation vector |
| $d$ | demand vector |
| $w, w^k$ | fictitious generation vector for the base case and for the $k$-th generation scenario |
| $f$ | vector of power flows |
| $\theta_i$ | voltage angle at bus $i$ |
| $\Omega$ | set of candidate branches |
| $\Omega_1$ | subset of generators in the lower limit |
| $\Omega_2$ | subset of generators in the upper limit |
| $N_b$ | number of buses |
| $\alpha$ | penalization factor of load shedding |
| $\delta$ | savings of supplying additional demand |
| $d_{total}$ | total system demand |
| $ng$ | number of generators |
| $gs$ | number of generation scenarios |
| $x^k$ | variable $x$ evaluated in the $k$-th generation scenario |
| $L_{max}$ | maximum allowed load shedding value |
| $BPC$ | basic planning constraints |
| $MPC$ | multiple generation scenarios constraints |
| $P_t$ | parent population of the optimization algorithm in the generational cycle $t$ |
| $Q_t$ | offspring population of the optimization algorithm in the generational cycle $t$ |
| $v_m^{max}, v_m^{min}$ | maximum and minimum value of the objective function $m$ |
| $v_m^{(I_{j+1}^m)}, v_m^{(I_{j-1}^m)}$ | neighbor solutions for configuration $j$ |
| $r_i$ | rank of solution $i$ |
| $\rho_{div}$ | number of different bits for diversity check |
| $\rho_{mut}$ | number of bits for mutation |

programming [9,14,15], dynamic programming [16], non-linear programming [17], mixed-integer programming [18], Benders [19,20], and also decomposition techniques such as Branch-and-Bound [21]. Besides classical techniques, metaheuristic methods have also been satisfactorily used as an alternative, for instance, references [1,22–28] show how TEP is solved using Simulated Annealing, Tabu Search, Genetic Algorithms and Particle Swarm Optimization. Other recent metaheuristic optimization techniques, such as frog leaping, immune systems, ant colony, chaos and bee colony algorithms, have also been used as referenced in [3].

### 1.2. Planning the transmission network in a market environment

Deregulation in electricity markets have led to new challenges in the planning process. Under a market environment, the network expansion must ensure equity in access for all system participants, which leads to additional complications in the model. The following paragraphs summarize some of the proposed approaches to face these new challenges.

Reference [29] develops a multi-period model which takes into account nodal prices, line congestion, financial investment parameters and their relation with the amortization during the planning period. The model is validated on the Spanish network and different scenarios of demand and contingencies are used.

A multiobjective methodology is presented in [30], incorporating investment cost, congestion cost and reliability level, which are to be minimized. A multi-period model is solved and the NSGA-II algorithm is used to return a set of non-dominated solutions.

Author in [31] used an improved differential evolution model to address the TEP. Market considerations were included by calculating annual generation cost for different technologies and by adding annuitized cost of transmission. The author also performs a comparison of the results of differential evolution and the genetic algorithm for the IEEE 30-bus system.

The work presented in [32] solves the TEP by including the curtailment cost for bilateral transactions and the one associated to customers for spot market, besides the investment for new transmission equipment. This way, the network is reinforced in such a way that congestion constraints are alleviated in order to allow market transactions. Benders decomposition is used and the methodology is validated on the South-Brazilian system.

Particle Swarm Optimization was used in [33] to obtain optimal plans for Garver and IEEE 24-bus systems. The problem considers a multi-year model and the expansion process depends on the investment costs, and the social welfare. A performance comparison of different swarm approaches is also carried out.

Another market approach is shown in [34]. The objective function includes operation cost, load curtailment and investment cost for different load levels, with the idea of providing equity to all market participants. The model considers multiple stages and the solution is found by a genetic algorithm for Garver and IEEE 24-bus system.

The approach presented in [35] used a congestion surplus index through lagrange multipliers, in addition to the transmission investment and the expected energy not supplied. All of the objectives are to be minimized and the Strength Pareto Evolutionary Algorithm (SPEA) was used to obtain a set of Pareto optimal solutions.

An alternative for treating the described problem is shown in [36]. In this work, a procedure for network reinforcement in a deregulated environment is designed, different patterns for power flow are considered and a decision scheme is incorporated to minimize the risk of the selected plan. The authors design and select a number of generation scenarios with a probability of occurrence for a future year. This problem was also faced in [37] considering network security (N-1 contingency criteria). The way of solving this problem using a mono-objective approach is shown in [38].

### 1.3. About the present work

This paper proposes an approach for the TEP when full open access for generators is considered. As a result, multiple power flow patterns need to be analyzed in order to obtain a set of investment proposals. An enhanced multiobjective algorithm is used to obtain a set of Pareto optimal expansion plans with different level of investment and future load shedding. The solutions provide adequate operative conditions for any load flow pattern resulting from any dispatch scenario, ensuring low potential values of load shedding. This is achieved by considering the feasible Multiple Generation Scenarios (MGS) and also taking into account demand and generation as a variable in a narrow range. The proposed method