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Analysis of the effect of voltage level requirements on an electricity market equilibrium model

Andrés Delgadillo [a,*], Javier Reneses [b]

[a] Florence School of Regulation (FSR), European University Institute, San Domenico di Fiesole I-50014, Italy
[b] Institute for Research in Technology (IIT), Technical School of Engineering (ICAI), Universidad Pontificia Comillas, Madrid E-28015, Spain

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ABSTRACT

This paper presents a conjectural-variation-based equilibrium model of a single-price electricity market. The main characteristic of the model is that the market equilibrium equations incorporate the effect of the voltage constraints on the companies' strategic behavior. A two-stage optimization model is used to solve the market equilibrium. In the first stage, an equivalent optimization problem is used to compute the day-ahead market clearing process. In the second stage, some generation units have to modify their active and reactive power in order to meet the technical constraints of the transmission network. These generation changes are determined by computing an AC optimal power flow.

Introduction

Deregulation in electric power systems has been conducted using different processes in the past decades in several countries. Electric power systems have gone from being centralized and vertically integrated to systems with different degrees of competition in their different activities. In the generation activity, electricity markets were created to determine the amount of energy scheduled of the generation units, as well as the ancillary services that they should provide in order to maintain system stability.

Several models have been developed to study electricity markets. Usually, these models are based on game theory and they try to determine the outcome of the interaction between different companies under the hypothesis of rational behavior. The companies' behavior is modeled using a strategic game where companies take an action knowing that the rest of companies play in the same way. Among the game theory models are Perfect Competitive models [1,2], Cournot models where companies compete in quantities [3–8], Bertrand models where companies compete in prices [3], Supply Function Equilibrium models where strategic behavior is modeled by means of supply functions that combine price and quantity competition [9–16], and Conjetural Variation Based Equilibrium models where the supply functions are parametrized with a parameter known as the company's conjecture [11,17–25].

Most of these models have focused on solving the day-ahead electricity market and they disregard ancillary service markets and mechanisms used to clear the different technical constraints that may appear on the electric power system. Some models include the effect of network congestion on the companies' strategic behavior [1,3–6,12–16,19–23]. However, they only study the congestion caused by the thermal limits of the transmission lines. Therefore, they use a DC approximation of the power flow equations, and it is not possible to analyze other technical constraints such as voltage constraints or reactive power requirements.

Few models [2,7–11,17] study the effect of voltage constraints on the companies' strategic behavior. However, all of them are focused on nodal-price electricity markets, and none of them assess the effect on single-price electricity markets. Almeida and Senna [2] proposed a bilevel optimization problem that models the active and reactive power dispatch under competence. The first level corresponds to the active power market and the second level minimizes the opportunity cost of the reactive power which is defined in terms of the marginal price of the power active market. Bautista et al. [7,8] presented a Cournot model to study the influence of the reactive power requirements on the active power dispatch. These works argue that the DC approximation of the power flow is not accurate enough because it does not take into account the capability curve of the generation units that models the tradeoff between active and reactive power. Bautista et al. [9] was an extension of the previous approaches using a supply function equilibrium model. Soleymani [10] developed a supply function equilibrium model for optimal bidding strategy of generation companies in active and

* Corresponding author.
E-mail addresses: andres.delgadillo@eui.eu (A. Delgadillo), javier.reneses@iit.upcomillas.es (J. Reneses).

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reactive power markets, where the companies have incomplete information about their rivals. Petoussis et al. [11] assessed different parametrization methods of the companies' supply functions in an active power market taking into account an AC representation of the network. Chitkara et al. [17] proposed a model to analyze the companies' strategic behavior in a reactive power market. This model assumes that the active power is already scheduled, thereby there is no feedback between the reactive and active power markets, i.e., reactive power requirements do not modify strategic behavior in the active power market.

This paper presents a conjectural-variation-based model of a single-price electricity market. The main characteristic of this model is that the companies' strategic behavior takes into account the effect of the voltage constraints. The market equilibrium equations are solved by means of a two-stage optimization problem. In the first stage, a mixed complementary problem models the day-ahead market clearing process. In the second stage, an optimal power flow is solved to determine the changes in active and reactive power needed to meet the voltage system requirements. Moreover, this paper presents an iterative algorithm to resolve the two-stage optimization problem. This model is based on the model proposed in [23]. The main difference between the two models is that the model in [23] only analyzes the effect of network congestion caused by the thermal limits of the transmission lines. Thus, the model in [23] uses a DC-OPF which assumes that there is enough reactive power compensation in all nodes to maintain voltage at the desired level, so the terms related to reactive power are discarded and the voltage levels are equal to 1 p.u. in all nodes. However, this DC approximation is not suitable to study the effect of the voltage level requirements because it is not possible to assume that voltage levels are constant in all nodes. Hence, the model presented in this paper uses an AC-OPF to properly model the voltage requirements at the transmission network. It is important to point out that in recent years optimal power flow has been used to assess the operation of the electricity systems not only in high voltage levels but also in medium and low voltage levels in the distribution grids, e.g., [26–28] studied the optimal operation of the system taking the integration of renewable generation, distributed generation and microgrids into account.

