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Automatic selection of candidate investments for Transmission Expansion Planning

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ABSTRACT

This paper deals explicitly with the problem of proposing candidate lines (sometimes referred to as *technical alternatives*) for Transmission Expansion Planning (TEP). Candidate lines have been traditionally regarded as expert-provided system information. However, given the need to plan larger networks, identifying interesting candidates is an issue of increasing relevance and complexity. This paper proposes a consistent method to tackle this problem.

First, an automatic and objective *candidate discovery* mechanism based on sensitivities proposes potentially interesting investments. Then, a *candidate management* strategy filters the list of candidates to keep problem size within tractable levels in a Mathematical Programming context without compromising global optimality. Finally, a *candidate analysis* tool reveals the relationships among investments from a relatively fast and simple power flow study. This information can be interesting to provide support for expansion decisions. These theoretical developments are complemented by a realistic case study which illustrates the applicability of the method.

1. Introduction

Transmission Expansion Planning (TEP), the problem of "deciding which new lines will enable the system to satisfy forthcoming loads with the required degree of reliability" [1], is one of the most fundamental issues that articulate power systems strategy. This practical importance is manifest in the extensive treatment that this subject has received in the academic literature [2]. The ramifications of this decision problem extend from system operation, static reliability and dynamic stability analyses to environmental and political considerations. For this reason, when confronted with this problem, TSOs tend to structure the decision process in different stages:

- Several alternative expansion plans are proposed. These proposals can be generated manually by the planner or obtained by applying optimization methods. In the latter case, the size of the problem makes it often necessary to simplify its scope by using a reduced model of the system and considering only some of the relevant objectives. The general approach seems to be to consider system operation cost and static reliability [2]. These two objectives are the ones that have arguably the largest impact on cost and can be efficiently incorporated into an optimization problem.

  The alternative expansion plans are evaluated, this time, in all the relevant objectives. These can include stability and short-circuit currents, flexibility [3], social acceptance or environmental impact as seen in other TEP and Generation Expansion Planning (GEP) studies [4].

- The decision maker selects his preferred expansion plan from the list of alternative expansion plans that score acceptably in his/her objectives. Multi-Criteria Decision Methods can be used to guide this selection [5].

When the alternative expansion plans are generated by optimization, the problem is generally understood as the selection of the best combination of individual investments from a pre-defined list of candidate lines and other equipment (also sometimes referred to

Abbreviations: TEP, Transmission Expansion Planning; MP, Mathematical Programming; TSO, transmission system operator; NERC, North American Electric Reliability Corporation; ENTSO-e, European Network of Transmission System Operators for Electricity; TYNDP, Ten-Year Network Development Plan; DCPF, Direct Current Power Flow; ACPF, Alternating Current Power Flow; LP, Linear Programming; MIP, Mixed-Integer Programming; MINLP, Mixed-Integer Non-Linear Programming; REE, Red Eléctrica de España; E-SIOS, Sistema de Información del Operador del Sistema Eléctrico Español.

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as *technical alternatives*). This list is generally considered part of the input data of the problem:

- Academic studies assume candidates are provided externally.
- Practical applications, usually carried out by the relevant transmission system operator (TSO), make use of the TSO's own knowledge and experience about the system. Candidate lines are defined manually according to the planner's expertise.

However, this traditional approach can lead to fundamental problems that are becoming increasingly relevant.

First, it is possible that the planner's expertise fails to identify candidate lines with a better potential than the ones actually included in the list, leading to a suboptimal final solution.

In addition, market integration means that there is a trend to plan increasingly large geographical areas where new generation (particularly renewable) can be located far away from demand areas [6]. TSO's have experience on their individual systems, which can be very large, as for instance in the NERC regions [7]. However, when planning several regions coordinately, most often there is no entity familiar with the whole area, and therefore large investments, stretching among several territories, could be overlooked. These investments constitute the backbone of supergrid architectures and are therefore extremely relevant for TEP in large regions. This is manifest in studies such as ENTSO-e's Ten-Year Network Development Plan (TYNDP) [8], which performs a bottom-up approach where investments are proposed by TSOs in the scope of their individual regions and are integrated at a later stage.

