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Transmission network expansion planning considering load correlation using unscented transformation

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ABSTRACT

In this paper, correlation between uncertainties related to loads is addressed in transmission network expansion planning (TNEP). The TNEP problem is formulated in a multi-objective form with objective functions of minimum investment cost, minimum congestion cost, and minimum risk cost. Load correlation is modeled using unscented transformation method and compared to a simulation method. Initially, the impact of load correlation on congestion cost and risk cost is shown. Then, using the Pareto solutions of this multi-objective TNEP problem, impact of load correlation on the TNEP solutions is illustrated. The Pareto solutions are obtained using the Non-dominated Sorting Genetic Algorithm II (NSGA II) that is capable in handling non-convex and non-linear problems with mixed integer structures. Test results are provided for the IEEE 24-bus Reliability Test System (RTS) and a representation of the actual Iranian 400 kV transmission network.

1. Introduction

Transmission Network Expansion Planning (TNEP) is one of the most important aspects of traditional power system planning, in which generation had to provide sufficient capacity to meet the anticipated needs of loads and energy had to be transferred in a reliable and economically efficient manner. However, after deregulation, TNEP has been focusing also on the necessity of providing nondiscriminatory and competitive market conditions to all participants with respect to reliability criteria [1,2].

In general, planning the expansion of transmission networks is majorly challenged by the presence of a high number of uncertainties. These uncertainties can significantly affect the results of expansion plans and, therefore, TNEP must always find an optimal solution able to withstand the effects of such uncertainties [2,3].

Generally, there are two categories of random and nonrandom uncertainties in power systems; random ones are mainly related to loads, wind farms' generation, non-programmable generation resources, generators' bids and outputs, availability of power system facilities, demand response policies, etc.; nonrandom uncertainties are usually to be found in generation plant expansion/shut down, load growth/reduction and in the evolution of market rules [3,4]. Each of these uncertainties must be tackled using proper modeling techniques. In general, the existing uncertainty modeling tools can be classified as probabilistic approaches, possibilistic approaches, hybrid possibilistic–probabilistic approaches, information gap decision theory (IGDT), and robust optimization [5].

Among all, load uncertainty has always been discussed in TNEP, since the future value of a load is notably uncertain and the actual final aim of power system is to supply energy to that load with a satisfactory reliability level. It is a fact, that a well-expanded transmission network is needed for achieving a reliable load supply [3,6–8]. However, addressing load uncertainty in TNEP calculations requires a proper modeling. Since load is characterized by a probabilistic behavior, probabilistic methods are considered proper to this end. In [9], the probabilistic method based on clustering is used to model uncertainty of load and output power of wind turbines. Ref. [10] modeled uncertainties of loads and wind speeds at wind farms as probabilistic distribution functions (PDFs).

Generally, the probabilistic methods are numerical or analytical [5]. From the numerical types, the Monte Carlo Simulation (MCS) is well-known in TNEP literature [3,7,11]. The point estimate methods, from the analytical methods, have been used in publications on TNEP [4,6,8]. However, in previous works on TNEP, correlation among uncertainties was not considered, mostly because basic MCS and point estimate methods are incapable in modeling correctly variables correlation. As shown in [12,13], in every power systems there are noticeable inherent correlations among different uncertain variables. Generally, it can be said that load values at near load centers increase/decrease together. The load correlation is mainly due to the presence of

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certain factors such as weather conditions that can affect large sets of consumers in a same way. Also, there are correlations among other uncertainties such as wind power generations and solar generations. Correlation among uncertainties may be either positive or negative and may appear among different types of uncertainties [12,13].

In [12], it was shown how correlation between uncertain input variables (load, generation and wind power generation) can significantly influence parameters of a power system, such as line flows. In such work, unscented transformation (UT) method was applied to consider correlations in probabilistic power flow calculations. The UT method is a suitable tool for assessing probabilistic and nonlinear problems in the presence/absence correlation between uncertain input variables [14]. Ref. [15] used copulas functions to model dependence of loads and wind parks generations in Netherlands. The copulas method is an improved MCS technique wherein dependency among dependent variables can be taken into account in sampling.

In this paper, a proper tool to consider the impact of correlation between uncertainties related to loads on TNEP problem is presented. It should be mentioned that as far as the authors know, the load correlation is not studied in the TNEP problem. The main contribution of this paper is studying the impact of this correlation on TNEP. Wherein, the TNEP is formulated as a multi-objective optimization problem where objective functions are aimed to minimize investment costs, congestion costs, and risk costs in a deregulated energy market environment. Initially, it is shown how different levels of load correlation can affect congestion as well as risk costs in power systems. The load correlation is modeled by UT method, and the results compared with those obtained by applying a copula method.

