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Discrete Optimization

Robust transmission expansion planning

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A B S T R A C T

The work reported in this paper addresses the problem of transmission expansion planning under uncertainty in an electric energy system. We consider different sources of uncertainty, including future demand growth and the availability of generation facilities, which are characterized for different regions within the electric energy system. An adaptive robust optimization model is used to derive the investment decisions that minimizes the system's total costs by anticipating the worst case realization of the uncertain parameters within an uncertainty set. The proposed formulation materializes on a mixed-integer three-level optimization problem whose lower-level problem can be replaced by its KKT optimality conditions. The resulting mixed-integer bilevel model is efficiently solved by decomposition using a cutting plane algorithm. A realistic case study is used to illustrate the working of the proposed technique, and to analyze the relationship between the optimal transmission investment plans, the investment budget and the level of supply security at the different regions of the network.

1. Introduction

Within an electric industry context, Transmission Expansion Planning (TEP) refers to the decision-making process faced by a Transmission System Operator (TSO) to resolve on the best way to expand or reinforce an existing electricity transmission network. De Dios, Soto, and Conejo (2007) provide an industry perspective of this important decision-making problem. The TSO is the publicly controlled entity in charge of operating, maintaining, reinforcing and expanding the electricity transmission network within a given jurisdiction. TSOs in the different European countries are coordinated through ENTSO-E (ENTSO-E, 2013). In the US, TSOs have generally more limited attributes than TSOs in Europe, and are generally referred to as Regional Transmission Organizations (RTOs). Well-known RTOs in the US are PJM (PJM Interconnection, 2013), and the Midwest Independent System Operator (Midwest Independent System Operator, 2013).

The aging of the electrical transmission infrastructure is nowadays apparent in many electric energy systems throughout the world, as pointed out in the MIT technical report (MIT Energy Initiative, 2011). Therefore, it is most needed the development of mathematical models and computation tools to help TSOs to make effective decisions regarding the improvement and updating of the electricity transmission infrastructure. Such decisions have to be made under great uncertainty due to the uncertain nature of both the electrical demand growth and the stochastic production of some generation facilities, such as wind- or solar-based units. This uncertainty has both spatial and temporal dimensions as demands and production facilities are located at different geographical sites, and the demand and the stochastic production are both temporally correlated (Baringo & Conejo, 2013). Additionally, uncertainty pertaining to equipment failure also affects the operation (Bouffard, Galiana, & Conejo, 2005) and thus the expansion/reinforcement planning of the transmission network.

Transmission planning decision-making involves usually a planning horizon of approximately 10 years with revisions every 2 years, as described, for instance, in De Dios et al. (2007). Nevertheless, this planning horizon might be shortened or lengthened depending on construction, environmental or policy considerations. Building time for transmission facilities are much shorter that such times for production facilities and range between 6 months and 2 years. Therefore TEP is a medium-term expansion planning problem with a smaller level of uncertainty than that involved in the investment in production facilities. Moreover, the planning exercise should account for the entire life of the infrastructure to be built. However, using a year-by-year representation of investment decisions may result in a very complex and computationally intractable model. In order to ensure tractability while keeping the model accurate enough, one or few target years are usually selected for the planning exercise and annualized investment costs are considered (see for instance

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De la Torre, Conejo, & Contreras, 2008; Garcés, Conejo, García-Bertrand, & Romero, 2009; Jabr, 2013; Sauma & Oren, 2006). Nevertheless, properly capturing the effect of the uncertain parameters on the investment outcomes is critical to achieve effective transmission investment plans.

The pioneering work on transmission expansion planning is reported in Garver (1970), while relevant contributions based on mathematical programming are due to Pereira and his collaborators in Brazil, e.g., Monticelli, Santos, Pereira, Cunha, Parker et al. (1982), Pereira and Pinto (1985) and Binato, Pereira, and Granville (2001). Relevant heuristics have been developed by Romero and his collaborators, e.g., Romero, Gallego, and Monticelli (1996). Stochastic programming is used, among other works, in De la Torre (2008) and Villumsen and Philpott (2013). Modeling explicitly a market environment in the decision-making process is addressed in Garcés et al. (2009), while an interesting game-theoretical approach is proposed in Sauma and Oren (2006).

Infrastructure is generally designed to be able to operate correctly under the worst plausible condition, e.g., a bridge should withstand a maximum weight under adverse climate conditions and a sea breakwater should withstand the strongest plausible wave. Thus, traditionally, any infrastructure is designed considering solely the worst plausible condition of future operation. In fact, regarding electricity transmission expansion planning, this is common practice.

Note that on a daily or hourly basis, the objective in electricity systems is generally minimizing expected operating costs. This is mainly because, in general, the different sources of uncertainty that are present in the system can be predicted accurately in the short-term, e.g., level of demand, wind power production, equipment availability, etc., and thus the probability of occurrence of an unforeseen event, with a high potential damage, is very small.

