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Robust dynamic network expansion planning considering load uncertainty

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ABSTRACT

This paper presents a dynamic transmission expansion planning framework with considering load uncertainty based on Information-Gap Decision Theory. Dynamic transmission planning process is carried out to obtain the minimum total social cost over the planning horizon. Robustness of the decisions against under-estimated load predictions is modeled using a robustness function. Furthermore, an opportunistic model is proposed for risk-seeker decision making. The proposed IGDT-based dynamic network expansion planning is formulated as a stochastic mixed integer non-linear problem and is solved using an improved standard branch and bound technique. The performance of the proposed scheme is verified over two test cases including the 24-bus IEEE RTS system and Iran national 400-kV transmission network.

Introduction

Background and literature review

The primary aim of power system planners and policy makers is to provide adequate generation and transmission facilities at a desired level of stability and security with minimum total cost. Deregulation of electricity industry has introduced new challenges and uncertainties in power system planning studies. Transmission Expansion Planning (TEP) problem as a major part of power system planning should be revised based on these new uncertainties.

Uncertainties of load prediction [1], wind power generation [2], and availability of power system facilities [3] are common types of these uncertainties. Many approaches have been proposed to deal with uncertainties in TEP problem. Monte Carlo Simulation method has been widely applied to handle the power system uncertainties [4,5]. Scenario-based techniques [6–8] and fuzzy-based models [9] are other approaches that have been proposed for uncertainty modeling. Each of these approaches has its own capabilities and drawbacks. The TEP problem could be formulated as an optimization task which could be solved using mathematical programming techniques [10], heuristics methods [11], intelligent methods such as Genetic Algorithm [12], Simulated Annealing [13], and Taboo Search [14].

Indeed the TEP problem is a mixed integer linear or non-linear problem and the current available optimization techniques do not guarantee to obtain the global optimal solution. The previously proposed TEP problems could be classified based on their objective functions and the related constraints. The objective function of traditional TEP problem is minimizing investment cost without considering production cost of generators [15]. Some of previously proposed TEP schemes have focused on market-based TEP (i.e. including price or cost of generation) to obtain minimum Total Social Cost (TSC) [16]. The equality constraints of TEP problem include load flow equations at each bus [15]. Due to simplicity and linearity, DC load flow formulation is widely used as the power balance equation in previously proposed TEP schemes [15,16]. The major drawbacks of using DC load flow formulation is neglecting the power losses. Due to accuracy and including active power losses the AC load flow formulation could be used as power balance model in TEP problem [17]. However, in addition of high computational burden, the ac load flow formulation may encounter the risk of infeasibility or divergence. Inequality constraints of TEP problem include line capacity limit, generation limit, number of lines in each path, etc. Other constraints in TEP problem include reliability and security criteria, which can be formulated as the objective function (i.e. soft constraint), or inequality constraint (i.e. hard constraint) [18]. TEP problem could be carried out for a single planning horizon year (i.e. static planning) or could be

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Nomenclature

$\overline{\{\bullet\}}$	symbol showing the maximum of a parameter
n_{ij}	number of new circuits added to the right-of-way $i-j$
n_{ij}^0	number of existing circuits in right-of-way $i-j$
c_{ij}	cost of a circuit that may be added to the right-of-way $i-j$
g/d	vector of generated active powers/vector of loads
p	vector of active power flows
l	vector of active power losses
r	vector of load curtailments
pf	penalty factor for load curtailment
s	node-branch incidence matrix
p_{ij}	active power flow in a branch in the right-of-way $i-j$
l_{ij}	active power losses in a branch of the right-of-way $i-j$
γ_{ij}/r_{ij}	susceptance/resistance of a branch in right-of-way $i-j$
θ_i	voltage angle at bus i (radian)
IC	investment cost of transmission expansion
OC	operation cost of power generation
t	yearly time index
T	planning horizon
k	load level index
$w(k)$	load level as a percentage of peak load level
$h(t,k)$	duration of load level of k at year t
$a_i,\ b_i,\ c_i$	cost coefficients of thermal units
Ω_l	set of existing and new right-of-ways
Ω_d/Ω_g	set of demand buses/set of generation buses
Ω_k/Ω_t	set of load levels/set of yearly time instants
Ω_{rn}	set of transmission lines obtained from risk-neutral model
$\Omega_{ro},\ \Omega_{op}$	set of transmission lines obtained from robustness model/opportunistic model
$\widetilde{d}$	vector of forecasted loads
$u,\ q$	uncertain variable/decision variable
$R(q,u)$	system model in IGDT method
$U(\alpha,\widetilde{u})$	uncertainty model in IGDT method
α	horizon of the uncertain variable
TSC	total social cost over planning horizon

