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Finding a representative network losses model for large-scale transmission expansion planning with renewable energy sources

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ABSTRACT

The global drive for integration of RESs (renewable energy sources) means that TEP (transmission expansion planning) has to be carried out over geographically wide and large-scale networks under high levels of uncertainty. This leads to complex combinatorial TEP optimization problems, requiring a huge amount of OPF (optimal power flow) computations. The algorithm employed to calculate the OPF must be reasonably accurate but computationally very efficient, because it has to be run for a lot of operational conditions. Overly simplified OPF formulations are not adequate, since they neglect aspects which play a relevant role in TEP. Specifically, network losses significantly influence TEP solutions, but they are often disregarded due to their computational burden. Given their potential impact on the optimal TEP solution, the main focus of this paper is to find an appropriate losses model in the context of medium to long-term TEP for large-scale power systems. Keeping the balance between accuracy and computation time is essential in such problems. The paper presents two alternative linear losses models, as well as two variants of existing ones. These models are compared and tested using case studies, including small, medium and large-scale networks. Practical conclusions and recommendations are drawn from numerical results.

1. Motivation and literature review

The global push for the integration of RESs (renewable energy sources) involves planning the expansion of the transmission grid over geographically wider areas. Moreover, the expected high penetration of RESs introduces significant uncertainties in the development and operation of the system, which need to be accounted for. In most cases, large-scale renewable generation projects will be located far away from major demand centers. Due to the intermittency of their production, ensuring an acceptable level of guarantee of supply in systems with very high RES (renewable energy source) penetration will require a well-developed transmission network with sufficient capacity to transport the renewable power produced at remote areas to any other area where renewable production is very low. Depending on the availability of RESs, the power flow patterns of the system are expected to undergo dramatic changes over time.

As a result, to properly address a TEP (transmission expansion planning) study, a large number of operational states (snapshots) and network investment candidates must be considered, together with several timeline scenarios (or storylines) to represent the uncertainty about the evolution of the system in the future. This leads to a very complex combinatorial TEP optimization problem, requiring a large number of OPF (optimal power flow) computations, which can eventually become intractable. The common practice of considering only the OPF for the peak demand scenario is no longer valid in such power systems, particularly in the context of TEP, where operational states stressing different parts of the network may be largely different. Thus, the OPF formulation considered in TEP should be computationally very efficient to ensure tractability while delivering results with an acceptable level of accuracy. For instance, using a full AC-OPF (alternating current optimal power flow) model, similar to the model used in Ref. [1], is not computationally affordable for such a problem, while the classic DC-OPF (direct current optimal power flow) [2] may not be a good solution either because it neglects transmission losses. In general, the OPF formulation should feature all aspects that are believed to play a non-negligible role in TEP, especially in large-scale systems.

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Network losses may change the economic generation dispatch and affect optimal solutions for the development of the network; see in Ref. [3] and more thorough analyses in Ref. [4]. In spite of this, losses are frequently neglected in TEP models or treated in an overly simplified way, mainly to reduce the computational burden when dealing with systems of a significant size. Finding an appropriate representation of losses is critical when the scope of the considered system becomes as wide as the full European transmission network [5]. Moreover, as mentioned previously, large power flows are expected in large-scale network of systems with high penetration of RESs, leading to higher losses which could in turn play a more relevant role in TEP.

When using the conventional AC-OPF model, network losses (both active and reactive) are implicitly modeled because such model includes all network parameters. However, the resulting problem is highly nonlinear and non-convex which makes computing the optimal solution very demanding. Acknowledging the complexity of the AC-OPF problem, distributed and parallel computation schemes are proposed in Ref. [6]. But in some cases, the AC-OPF problem is directly solved via mathematical optimization techniques (for example, the interior–point method in Ref. [7]). Due to the nature of the problem, such techniques often rely on a series of approximations to reduce its complexity. Moreover, the nonlinear and non-convex nature of the problem means global optimality could be highly compromised because the solution algorithm could get stuck at local optima. This limitation, combined with the complexity of the AC-OPF problem, led researchers to resort to different heuristic and meta-heuristic solution methods which are based on different nature-inspired algorithms such as: harmony search [8], evolutionary programming [9], imperialist competitive [1], chaotic invasive weed optimization [10], particle swarm optimization [11], shuffle frog leaping [12] and many others [13]. Such solution approaches are claimed to find “good” solutions within an acceptable computational time but provide no guarantee of achieving global optimality. Generally, even if the AC-OPF network model is the most detailed and accurate modeling approach, its practical application is only limited to flow analysis pertaining to single or very few system snapshots due to its mathematical complexity. In other words, it is computationally expensive, if not impossible, to carry out multi-faceted analysis using an AC-OPF based network model and given the sheer size of current power system networks with a high level of uncertainty (for example, long-term TEP problems). Therefore, a full modeling of losses (i.e. using an AC power flow model) is not computationally affordable, especially in the TEP context. Therefore, a tradeoff between accuracy in losses representation and efficiency (in computational terms) of the OPF model becomes critical to address TEP studies with high renewable generation penetration scenarios and large-scale networks. This paper addresses this objective and contributes losses formulations and a strategy to solve the resulting problem that best achieves this trade-off. The proposed losses models andother existing ones are compared in terms of accuracy in losses representation and computational efficiency.

