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Generation expansion planning in electricity markets: A novel framework based on dynamic stochastic MPEC

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ABSTRACT

This paper presents a novel framework for generation expansion planning (GEP) of restructured power systems under uncertainty in a multi-period horizon, which includes generation investment from a price maker perspective. The investment problem is modeled as a bi-level optimization problem. The first level problem includes decisions related to investment in order to maximize total profit in the planning horizon. The second level problem consists of maximizing social welfare where the power market is cleared. Rival uncertainties on offering and investment are modeled using sets of scenarios. The bi-level optimization problem is then converted to a dynamic stochastic MPEC and represented as a mixed integer linear program (MILP) after linearization. The proposed framework is examined on a typical six-bus power network, MAZANDARAN regional electric company (MREC) transmission network as an area of IRAN interconnected power system and IEEE RTS 24-bus network. Simulation results confirm that the proposed framework can be a useful tool for analyzing the behavior of investments in electricity markets.

Introduction

During past decades, power industry has experienced major changes in structure and regulations of the markets in order to improve economic efficiency and promote sustainable development [1]. Regarding the expansion planning and the operation decisions by companies, the issue of profitability has attracted more attentions in the short-term and long-term planning [2]. Since one of the main drivers of generation capacity expansion is the expected electricity price in the future, appropriate market-clearing models should be used to determine the price of electricity in the short and medium term. On the other hand, one of the major challenges of market operators in electricity markets is maintaining the adequacy of generation capacity [3]. To this end, regulators should make appropriate policies to encourage producers to invest new generation capacities [4].

It is very important to apply appropriate model for the generation expansion and study the impact of different markets on the investment. Accordingly, researchers have been providing models and programming methods to treat the investment problem. A bi-level model for generation expansion (Cournot modeling) is presented in [5]. The impact of transmission congestion and competition in generation investment is reviewed by the Cournot model in [6]. The presented GEP models in [5,6] are static without considering uncertainties. In [7], a probabilistic dynamic programming model has been proposed to solve the investment problem in the presence of demand uncertainty. Strategic producer behavior has been investigated in [8] using a bi-level model considering uncertainties related to demand and rival offers. A static model is proposed in [9] to solve the generation investment problem from a strategic producer point of view. The static model of [9] has been extended in [10] to consider demands uncertainties, behavior of rival producers and their offers at a specified time horizon. Also, Bender's decomposition has been used to solve the investment problem. A hybrid DP/GAME framework is proposed in [11] to deal with GEP problem in which DP was applied to solve the investment problem and Cournot game was used to model strategic behavior of the producers in the spot markets. In [12], the expansion planning has been solved for a set of non-strategic producers in the liberalized electricity market. The market clearing problem is modeled using conjecture price approach in the lower level problem. An open-loop model is used in [13] as an approximation of closed-loop model for reducing computational time where the problem is modeled as an EPEC without considering uncertainties. In [14,15], a bi-level model was proposed to characterize generation investment equilibria in a single horizon pool-based electricity market neglecting uncertainties where the producers behave strategically. Also, strategic offers of producers were considered through stepwise supply function.

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This paper provides a multi period framework to study the generation expansion of a strategic producer under uncertainties in electricity markets. The investment problem is modeled as a bi-level optimization problem. The upper level includes decisions taken by a strategic producer who investigates installments of new generating units in a given time period and the future possible productions, to maximize the total profit in the planning horizon. The lower level problem models the responses provided by a competitive fringe in terms of production bids, which are sorted by a market operator, who clears the market obtaining Locational Marginal Prices (LMPs) as dual variables of the nodal balancing constraints and the objective of maximizing social welfare. Rival uncertainties on offering and investment are modeled using sets of scenarios. The considered bi-level optimization problem is then converted into a single level optimization problem. The single level optimization problem is considered as a Mathematical Program with Equilibrium Constraints (MPEC) [21]. Then, the single level problem is linearized and converted to an MILP. The proposed framework uses dynamic stochastic MPEC. To the best of our knowledge, dynamic nature of investment decisions have not been considered in the MPEC models presented in the literatures to solve GEP problems in a dominant producer point of view. Thus, the multi period stochastic MPEC model is the main contribution of this paper, which also considers transmission network constraints. The presented model can also be treated as a mixture of operation and expansion problems of power systems. The supply function model is also used as offer strategies of the producers in the spot market, which is a more realistic model of spot market than the other models. It should be noted that the supply function model is a more detailed description of the actual electricity market compared to Cournot, Bertrand and conjecture variations models. Moreover, the considered multi period bi-level problem is formulated as an MPEC problem.