A similar problem arises when the object of TEP is a new region where there is no previous experience. An interesting example is the design of an offshore grid in the North, Ireland and Baltic Seas [9].

It is also important to note that the inherent computational difficulty of optimal TEP (usually formulated as a discrete combinatorial problem) makes it necessary to limit the size of the candidate list in order to keep the problem tractable. It is therefore impossible to consider all the feasible investments as a way to avoid the candidate selection problem. What is more, in very large systems, even a reduced list of *interesting* candidates (as opposed to all feasible candidates) can be excessive for optimization.

The method proposed in this paper stems from the need to deal rigorously with these issues:

- Candidate investment proposal demands automatic, objective methods rather than manual processes relying on individual or institutional expertise.
- The potentially large number of interesting candidates should be managed in order to keep problem sizes tractable.
- When candidates are proposed by the planner, they can be easily related to specific needs in the existing network (e.g. integrating new generation or reinforcing a congested corridor). The relationships among them are therefore understood (e.g. alternative circuits that serve the same function or lines that complement each other to create a longer corridor). However, if candidates are proposed automatically, this information is no longer available. It would be desirable to recover as much of this knowledge as possible and make it available for decision support.

These identified needs, which do not seem to have been explicitly dealt with in the literature, are the three main points around which the contributions of this paper are articulated. An automatic candidate discovery method is proposed. In addition, an algorithmic candidate reduction algorithm is developed in order to keep problem sizes tractable while guaranteeing optimality. This algorithm has been efficiently incorporated into a Benders' decomposition framework so that existing cuts can be easily updated to incorporate the newly discovered candidates. Finally, a candidate explanation mechanism elicits the relationships among candidates with the aim of supporting decision making. This article is structured as follows. First, the TEP problem is introduced in Section 2. Then, the developed method is shown in Section 3. Sections 3.1–3.3 detail the candidate discovery, management and explanation techniques that conform the main contributions of this paper. The case study is described in Section 4 and its results are summarized in Section 5. Finally, Section 6 discusses these results and extracts conclusions.

2. Material and methods

The TEP problem consists in selecting the optimal network additions that minimize the sum of first-stage (investment) and second-stage (operation) costs.

Several modeling decisions characterize TEP applications. As far as decision structure is concerned, most TEP studies solve a static version of the problem [10], where only a particular moment in time is represented. Some consider a sequential static case [11], with several instants that are optimized successively and a few applications include a complete dynamic description [12]. Uncertainties naturally present in the problem (demand, renewable generation production or contingencies) have been incorporated through stochastic optimization [13], which minimizes the expected cost, or robust optimization [14], which carries out a worst-case approach. Medium term studies usually consider centralized TEP with competitive operation [15], while long-term models most frequently deal with centralized TEP with cost-based operation [16]. Power flows can be described with a transportation model [17] or a DCPF [10], which seems to be the preferred option. In general, a full ACPF is generally computationally intractable for TEP optimization [2], although some heuristic models have been proposed [18]. It should be noted that optimizing on a DCPF model does not imply ignoring the considerations that can only be captured with an ACPF (such as stability). They will be incorporated at a later stage of the planning, in the exhaustive evaluation of the alternative expansion plans that have been defined.

A wide array of techniques has been applied to the TEP problem. LP applications consider continuous investment and use a transportation model or a DCPF [19]. MIP considers discrete investment variables [20]. Some MINLP approaches have also been proposed [21]. Stochastic decomposition techniques have also been extensively applied as a result of a problem structure particularly amenable to these techniques as will be discussed [13,16,22,23]. Outside the classical optimization space, the TEP problem has been undertaken using methods such as greedy searches [24] (in particular, guided by sensitivity analyses [25]), Expert Systems [26], or metaheuristics like Genetic Algorithms [27], Simulated Annealing [28] or Swarm Intelligence [29].

A stylized formulation of the problem is shown below, which is based on the simpler model which appears on [30]. The stochastic scenarios refer to the different sources of uncertainty present in the problem such as load levels, renewable energy production or contingencies.

2.1. Indices

i, j	nodes
c	circuit
EL, CL	existing and candidate lines respectively