With the application of different correlation coefficients, the complete TNEP problem is solved showing how load correlation can change transmission network expansion solutions and plans. Optimal solutions are identified considering the Pareto solutions of the mentioned multi-objective problem, showing the impact of load correlation on objective functions and network expansion plans. In this paper, the Non-dominated Sorting Genetic Algorithm II (NSGA II) is used to identify such solutions. This algorithm is capable in handling a non-convex and nonlinear problem with mixed integer structure [16,17]. Finally, for each value of load correlation factor, a final optimum plan is found to reduce congestion cost and risk cost to predefined values. The simulations are implemented in MATLAB platform on the case studies of IEEE 24-bus Reliability Test System (RTS) and on the Iranian 400 kV transmission network.

The reminder of this paper is as follows. Section 2 explains some basic concepts, mathematical modeling and solution methodology of the problem. The simulation results are presented in Section 3 and the drawn conclusions are in Section 4.

2. Modeling and methodology

The basic concepts, the problem mathematical modeling and solution methodology are presented in this section.

2.1. Formulation of TNEP problem

In deregulated power systems, different objectives are pursued in TNEP. In this paper, the most commonly adopted objective functions have been considered: namely, minimum investment cost, minimum congestion cost, and minimum risk cost of network. These objective functions are respectively calculated using (1)–(3) by power system planner; to calculate congestion cost described by (2) and risk cost defined as (3), the one-sided power market is performed by ISO. This market is modeled as a DC OPF presented in Section 2.2. In the following, mathematical formulation of the multi-objective TNEP is explained.

2.1.1. Investment cost minimization

Conventionally, the main objective of TNEP problem is minimization of the needed investment cost for network expansion. In deregulated environments, minimizing the investment cost reduces the tariffs of transmission services and facilitates competition for power market participants [1].

Moreover, given the challenges that nowadays related to the social acceptance of new transmission lines, this minimization also allows obtaining more feasible plans from social and economic point of views.

The investment cost is calculated as:

$$IC = \sum_{(i,j)\in\Omega} c_{ij} n_{ij} \tag{1}$$

where c_{ij} is the cost of an added line between the bus i and the bus j of the network, n_{ij} is the number of added lines to the corridor (i, j); Ω is the set of available corridors.

2.1.2. Congestion cost minimization

A congested transmission network prevents perfect competition among power producers and nondiscriminatory access to grid for consumers. In general, from the classical electricity market theory, social welfare increases by reducing network congestion [3,18]. The reduction of social welfare due to physical limitation in power transfer and subsequent market splitting is usually considered as congestion cost. Assuming a locational marginal price (LMP)-based market [3], congestion cost can be calculated as follow:

$$CC = \sum_{(i,j)\in\Omega} f_{ij}(LMP_j - LMP_i) \tag{2}$$

where f_{ij} is power flow in the corridor (i, j), and LMP_i and LMP_j are locational marginal prices at buses i and j, respectively. Mathematically speaking, they are the Lagrange multipliers of power flow constraints (shadow prices) and can be evaluated at any operating point of power system. However, here to reduce computational burden of the TNEP problem, LMPs are calculated at annually mean loads after the solution of a DC optimal power flow. The choice of DC OPF relies on the consideration that given the high level of uncertainness in the approximation of future operating points, a rough estimation of power flows is more than sufficient to provide a good assessment of such costs. The formulation of the adopted DC OPF problem is given in the next subsection.

2.1.3. Risk cost minimization

Finally, a third objective function is considered to improve network reliability. A reliable transmission network is needed for competition and successful trading in competitive electricity market. Using artificial generation installation at each load bus (i.e. load interruption), adequacy and security criteria are modeled as in the objective function (3). This function is aimed at imposing the respect of operational constraints (the power system must be able to withstand any single-contingency) and minimizing the amount of interrupted loads in post-contingency situations [7,19]:

$$RC = p_f p \sum_{k\in B} r_k + p_f \sum_{(m,n)\in\Psi} p^{mn} \sum_{k\in B} r_k^{mn} \tag{3}$$

where r_k is curtailed load at bus k in normal (no contingency) condition and r_k^{mn} is curtailed load at bus k when the lines in the (m, n) corridor are out of service (assuming the $N-1$ security criterion). p and p^{mn} are the probabilities of occurrence for no-contingency and contingency (m, n) scenarios, respectively. B is the set of load buses, Ψ is the set of contingencies and p_f is penalty factor for load curtailment (for example the value of lost load).

In order to calculate curtailed loads, a DC OPF is performed for both normal and single-contingency cases. A contingency screening strategy is adopted to select credible contingencies to avoid extra computations, in the reliability analysis. In the base-case (or non-expanded) system, all