The remainder of this paper is organized as follows: Section 'Market equilibrium model' presents the market equilibrium model that includes the effect of the voltage constraints on the companies' strategic behavior. Section 'Numerical example' provides and analyzes a numerical example. Finally, Section 'Conclusions' draws the most relevant conclusions.

Market equilibrium model

This section generalizes the model presented in [23] in order to study the effect of voltage constraints on the companies' strategic behavior in a single-price electricity market. In the electricity market, the scheduled day-ahead generation is usually determined first. Then, a subsequent procedure is carried on if the day-ahead market solution does not meet the technical requirements necessary to maintain system stability. Different technical constraints are assessed and the power produced by units may change with respect to the scheduled day-ahead generation.

Market clearing conditions

The day-ahead market clearing process determines the active power P_j of each generation unit j as well as the market price λ. Since it is a single-price electricity market, the total generation and demand have to be balanced (1) and the market price λ is equal to the bid of the marginal unit:

$$\sum_{j\in J} P_j = \sum_{a\in A} DP_a + losses \tag{1}$$

Subsequently, the changes in production necessary to maintain system stability are determined using a mechanism to solve the technical constraints. There are different schemes to remunerate the power active changes as presented in [29–32]. In this paper, the Spanish mechanism [29] is modeled in which the power active increments X_j are paid at the price γ while the reductions W_j are charged at the day-ahead market price λ. In order to maintain the system active power balance, the total active power increment is equal to the total active power reduction:

$$\sum_{j\in J} X_j = \sum_{j\in J} W_j \tag{2}$$

The company's problem

A generation company i will try to maximize its profit by determining the production of its generation units, P_j, as well as the production changes, X_j and W_j, required to meet the technical system constraints. Moreover, since the generation company behaves strategically, it can change the electricity prices when the production of its units changes. This strategic behavior could be modeled by means of the parameters θ_i and β_i. θ_i corresponds to the conjectured-price response in the day-ahead market [18] and β_i to the conjectured-price response in the subsequent mechanism.

Since the reductions are charged at the day-ahead market price, it is possible to represent the quantity reduced W_j as a ratio of the day-ahead market production P_j, i.e., $W_j = m_j \cdot P_j$, where m_j represents the proportion of the active power generation that unit j has to reduce in order to meet the network constraints. Thus, the value of m_j has to be computed taking into account the power flow constraints.

Therefore, the profit maximization problem of company i is:

$$\max_{\lambda_i,\gamma_i,P_j,X_j} \lambda_i \cdot \sum_{j\in J_i} (1-m_j)\cdot P_j + \gamma_i \cdot \sum_{j\in J_i} X_j - \sum_{j\in J_i} C((1-m_j)\cdot P_j + X_j) \tag{3}$$

s.t.

$$\lambda_i = \lambda^* - \theta_i \cdot \left(\sum_{j\in J_i} P_j - \sum_{j\in J_i} P_j^*\right) \tag{4}$$

$$\gamma_i = \gamma^* - \beta_i \cdot \left(\sum_{j\in J_i} X_j - \sum_{j\in J_i} X_j^*\right) \tag{5}$$

$$\overline{P_j} - P_j \geqslant 0 : (\overline{\mu_j}) \qquad \forall j \tag{6}$$

$$\overline{P_j} \cdot w_j - X_j \geqslant 0 : (\overline{v_j}) \qquad \forall j \tag{7}$$

$$\overline{P_j} - P_j - X_j \geqslant 0 : (\overline{\xi_j}) \qquad \forall j \tag{8}$$

$$P_j \geqslant 0, \quad X_j \geqslant 0 \qquad \forall j \tag{9}$$

In the event that the scheduled active power determined in the day-ahead market does not meet the technical system constraints, the units' generation has to be modified in the subsequent mechanism. Assuming that these modifications happen on a regular basis, the companies can predict them, and may use this information to behave strategically. Thus, in the company's optimization problem, this information is modeled using the reduction factors, m_j, and the binary variables, w_j, that indicate which units have to increase generation. Both are determined in the subsequent mechanism as shown in Section 'Subsequent mechanism'. The Eq. (3) is the profit of the company i. Constraints (4) and (5) represent how the company conjectures that electricity prices will change if the company changes its production. Each company i has an estimation of the prices λ_i and γ_i. However, in the equilibrium these prices are equal to the day-ahead market price, λ^*, and the price of the active power increments, γ^*, respectively. Constraint (4) is the