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Analysis and decomposition of active and reactive power spot price in deregulated electricity markets

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ABSTRACT

Electricity markets have suffered important modifications in recent decades in many countries, in which a competition framework has been established with the aim of improving market efficiency and reducing energy prices. However, this new paradigm does not assure optimal solutions, as new constraints can be introduced in optimization processes that can affect the resulting prices. An example of this situation is the establishment of power purchase agreements between producers and consumers. A wide literature can be found regarding electricity markets. Some of this literature refers to the theory of spot prices and its application to them. This paper deals with the obtaining, decomposition and deduction of behavior rules of spot prices, and their influence on established contractual relationships in a deregulated market environment which allows power purchase agreements between consumers and producers. It is performed by a deterministic modeling of the complete generation-grid system. The influence of the existence of this kind of agreements on both total costs and spot prices is discussed.

Introduction

The establishment of a marginalist remuneration system based on spot prices with space-time discrimination presents a high difficulty. However the need for improved market efficiency due to the rising prices, the possibility of integrating demand management processes and the development of smart grids encourages its feasibility in a near future.

It must be also pointed out that it accomplishes two basic premises:

- Under suitable conditions, remuneration based on marginal prices ensures the complete recovery of costs.
- It is the most appropriate means of providing the market with the proper economic signals of the system's performance, maximizing the Social Welfare that can be attained with the product.

Formerly, energy markets were characterized by large vertically-integrated companies which performed generation, transmission and distribution of electric energy. Later, the increase of both demand and energy cost and the need for efficient market management led to important regulatory changes in many countries to incorporate competition mechanisms. The nature of such regulatory changes varies with the country and the time period, but most developed countries have promoted the vertical unbundling of generation, transmission and distribution activities. In addition, the establishment of direct buying and selling contracts between producers and consumers or retailers – they are usually called power purchase agreements – are facilitated with the aim of reducing the uncertainty and risk inherent to electricity markets [1,2]

This paper deals with the development of the theory of spot prices according to marginalist criteria for rate-setting and its application to electricity markets. It continues and completes that proposed in [3], also taking into account all the existing constraint on the basis of an analysis of their influence over the system.

The considered scenario corresponds to a market in which a system operator fixes each generator production, but respecting power purchase agreements, with the aim of achieving an optimal behavior on a global basis while satisfying both technical requirements and contracts.

The influence of power purchase agreements over energy price will be analyzed, and it will be pointed out how they could move it from the optimal point, even noticeably influencing the cost distribution among agents. A wide amount of indices are described in literature to analyze the competition rate and the foreseeable

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behavior of deregulated markets, like Herfindahl–Hirschmanindex (HHI), Lerner index, Must Run Ratio (MRR), Must-Run Share (MRS) and other ones presented in [4]. Although spot price may not be considered as one of these indices, we try to deduce simple behavior rules, starting from its analysis, in order to rapidly obtain information about the influence of power purchase agreements over the market rules and the energy price.

Mathematical formulation of the model for the complete system generation-grid. Scenario with grid operator

In the considered electricity market, we distinguish three kinds of agents: the first one is constituted by the energy producers; the second one corresponds to the buying agents: consumers, retailers and distribution companies that sell energy to its clients; the last one is the grid operator, which manages it according to established contracts, technical restrictions and security and environment concerns.

With the aim of optimizing the participation of every agent on an economically efficient basis, the function called Social Welfare [5,6], must be maximized:

$$\text{Social Welfare} = \sum_{j=1}^{m} \text{Consumer surplus}_j + \sum_{i=1}^{n} \text{Producer surplus}_i \quad \forall j \in \textit{Consumer}, \forall i \in \textit{Generation} \tag{1}$$

Assuming that acquisition costs are equal to selling incomes, the following is obtained:

$$\text{Social Welfare} = \sum_{j=1}^{m} \text{Utility funtions from use of the product}_j - \sum_{i=1}^{n} \text{Production cost}_i \tag{2}$$

According to (2) and taking into account that in a short term the installed capacity of generation is fixed, the Social Welfare function is therefore:

$$\text{Social Welfare} = \sum_{j=1}^{m} B_j(D_j, R_j) - \sum_{i=1}^{n} C_j(P_{gen\,i}) \tag{3}$$

where:

B_j is the benefit that a consumer j obtains with the use of the electric power, function of D_j and R_j.
C_i is the production cost of generator i, function of $P_{gen\ i}$.
D_j is the active power demanded by consumer j.
R_j is the reactive power demanded by consumer j.
$P_{gen\ i}$ is the active power generated by generator i.