carried out over a planning horizon (i.e. dynamic planning). Less efforts have been done for modeling and solution of dynamic TEP problem. This paper presents a dynamic TEP framework over a ten years planning horizon based on forward recursion and backward recovery method [19]. Information-Gap Decision Theory (IGDT), developed in [20], recently has been applied to decision making process in uncertain environments. In fact IGDT technique is a performance satisfying procedure. IGDT technique recently has been applied to many power system studies such as self-scheduling of GenCos, optimal demand-side scheduling and bidding strategy problems [21]. One of major advantages of IGDT method is the risk-based management of the strategy of decision making without the information about the probability distribution functions of uncertain parameters.

Contributions

The contributions of this paper are highlighted as follows:

- **Uncertainty modeling:** This paper proposes a new non-probabilistic method for Dynamic Transmission Expansion Planning (DTEP) problem with considering load uncertainties based-on Information-Gap Decision Theory. The proposed formulation has two major decision-making models including risk-averse robustness model and risk-seeker opportunity model. The aim of risk-averse model is to find the optimal expansion plan under severe uncertainty. The aim of risk-seeker opportunity model is to find the optimal expansion plan for over-estimated load values close to forecasted loads. In other words in risk-seeker opportunity model the total profit of decision-maker is maximized by decreasing investment cost over planning horizon.
- **Modification of equality constraints:** Transmission expansion planning is a very complex problem of great computational effort. The major drawback of DC power flow is neglecting the effects of power losses. Also the AC power flow formulation have a high computational burden with the risk of divergence under heavy loading conditions. Here to overcome these problems and obtain a confident solution a linearized DC model incorporating line losses, called LL-LDC model is used as equality power balance equation. Also a Load Duration Curve (LDC) is assumed at each year for including all credible load levels. Indeed assuming a standard LDC at each year gives practical results rather than assuming only the peak loads.
- **Solution process:** The proposed IGDT based dynamic TEP is solved using the standard branch and bound technique based on a forward recursion and backward recovery method.

Paper organization

The rest of this paper is organized as follows. In Section 'Conventional deterministic TEP formulation', the fundamentals of conventional deterministic TEP formulation is presented. The details of the DTEP problem are described in Section 'Dynamic TEP formulation'. The proposed IGDT-based DTEP problem is described in Section 'IGDT theory'. The results of applying the proposed method over IEEE-24 bus test system and Iran 400-kV transmission network is given in Section 'Proposed IGDT-based TEP problem'. Finally, the conclusions are provided in Section 'Simulation results'.

Conventional deterministic TEP formulation

The most widely used traditional deterministic TEP model is formulated as follows [22]:

$$\min \sum_{ij\in l}(c_{ij} * n_{ij}) + \sum_{i}(pf_i * r_i) \tag{1}$$

subject to

$$g - d = s^T p + r \tag{2}$$

$$p_{ij} = \gamma_{ij}(n_{ij}^0 + n_{ij})(\theta_i - \theta_j) \tag{3}$$

$$|p_{ij}| \leqslant (n_{ij}^0 + n_{ij})\overline{p}_{ij} \tag{4}$$

$$0 \leqslant g \leqslant \overline{g} \tag{5}$$

$$0 \leqslant n_{ij} \leqslant \overline{n}_{ij} \tag{6}$$

$$n_{ij} \in integer, \quad \forall ij \in \Omega_\ell \tag{7}$$

The aim of above mentioned TEP formulation is to find a transmission plan with minimum investment cost while supplying the forecasted yearly peak load. Equality constraints given by (2) and (3) refer to the DC formulation of nodal active power balance and line flow equations, respectively. Inequality constraint given in (4) is an