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A bi-level probabilistic transmission planning with intermittent generations based on life cycle cost

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ABSTRACT

With the growing development of intermittent renewable energy sources, such as wind and solar, transmission planners are faced with uncertainly varying generations and resultant probabilistic power flow. A bi-level programming model is proposed to coordinate the process of decision making and reliability assessment. Based on the concept of life cycle cost (LCC), its minimization can be defined as the objective function of a transmission planner. This upper level problem needs to be solved jointly with the lower probabilistic optimal power flow problem of minimizing the load shedding in the system. Hence the bi-level problem is transformed into a Mathematical Programming with Equilibrium Constraints (MPEC) with Karush-Kuhn-Tucker conditions. Due to the nonlinearity nature of MPEC, disjunctive inequalities and Generalized Benders Decomposition methods are used to solve this problem. Results of both Garver's 6-bus test system and a realistic 63-bus system are used to illustrate the rationality and validity of the proposed method.

1. Introduction

There has been a tremendous interest and development in the area of harnessing energy from intermittent renewable energy sources (IRES). IRES generally include wind energy resource, solar energy resource, biomass, and other types of resources. Yet, these kinds of resources created significant challenges to both operation and planning of a power system. For example, the output from wind farms (WF) or photovoltaic stations (PVS) are not susceptible to control and dispatch resulting in additional uncertainty to the system operator. By the same token, the generation outputs from future WF and PVS are difficult to forecast, hence adding complexity to the system planner in managing various uncertainties.

However, system planners still have to plan for adequacy and reliability of future power system, despite these uncertainties. Thus, these uncertainties must be taken into consideration when planning for a future reliable system. Generally, system planning involves planning for both generation and transmission [1]. In competitive electricity markets, transmission expansion planning (TEP) is relatively independent from generation expansion. Generation expansion is driven by market forces, while TEP is managed by independent system operators [2]. Hence, our present work will focus on TEP only.

Many research works have been done on this important topic of transmission planning. Various objectives are formulated in TEP process as follows: (1) minimization of static investment or the length of expanded lines [3]; (2) minimization of investment and load curtailment multiplied by sufficiently large penalty factors [4]; (3) minimization of investment and one or more operation costs, including generator cost [5], energy deficit cost [6], loss cost [7] and congestion cost in deregulated market [8]; (4) minimization of maximum regret with risk analysis [9]; (5) maximization of investment and delivery of marginal rate in a fuzzy form [10]. Some of the objectives mentioned above are not purely defined from the nature of network. Most researchers transformed the operation and reliability indexes of TEP into value-based objectives to be included in the objective function. Nevertheless, the economic evaluation of a TEP decision is not only a problem of static investment, but also the direct and indirect outlays produced at the various stages of planning, operation, maintenance, retirement and scrap. To deal with that TEP problem, the application of life cycle cost (LCC) theory brought a novel methodology to the transmission planning and future asset management. In [11], an economic evaluation method for the design of HVDC based on LCC

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Nomenclature

N_B	electricity nodes indexed by i, j, li (start of corridor l) and lj (terminal of corridor l)
N_D	demand nodes indexed by d
N_G	generation nodes indexed by g
N_L	transmission corridors indexed by l
N_P	uncertain scenarios indexed by s
T_S	expansion planning time periods indexed by t
N_+	set of positive integers
n_l	integer decision variables for expanded lines
n_l^{sum}	line amount of corridor l
θ	voltage angles at electricity nodes
P_g^G	conventional power plant output (MW)
P_g^S	photovoltaic station output (MW)
P_g^W	wind farm output (MW)
R_d	load shedding at demand nodes (MW)
P_{loss}	expected network power loss (MW)
c_{LCC}	life cycle cost of expansion plan ($)
c_I	investment of expanded lines ($)
c_O	expected network operation cost ($)
c_M	maintenance cost of transmission network ($)
c_F	expected network failure cost ($)
c_D	discard cost of expanded lines ($)
c_{Fd}	expected direct failure cost ($)
E_{EENS}	annual expected energy not supplied (MW h)
E_{LSE}	annual expected power of load shedding (MW)
P_l	power flow of corridor l (MW)
$\mathcal{L}_s$	Lagrange function of the lower level model
b	binary variables in linearized upper model
z	product of θ and b
q	binary variables in linearized KKT conditions
S_L	service life of expanded lines (year)
r_D	basic discount rate
r_R	residual rate
$c_{I\ l}$	unit investment of lines in corridor l ($/km)
L_l	length of lines in corridor l (km)
c_{price}	average electricity price ($/MWh)
T_O	annual operation hours of network (h)
δ_l	annual failure rate of lines in corridor l (/km)
c_{Ml}	unit maintenance cost of lines in corridor l ($)
f	ratio of indirect failure cost to the direct one
c_{Du}	unit disposal cost of discarding line ($/km)
x_l	reactance of transmission lines (Ω)
D_d	demand at demand nodes (MW)
n_l^0	amount of existing transmission lines
n_l^{max}	maximum line amount of corridor l
P_l^{max}	transfer capability of transmission lines (MW)
$P_g^{G,min}$	minimum output of conventional plants (MW)
$P_g^{G,max}$	maximum output of conventional plants (MW)
$P_g^{S,max}$	maximum output of photovoltaic plants (MW)
$P_g^{W,max}$	maximum output of wind farms (MW)
p_s	weighted factor of scenario s
K	sufficiently large positive constant.