Maximization of this function is subjected to some constraints, including the existence of power purchase agreements. The following constraints are put into groups according to the element of the system they concern:

In each node i of the grid, the following requirements have to be met:

$$\sum P_{ie} + \sum P_{gen\ i} - \sum D_i - \sum P_{is} = 0 \tag{4}$$

$$\sum Q_{ie} + \sum Q_{gen\ i} - \sum R_i - \sum Q_{is} = 0 \tag{5}$$

$$V_{\min\ i} \leqslant V_i \leqslant V_{\max\ i} \tag{6}$$

where:

P_{ie} is the active input power at node i.
Q_{ie} is the reactive input power at node i.
P_{is} is the active output power at node i.
Q_{is} is the reactive output power at node i.
$P_{gen\ i}$ is the active power generated at node i.
$Q_{gen\ i}$ is the reactive power generated at node i.
D_i is the active power demanded at node i (active load connected to the node).
R_i is the reactive power demanded at node i (reactive load connected to the node).
V_i is the voltage of node i.
$V_{\min i}$ is the minimum voltage admissible at node i (pre-set limit).
$V_{\max i}$ is the maximum voltage admissible at node i (pre-set limit).

The relationships between variables are the following:

$$\begin{aligned}
P_{ie} &= f(P_{gen\,1}, \ldots, P_{gen\,n}, Q_{gen\,1}, \ldots, Q_{gen\,n}, D_1, \ldots, D_m, R_1, \ldots, R_m) \\
Q_{ie} &= f(P_{gen\,1}, \ldots, P_{gen\,n}, Q_{gen\,1}, \ldots, Q_{gen\,n}, D_1, \ldots, D_m, R_1, \ldots, R_m) \\
P_{is} &= f(P_{gen\,1}, \ldots, P_{gen\,n}, Q_{gen\,1}, \ldots, Q_{gen\,n}, D_1, \ldots, D_m, R_1, \ldots, R_m) \\
Q_{is} &= f(P_{gen\,1}, \ldots, P_{gen\,n}, Q_{gen\,1}, \ldots, Q_{gen\,n}, D_1, \ldots, D_m, R_1, \ldots, R_m) \\
V_i &= f(P_{gen\,1}, \ldots, P_{gen\,n}, Q_{gen\,1}, \ldots, Q_{gen\,n}, D_1, \ldots, D_m, R_1, \ldots, R_m)
\end{aligned}$$

In each generator, the following must be accomplished:

$$P_{\text{genmin}\ i} \leqslant P_{gen\ i} \leqslant P_{\text{genmax}\ i} \tag{7}$$

$$Q_{\text{genmin}\ i} \leqslant Q_{gen\ i} \leqslant Q_{\text{genmax}\ i} \tag{8}$$

$$E_{\text{genmin}\ i} \leqslant E_{gen\ i} \leqslant E_{\text{genmax}\ i} \tag{9}$$

$$\delta_{gen\ i} \leqslant \delta_{\text{genmax}\ i} \tag{10}$$

$$H_{gen\ i}(P_{gen\ i}, Q_{gen\ i}) = 0 \tag{11}$$

where:

$P_{\text{genmin}\ i}$ is the minimum technical limit of active power to generate for generator i.
$Q_{\text{genmin}\ i}$ is the minimum technical limit of reactive power to generate for generator i.
$P_{\text{genmax}\ i}$ is the maximum technical limit of active power to generate for generator i.
$Q_{\text{genmax}\ i}$ is the maximum technical limit of reactive power to generate for generator i.
$\delta_{gen\ i}$ is the phase difference angle between the emf of generator i and the node connection voltage.
$\delta_{\text{genmax}\ i}$ is the maximum phase difference angle between the emf of generator i and the node connection voltage (pre-set limit).
$E_{gen\ i}$ is the open-circuit voltage (emf) for generator i.
$E_{\text{genmin}\ i}$ is the minimum open-circuit voltage value for generator i.
$E_{\text{genmax}\ i}$ is the maximum open-circuit voltage value for generator i.
$H_{gen\ i}$ is the coupling between the active and reactive powers generated by generator i.

If besides a generator has established power purchase agreements with the group of consumers l, the following constraints must be added:

$$P_{gen\ i} \geqslant \sum_{l} D_j \geqslant P_{\text{genmin}\ i} \tag{12}$$

$$Q_{gen\ i} \geqslant \sum_{l} R_j \geqslant Q_{\text{genmin}\ i} \tag{13}$$

The last two expressions show contractual relationships between suppliers (generators) and consumers, corresponding to bilateral purchase agreements with direct energy delivery. In this