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Optimal bidding strategy in transmission-constrained electricity markets

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ABSTRACT

This paper addresses the problem of developing an optimal bidding strategy for a strategic producer in a transmission-constrained day-ahead electricity market. The optimal bidding strategy is formulated as a bi-level optimization problem, where the first level represents the producer profit maximization and the second level represents the ISO market clearing. The transmission network is incorporated into the ISO problem under two different approaches based on the Nodal and PTDF formulation, respectively. The bi-level problem is converted to a mathematical program with equilibrium constraints (MPEC) which, in turn, is transformed into a mixed-integer linear programming (MILP) model using the Karush–Kuhn–Tucker (KKT) optimality conditions and the strong duality theory. Test results on the IEEE 24-bus and 118-bus systems show that the PTDF formulation of the transmission constraints is computationally far more efficient than the Nodal formulation.

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1. Introduction

The day-ahead electricity market is the most common form of centralized daily transactions in competitive electricity markets. In such markets, the electricity producers face every day the fundamental problem of how to bid into the market so as to maximize their expected profits.

For the construction of his optimal bidding strategy, the producer must formulate and solve an appropriate optimization model taking into account various techno-economic data and operating constraints of his generating units, such as start-up and shut-down costs, ramp-rate limits, minimum-up/down time constraints, start-up and shut-down procedures, etc. Additionally, the producer must take into account the behavior of his competitors, as well as specific characteristics and enacted rules of the electricity market. In this context, the transmission network plays an important role in an electricity market, since it can have a notable impact on the daily market operation. Although the transmission network is necessary for the proper formulation of the producer optimal bidding strategy problem, many challenges arise owing to its modeling complexity.

In recent years many optimization models have been presented in the literature for the solution of the producer optimal bidding strategy problem. These models can be categorized according to the extent that the strategic producer takes into account the behavior of his rivals. In this sense, there are two main modeling directions, namely (a) the single firm optimization models, which ignore the strategic interaction of the market players and can be further divided into price-taker [1–9] and price-maker [10–22] producer models and (b) the market equilibrium models, which take into account the strategic interaction of all players, i.e. their reaction to the decisions of their rivals [23–30].

Although various models including detailed description of the operating constraints of the generating units have been proposed in the literature, only a few have considered the effect of the transmission network on the producer bidding strategy and on market clearing. A single-firm optimization model, formulated as an MPEC, is presented in [23], where a linearized DC optimal power flow (OPF) model is considered in the lower level and a penalty interior point algorithm is used to compute a local optimal solution of the MPEC. In this model, a single-period modeling is adopted, thus ignoring all inter-temporal and commitment constraints related to the producer units realistic operation. In addition, the use of the penalty interior point algorithm cannot guarantee that the global optimal solution of the MPEC has been found. The authors of [14] propose a binary expansion (BE) solution approach to the MPEC problem in order to transform it into an MILP model. They describe how the transmission network constraints can be incorporated into the problem, without, however, providing further analysis or test

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Nomenclature

$\ell(L)$	index (set) of branches
$d(D)$	index (set) of loads
$f(F^i)$	index (set) of steps of the offer curve of unit i
$i(I)$	index (set) of generating units $I = I^S \cup I^R$
I^s	set of generating units of the strategic producer
I^R	set of generating units of the rivals (non-strategic producers)
$n(N)$	index (set) of buses
n_i/n_d	bus at which generator i/load d is connected
$t(T)$	index (set) of hours of the planning horizon
Θ_n	set of buses connected to bus n via branches
ψ_n	set of units located on bus n
Φ_n	set of loads located on bus n
r	reference (slack) bus index $r \in N$
$c_{it}(q_{it})$	total hourly production cost of unit i in hour t at level q_{it}, in \$/h
A^{ℓ}_{nr}	power transfer distribution factor (PTDF) of branch ℓ for power transfer from node n to node r
B_{ℓ}	susceptance of branch ℓ connecting node n and node m $B_{\ell} = B_{nm}$
L_{dt}	load demand of load d in hour t, in MW
$Fl^{\max}_{\ell}$	capacity of branch ℓ (connecting node n and node m), in MW ($Fl^{\max}_{\ell} = Fl^{\max}_{nm}$)
$Q^{\max}_i$	maximum power output of unit i, in MW
SDC_i	shut-down cost of unit i, in \$
SUC_i	start-up cost of unit i from standby until load with synchronization, in \$
p_{ift}	offer price of step f of the ith unit's offer curve in hour t, in \$/MWh
Q_{ift}	offer quantity of step f of the ith unit's offer curve in hour t, in MW
q_{ift}	portion of step f of the ith unit's offer curve accepted by the ISO in hour t in the day-ahead energy auction, in MW
u_{it}	binary variable which is equal to 1 if unit i is committed during hour t
y_{it}	binary variable which is equal to 1 if unit i is started-up during hour t
z_{it}	binary variable which is equal to 1 if unit i is shut-down during hour t
δ_{nt}	voltage angle of bus n in hour t, in rad
λ_{nt}	locational marginal price of node n in hour t, in \$/MWh
Π_i	set defining the feasible operating region of unit i