However, this framework drastically changes when the operation of the system is seen years in advance, and planning decisions, like transmission expansion, need to be made. In this case, there is a high uncertainty about which would be the operating conditions within the lifetime of the new infrastructure (30–50 years ahead). Moreover, these investment decisions are in general irrevocable because of their high investment costs.

Therefore, infrastructures must be designed so that they perform well under extreme operating conditions. Note that this is generally guaranteed by ensuring the correct functioning of the system under the worst possible operating condition.

However, the worst future condition is unknown and we have to cope properly with this uncertainty with real reliability and economic consequences. If we are conservative and design a transmission system around a worse-than-actual condition, we end up building a stronger transmission system than needed at higher cost. If we, conversely, design a transmission system around a better-than-actual worst-case, we build a transmission system unable to withstand the actual worst condition, resulting in collapse or losses. To confront this challenge, we propose describing uncertainty through plausible robust sets. These sets are meant to represent a range of possible worst-case outcomes for use in infrastructure planning.

Additionally, we need to ensure that the future transmission system will be able to withstand the worst plausible operation condition, hence we will work on robust optimization approaches, i.e., approaches that guarantee worst case protection within a plausible uncertainty set. Moreover, since the robust sets that we use are parameterized through a set of conservatism parameters, we are able to characterize the critical tradeoff security vs. cost and generate an array of efficient design solutions for the decision-maker to choose.

Adaptive robust optimization (ARO) (Bertsimas, Brown, & Caramanis, 2011) allows modeling decision making under uncertainty with recourse. For transmission expansion problems, ARO involves three steps: investment decision making pursuing maximum social welfare, worst uncertainty realization within a plausible uncertainty set that respects the physics of the problem, and operation decision making to mitigate the negative effect to the uncertainty realization and to achieve maximum social welfare. Traditional robust optimization techniques (Soyster, 1973) do not allow for controlling the level of robustness, i.e., conservatism, of the solution attained, which is a major drawback; however the work in Bertsimas et al. (2011) introduces formulations that make it possible to control the level of robustness of the solutions attained. Such formulations allow developing valuable planning tools, which are relevant in practice.

ARO has two important advantages with respect to stochastic programming models that generally require a large number of scenarios to represent the uncertainty involved (Gabrel, Murat, & Thiele, 2013). On one hand, scenarios need not to be generated, and since generating scenarios, based on statistics distributions or others, may entails a crude approximation on the description of the uncertain parameters, not needing scenarios is an advantage. Instead, robust sets are used in ARO models (Bertsimas & Brown, 2009), and constructing such sets is generally much simpler than generating scenarios. On the other hand, an ARO model has commonly a moderate size, which does not grow with the number of scenarios, and thus, computational tractability is not at stake. On the contrary, the size of a stochastic programming model grows with the number of scenarios, which may result in intractability; and often, a large number of scenarios is needed to accurately represent the uncertain parameters.

A recent application of ARO to transmission expansion planning is reported in Jabr (2013). This approach is similar to the one presented in this paper but differs in the solution methodology, the technical features of the proposed model, and the type of analysis performed. First of all, a Benders decomposition scheme, which requires the computation of dual variables, is used in Jabr (2013) to solve the ARO problem while we apply a constraint-and-column generation method solely based on primal cuts. Second, the uncertainty budget used in Jabr (2013) limits the number of uncertain parameters that are allowed to change. The subproblem is then simplified assuming that all the uncertain parameters need to be equal to their upper or lower limits in the worst case scenario. However, the uncertainty budget considered in this work is more general since we just limit the level of variation of the uncertain parameters within the robust set, which also allows characterizing regional uncertainty budgets. Third, Jabr (2013) does not account for the investment budget while part of our study is focused on analyzing the effect that this budget has on the optimal transmission planning. Finally, we also study in detail how an increase of the uncertainty level and/or the investment budget reconfigures the optimal set of lines to be built.

To tackle the transmission expansion planning problem, we propose a novel adaptive robust optimization model that includes the features below:

1. The objective is to minimize the system's investment cost plus the worst possible operating costs (under different levels of conservatism) over the considered planning horizon.
2. Uncertain parameters involving demand growth, stochastic generation levels and equipment failures are described using a robust set.
3. The level of robustness is controlled using a variety of physically-based budget constraints over the robust set.
4. The three-level decision framework considered involves (i) making investment decisions pursuing minimum total cost, (ii) worst uncertainty realization within the plausible uncertainty set, and (ii) implementation of operation decisions pursuing minimum total cost.

Mathematically, the proposed model materializes in a min-max-min problem apparently hard to solve. However, using the optimality condition of the right-hand-side min problem, the two inner problems (max-min) can be merged into a single max problem. This results in a final min-max problem with bilinear terms that can be efficiently