The paper is organized as follows. In Section 'The proposed framework', the proposed framework and the bi-level model is introduced. The mathematical formulation of the problem is presented in Section 'Mathematical formulation'. Section 'Case studies' provides simulation results and analysis for three case studies. Finally, Section 'Conclusion' provides some relevant conclusions.

The proposed framework

The proposed framework is generally depicted in Fig. 1. The main block of the proposed framework represents the bi-level model. The upper level represents the investment problem of a dominant producer who is seeking to maximize the present value of the total profit of investment. In the upper level, investment decisions of rival producers are modeled using set of scenarios. Investment decisions of producers and their offers to the spot market are outputs of the upper level problem. Due to dynamic nature of the planning problem, dynamic constraints exist in the upper-level. The lower-level problem represents the market-clearing. The clearing of the market for any given operating condition is represented as an optimization problem that identifies the operating decisions through maximizing social welfare. The market clearing problem is constrained by DC power flow equations and limitations of transmission network and units' capacity. Output of the lower level problem is nodal prices (dual variables associated to the power balance constraints), which are fed back to the upper level.

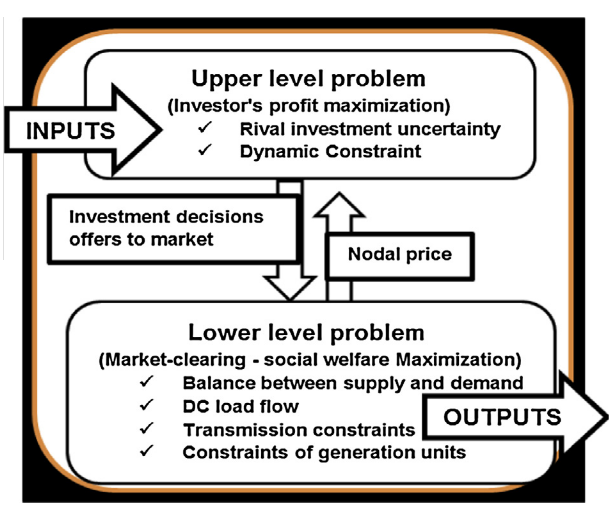

Fig. 1. Schematic of the proposed framework.

Mathematical formulation

Mathematical formulation of the proposed framework is presented in the following sub-sections. In order to introduce the model, we define the following sets, parameters and decision variables.

Indices

d: index for demand,
h: index for size of investment option,
i/k: index for new/existing generation unit of strategic producer,
j: index for generation unit belonging to other producers,
n/m: index for bus,
t: index for demand blocks,
y: index for year,
w: index for scenario.

Parameters

B_{nm}: Susceptance of line n–m (p.u.).
CO_{tjw}: Price offer of units j of other producers in demand block t and scenario w (€/MW h).
C_i^S/C_k^{ES}: Marginal cost of new/existing unit of strategic producer (€/MW h).
f: Discount rate.
$F_{nm}^{\max}$: Transmission capacity of line n–m (MW).
$K^{\max}$: Available investment budget (M€).
K_{yi}: Annual investment cost of new generating unit (€/MW).
$P_j^{O\max}$: Capacity of generation unit j of other producer (MW).
$P_k^{ES\max}$: Capacity of existing generation unit k of strategic producer (MW).
$P_{ytd}^{D\max}$: Maximum load of demand d in block t and year y (MW).
U_{ytd}^D: Price bid of demand k in demand block t and year y (€/MW h).
X_{yih}: Option h for investment capacity of new unit i (MW).
σ_{yt}: Weight of demand block t in year y.
φ_w: Weight of scenario w.

Decision variables

P_{ytkw}^{ES}/P_{ytiw}^S: Power produced by existing/new unit k/i of strategic producer in year y, demand block t and scenario w (MW).
P_{ytjw}^O: Power produced by unit j of other producers in year y, demand block t and scenario w (MW).