results. An MPEC model that uses the same BE approach for the discretization of the offer quantities and prices taking also into account the effect of the transmission network on the producer strategic behavior is analyzed in [15]. In both works [14,15], the proposed models were also formulated for single-period time intervals only. Moreover, the proposed binary expansion methodology failed to converge when tested to large test systems due to computational issues.

The transmission network is also taken into account in [16], where the proposed model is based on the bi-level programming and a primal-dual interior point method (PDIPM) is developed for the solution of the ISO market clearing problem, which included a DC power flow. In addition, sensitivity functions are developed from linear programming for the modeling of the producers' payoffs with respect to bidding strategies to solve the bi-level problem. In this model, a single-period modeling is used, ignoring the inter-temporal and unit commitment constraints. In addition, there is no guarantee that the algorithm converges to the global optimum. A network-constrained market-clearing algorithm is considered in [17], where the authors proposed an MPEC model that is subsequently reduced to an MILP model using the duality theory and the Karush–Kuhn–Tucker (KKT) first-order optimality conditions. The authors incorporated a DC power flow modeling for the transmission network representation under the Nodal formulation. In addition, although a 24-h scheduling horizon is considered, only simple unit inter-temporal constraints (i.e. ramp-rate limits) are modeled. In [18] the producer profit in a network-constrained electricity market is optimized based on the transmission-constrained residual demand derivative (TCRDD), thus avoiding the representation of the full network model. A limitation of the proposed model is that all the units of the strategic producer must be located on the same bus. In addition, a local search algorithm is used, which cannot guarantee convergence to the global optimum. Finally, single-period modeling is used, ignoring the inter-temporal and unit commitment constraints.

To sum up, the models of [14–16,18,23] are formulated for single-period time intervals, ignoring the inter-temporal and unit commitment constraints for the strategic producer units modeling. A 24-h scheduling horizon with only simple inter-temporal constraints (i.e. unit ramp-rate limits) considered in the formulation of the producer's profit maximization problem (first-level problem) is adopted in [17].

In this paper a bi-level model is proposed for the development of the optimal bidding strategy of a strategic producer, who owns a number of generating units located on different nodes throughout an electricity network and is able to manipulate the market clearing prices to his own benefit through his offering strategy. The bi-level model consists of a first level, which represents the producer profit maximization problem and a second level, which represents the ISO market clearing problem, as in [14–17].

In the first-level a detailed unit-commitment model is used for the strategic producer's units, while in the second-level it is assumed that the market clearing is performed by the ISO on an hour-by-hour basis ignoring the associated unit commitment constraints, so that the second-level problem is convex and can thus be replaced by its first-order KKT optimality conditions, yielding a mathematical program with equilibrium constraints (MPEC). Subsequently, the MPEC is transformed into an MILP model using the methodology proposed in [17]. The transmission network modeling is incorporated into the ISO market clearing algorithm under two different approaches, the Nodal and the PTDF (preferred) formulation.

The main contributions of this paper are threefold:

- An MPEC problem is formulated and solved for the determination of the optimal offering strategy of a strategic producer over a 24-h scheduling horizon. A detailed unit commitment modeling in the strategic producer profit maximization (first-level) problem is used, in contrast to [17] that takes into account only the capacity and the ramping limits of the generating units. In addition, the transmission network is effectively incorporated into the ISO (second-level) problem. The proposed MPEC model is effectively transformed into an MILP model, which is solved using a commercial MILP solver.
- A PTDF modeling of the transmission network constraints is proposed and compared to the respective Nodal formulation used in [17]. Although PTDF modeling has been extensively used for the formulation and solution of the standard unit commitment problem solved by the ISO in pool-type day-ahead electricity markets in order to clear the market [31], it is the first time that this transmission modeling is used for the formulation of the

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