was proposed. Economic evaluations of proposed transmission projects were done without considering life cycle cost [12]. Only a few applications of this technical and economic management can be found in TEP.

Mathematically, even with the dc power flow model, it is generally difficult to find the optimal solutions for the TEP problem, which is a mixed-integer nonlinear programming (MINLP) problem, due to its nonconvex nature [3]. The optimization methods to solve TEP model are classified as heuristic approach and mathematical approach. Heuristic approach mainly includes particle swarm optimization [6], tabu search [7], genetic algorithm [13], and many other meta-heuristic algorithms. It is convenient to search the solution sets without modifying the original models with heuristic methods. However, the performance depends mainly on the control parameters and the solutions might be locally optimal. Researchers usually converted MINLP models into mixed-integer linear programming (MILP) models [3], and solved it with branch & bound [10], cutting plane [14] or decomposition methods [15]. Many commercial solvers can be applied to solve MILP models directly. The shortcoming of these methods is that plenty of binary variables are introduced to MILP model. Reduction of variables still remains an obstacle in improving the computational efficiency.

The methods to tackle the uncertainties of TEP can be classified into three groups: scenario-based method, analytical method, and interval method. The research in [16] simulated thousands of deterministic operational scenarios with Monte Carlo simulation (MCS). The results of MCS are generally accurate but there still exists significant computational burden. Hence scenario reduction technique was used in [17]. Ref. [18] assumed several typical scenarios to represent the uncertain operational conditions and a scenario tree is assumed in [19]. The accuracy of these methods depends mainly on the subjectively chosen scenarios. A chance-constrained programming method which incorporates the probability distribution into the analytical probabilistic dc power flow calculation is proposed in [20]. The calculation of this method is complex with a large amount of convoluted computations. Interval method was used in [21], but the distribution of stochastic parameters cannot be easily obtained.

Our paper provides a bi-level probabilistic timing TEP model for bulk transmission system which is integrated with large amount of IRES while coordinating process of decision making and reliability assessment. The main contributions of this paper include four aspects: (1) a bi-level timing TEP model considering probabilistic optimal power flow (POPF) which is formulated with the objective of evaluating the LCC of a TEP decision; (2) three point estimate method (3PEM) [22] is first applied in the TEP method to account for the uncertainties including random generation output from IRES, transmission outages and load fluctuations; (3) the bi-level model is reformulated as a mathematical programming with equilibrium constraints (MPEC) which models the lower level problem as constraints to the upper level by using Karush-Kuhn-Tucker (KKT) optimality conditions, so that the bi-level problem can be solved in a joint manner; (4) an alternative linearization method for the proposed nonlinear MPEC is derived to reduce the binary variables in the equivalent linear form and improve the computational efficiency of Generalized Benders Decomposition (GBD).

The remainder of this paper is organized as follows. Section 2 provides the problem description and formulation of proposed bi-level probabilistic timing TEP, the equivalent MPEC and its equivalent linear form. Section 3 provides the results of an illustrated example in detail to examine the performance of the proposed methodology. Section 4 provides the results of a realistic case study to illustrate the practicability of the method in the application to the bulk power system. Section 5 draws conclusions.