A review of some of the existing linear modeling approaches of losses is provided in Ref. [14]. A losses model based on mixed integer linear programming is reported in Ref. [4], applying a piecewise linear approximation of the quadratic expression of losses. And, the same model is applied in TEP studies in Ref. [15]. An iterative way of adding linear constraints is adopted in Ref. [14] using a dynamic piecewise linear model. In this case, the fully accurate expression of losses is iteratively approximated by adding linear cuts of actual transmission losses. A further extension of this iterative approach is reported in Ref. [16], where losses are approximated by progressively adding linear cuts of equally distributed nodal losses, instead of line losses. The node-based approach in Ref. [16] is reported to take advantage of the fact that there are fewer nodes than lines in a typical power system. Iterative or dynamic methods to compute losses are feasible in small to medium-scale systems, but in very large-scale systems, performing several iterations may be computationally unaffordable.

In some cases, a single linear losses equality constraint determined by curve fitting is used [17], but this may either overestimate or underestimate transmission losses, depending on the parameters of the constraint (i.e. slope and intercept). In a similar manner, the authors in Ref. [18] simply represent losses in a given line as a certain percentage of its flow. In other cases, a quadratic function of losses is merely added to a DC branch flow model to account for losses in TEP [19]. But this adds nonlinearity to the problem, thus, negatively influencing the convergence speed of the computation process. Elsewhere, in problems other than TEP such as locational marginal price calculations, transmission losses are modeled by a fictitious load either concentrated at a single node (often the slack bus) or distributed among all nodes of the system. The distribution of losses is based on either predefined [20] or adaptive coefficients (alternatively termed as distribution factors of losses) [21]. In Ref. [20], the entire system losses are distributed among all nodes based on fixed losses distribution factors obtained from an AC power flow analysis; whereas, the authors in Ref. [21] assume the losses in each line are distributed as additional loads between its terminals. In the latter case, the distribution factors are computed by means of a DC power flow analysis and losses are iteratively estimated. A further extension of the work proposed in Ref. [20], with adaptive coefficients instead of fixed ones, is presented in Ref. [22], and authors in Ref. [23] combine and extend the methods developed in these works, i.e. an iterative linear approximation of losses with adaptive coefficients is employed in Ref. [23]. These coefficients are modified iteratively based on information obtained from an AC power flow analysis, the operational system states, the operation point of generators and the network parameters.

In GEP (generation expansion planning) frameworks, transmission losses and hence their associated impacts on the system are mostly neglected because GEP is often carried out without considering transmission networks. A few works in the GEP subject area incorporate losses by using certain loss allocation methods. For example, losses in transmission and distribution networks are simply considered to be a certain percentage of the demand to be supplied at each node in Ref. [24]. The authors in Ref. [25] account for losses by multiplying the total power generation at each node with a predefined coefficient (which ranges from 1.08 to 1.10). Similarly, power injections at each node are assumed to comprise a certain ratio of losses [26]. Losses estimated using such approaches may be sufficient in the GEP context; however, such a rough estimation method cannot be extended to TEP, which must consider the entire network system.

Another losses modeling approach, mostly common in ED (economic dispatch) problems, is Kron's loss formula [27], which is based on the concept of marginal transmission losses allocation. Here, losses are represented as a function of levels of power injections (i.e. power generation levels of generating units). This can be understood as an approach which calculates the marginal increase in transmission losses due to an increase in the load or generation level. The so-called B-loss coefficients [27] capture such sensitivity factors i.e. the transmission loss coefficients. These coefficients are determined once using power flow analysis and often considered to remain unchanged over a large set of operational situations, which seems to be a very conservative assumption. In Ref. [28], Kron's loss formula is used to estimate losses in an ED problem which minimizes the total cost of power generation. Transmission losses are also modeled using the same formula in a stochastic [29] and a deterministic [30] multi-objective ED