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Modeling and analysis of strategic forward contracting in transmission constrained power markets

C.W. Yu[a,*], S.H. Zhang[b], X. Wang[b], T.S. Chung[a]

[a] Department of Electrical Engineering, The Hong Kong Polytechnic University, Hong Kong, China
[b] Department of Automation, Shanghai University, Shanghai 200072, China

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ABSTRACT

Taking the effects of transmission network into account, strategic forward contracting induced by the interaction of generation firms' strategies in the spot and forward markets is investigated. A two-stage game model is proposed to describe generation firms' strategic forward contracting and spot market competition. In the spot market, generation firms behave strategically by submitting bids at their nodes in a form of linear supply function (LSF) and there are arbitrageurs who buy and resell power at different nodes where price differences exceed the costs of transmission. The owner of the grid is assumed to ration limited transmission line capacity to maximize the value of the transmission services in the spot market. The Cournot-type competition is assumed for the strategic forward contract market. This two-stage model is formulated as an equilibrium problem with equilibrium constraints (EPEC); in which each firm's optimization problem in the forward market is a mathematical program with equilibrium constraints (MPEC) and parameter-dependent spot market equilibrium as the inner problem. A nonlinear complementarity method is employed to solve this EPEC model.

1. Introduction

Electricity restructuring has been accompanied by extensive research on market power analysis of oligopolistic electricity markets [1–3]. It is widely acknowledged that forward contract trading, physically or financially, plays an important role as means for market power mitigation in electricity markets [4]. As such, forward contract markets exist in parallel with spot markets in most electricity markets currently implemented around the world. While risk-averse generation firms wish to employ forward contracts to hedge the risk of spot price fluctuation, strategic impacts of firms' forward contract sales on the competition in generation spot markets could give rise to an incentive even for risk-neutral firms to sign forward contracts. It is shown in [5,6] that under Cournot-type competition in the spot market, if one firm signs forward contracts and the others do not, then the firm with forward contracts would have a strategic benefit of producing a larger quantity and be able to gain a larger profit as compared with those with no contracts. Therefore risk-neutral firms would voluntarily sign contracts due to the incentive that arises from the interaction of strategies in the spot market and forward contractual arrangements. Firms' forward contracting induced by this incentive is referred to as strategic forward contracting, which is the main focus of this paper.

Equilibrium models using game-theoretic behavioral assumptions are broadly employed to examine strategic interactions among participants in oligopolistic electricity markets [1–3]. Among the most extensively used models are the Cournot and linear supply function (LSF) equilibrium models. It is worth noting that there are several choices for the parameters specifying the bid of LSF and such parameterization of LSF has a significant impact on the equilibrium outcomes [7]. Especially, for a single pricing period with no uncertainty of demand, there are almost inevitably multiple equilibria when firms have full discretions in choosing the parameters specifying their bids of the LSFs and are not constrained to bid the same supply function over multiple pricing periods. In addition, the DC power flow approximation is widely applied in these equilibrium models not only because of its linearity, but also because numerical tests have found that DC congestion costs are good approximations if thermal constraints are the main concerns [8].

Cardell et al. [9] present a spot market equilibrium model with Cournot generation firms that may own plants at multiple locations in a network. In this model, each strategic firm's optimization problem is a two-level program. Such bi-level problems are inherently nonconvex and no algorithm can guarantee to give optimal solutions. A diagonalization algorithm is introduced to solve the problem iteratively using different penalty parameters in each run until the equilibrium conditions are approximately satisfied. Hobbs et al. [10] develop a LSF-based model in which each strategic firm is assumed to manipulate the intercepts of the bid functions. A

* Corresponding author.
E-mail address: eecwyu@inet.polyu.edu.hk (C.W. Yu).

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bi-level program is obtained for each strategic firm, in which the upper level chooses the bid parameter and the lower level simulates the market-clearing algorithm of the system operator (SO). This bi-level program is formulated as a mathematical program with equilibrium constraints (MPEC) and solved by a penalty interior point algorithm (PIPA). A diagonalization algorithm, analogous to that used in [9], is employed to solve the equilibrium problem with equilibrium constraints (EPEC) for multi-firm cases. Wang et al. [11] solve a similar multi-firm EPEC using a nonlinear complementarity method. Unlike the iterative approaches using MPEC-based algorithms as in [9,10], the nonlinear complementarity method allows a set of MPEC problems, each parametric on the other MPECs' decision variables, to be solved simultaneously.

The above approach of embedding the first-order optimality (Karuch–Kuhn–Tucker (KKT)) conditions for the SO's optimization problem within each generation firm's problem implies that firms will take into account how their actions affect transmission prices. If the main purpose is to examine firms' behaviors in the energy market, assuming the agents act as price takers in the transmission market will remove the nonconvexity from each firm's optimization problem in the spot market [12,13]. Hobbs [12] presents a Cournot equilibrium model under the assumption of linear demand and cost functions. In a bilateral market without arbitrageurs, noncost-based price differences can arise because the bilateral nature of the transactions gives firms more degrees of freedom to discriminate between electricity demands at various nodes. In the bilateral market with arbitrageurs, any noncost-based price differences are eliminated by speculators who buy and sell electricity at nodal prices and the equilibrium is shown to be equivalent to a Cournot equilibrium in a POOLCO-type market. Day et al. [13] further extend the above work to large scale applications by presenting a linear conjectured supply function (CSF) model, as an alternative to the Cournot and SFE models. To solve the above equilibrium models, the KKT conditions of each market participant's optimization problem, along with the market-clearing conditions, are combined to form market equilibrium conditions. These market equilibrium conditions can be formulated as mixed linear complementarity problems (LCP), which could easily be solved using the LCP software in GAMS [14]. Furthermore it can be noted from these studies that if there is perfect competition among marketers so that they arbitrage away any noncost-based price differences between different locations, then the POOLCO and bilateral trading systems are generally equivalent in equilibrium outcomes.

To date, in most of the equilibrium analysis of electricity markets with forward contracts, the forward contracts are taken as fixed rather than decision variables [15–18]. In the absence of transmission constraints, it is pointed out in [19,20] that no strategic forward contracting will take place when generation firms compete with LSFs in the spot market, together with the assumption of Cournot-type competition in the strategic forward market. It should be noted that in these studies, either a single LSF applying across multiple pricing periods or a single pricing period with uncertainty of demand is assumed; unique LSF equilibrium can be calculated under the case where each firm chooses the intercept and slope of its bid of LSF arbitrarily. Kamat et al. [21] extend the work in [5] to a transmission constrained system and analyze two-settlement markets over two- and three-node networks. The Cournot-type competition is assumed both in the spot and forward markets and it is shown that the firms have incentives for strategic forward contracting.

In this paper, a two-stage game model is proposed to analyze generating firms' strategic forward contracting and spot market competition in a transmission constrained electricity market. The LSF competition among generation firms in the spot market is considered and the nonlinear complementarity method is employed to solve the complicated model. In order to focus on examining firms' behaviors in the forward market and avoid complications in the spot market model with transmission constraints, the common assumption that all market participants do not game the transmission system in the spot market as used in [12,13] is followed in this paper. Generation firms behave strategically by submitting bids at their nodes in a form of LSF and there are arbitrageurs who buy and resell power at different nodes where price differences exceed the cost of transmission in the spot market. The owner of the grid is assumed to ration limited transmission line capacity to maximize the value of the transmission services. These assumptions make the spot market equilibrium equivalent to that of the POOLCO trading system, where the SO is assumed to take the roles of both the grid owner and arbitrageurs. Furthermore, assuming all market participants do not game the transmission system in the spot market has important computational advantages for market equilibrium calculation. First-order optimality conditions for all the strategic firms and transmission owners can be aggregated along with the market-clearing conditions, and the spot market equilibrium can be solved directly as a complementarity problem. In the strategic forward contract market, the Cournot-type competition is assumed among generation firms.

The two-stage model is formulated as an EPEC problem, in which each firm's optimization problem in the forward market is an MPEC with a parameter-dependent spot market equilibrium as the inner problem. A nonlinear complementarity method is employed to solve this EPEC model. In this method, the optimality conditions for the nonlinear programs defined by firms' MPECs are derived, in which the complementarity conditions can be transformed into nonlinear algebraic equations using a nonlinear complementarity function. The aggregated optimality conditions of the entire EPEC model are reduced to a set of algebraic equations and thus can be simultaneously solved by an inexact Levenberg–Marquardt algorithm [11]. A numerical example is presented to verify the effectiveness of the proposed modeling and solution methodology.

2. The model

A two-stage game model is used to formulate generation firms' strategic forward contracting and spot market competition in a transmission constrained electricity market. In the first stage, generating firms sell forward contracts in the forward market. In the second stage, i.e. in the spot market that the forward contract clears against, firms decide their strategic bids, arbitrageurs buy and resell power at different nodes where price differences exceed the cost of transmission and the grid owner rations the limited transmission line capacity. The forward and spot decisions are taken sequentially. This means that the spot market equilibrium taking as given the positions previously decided on the forward market can be derived. At the same time, the forward market equilibrium can be determined taking into account the impacts that these forward decisions will have on the spot market equilibrium.

2.1. Assumptions

A power market system having I nodes is considered. It is assumed that there are N strategic generation firms in the market. These generation firms are economically rational and risk neutral. Let S_f denote the set of generating units owned by firm f (f = 1,2,. . .,N), G_i the set of generating units located at node i (i = 1,2,. . .,I) and P the set of all generating units in the market. For simplicity, we assume that each firm owns no more than one unit at each node of the network. Let f_i denote the generating unit owned by firm f (f = 1,2,. . .,N) and located at node i (i = 1,2,. . .,I). The generating unit f_i is characterized by a quadratic cost function $C_{f_i}(q_{f_i}) = a_{f_i}q_{f_i} + 0.5b_{f_i}q_{f_i}^2$ and a linear marginal cost $mc_{f_i} = a_{f_i} + b_{f_i}q_{f_i}$, where