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Nash Equilibrium in a two-settlement electricity market using competitive coevolutionary algorithms

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ABSTRACT

This paper investigates the use of competitive coevolutionary algorithms to calculate suppliers' optimal strategies in a deregulated electricity market. The two settlement model is used, consisting of a spot and a forward market. Agents can take part in both spot and forward transactions, and act strategically to maximise their profit from both markets. The strategic interactions of market agents are modelled as a non cooperative game. The competitive coevolutionary Algorithm is used to calculate the Nash Equilibrium strategies ensuring the best outcome for each agent. Results demonstrates the effectiveness of the coevolutionary approach to find the optimal strategies in different market situations.

1. Introduction

The electricity industry underwent major restructuring and changes in the two last decades. The formerly monopolistic electricity markets are being opened to competition, suppliers, retailers and distributors can buy and sell their energy in a liberalized market. The electricity market is no longer a monopoly but far from a perfect market. The size of investments needed in the market (acquisition or construction of a power plant or distribution system) makes the degrees of penetration of competition in the production sector remain low [1–5].

From an economic perspective, the deregulated electricity market is an oligopoly: a market with imperfect competition where producers can influence the prices by behaving strategically. The analysis of such a system requires an approach based on the theory of non-cooperative games which allows us, through the concept of Nash Equilibrium, to study the strategic behaviour of market agents [6–8].

Game theory teaches us that Nash Equilibrium is the optimal state where each player maximizes his profit, considering other players' strategies. Once the equilibrium is reached, no agent will deviate from his strategy of equilibrium at the risk of reducing his profit [9–11].

The traditional approach to finding the suppliers optimal strategies in an electricity market is to formulate the problem as an Equilibrium Problem with Equilibrium Constraints (EPEC), where agents face a Mathematical Program with Equilibrium Constraints (MPEC) parametric on other agents' strategies. In this approach, the cost functions have to be linear and the forward prices have to be equal to the expected spot prices [12–14].

Meta-heuristic algorithms [15] and especially evolutionary algorithms are used to calculate the equilibrium point of electricity markets. Two approaches have been proposed in literature: the equilibrium problem is formulated as an optimization problem and the evolutionary algorithm is used to find the optimal solution [16]. A more interesting approach simulates the strategic interactions between market agents with the mean of a coevolutionary algorithm [17–20].

Another interesting approach is based on agent-based modelling, market participants are modelled as autonomously acting software agents maximizing their profits by learning from the interactions in the electricity markets [21–24].

The aim of the paper is to propose an approach allowing the analysis of strategic interactions in the deregulated electricity market, by using a competitive coevolutionary algorithm to find the Nash Equilibrium of the market game. To achieve this goal, market agents are modelled as evolutionary agents who learn from their interactions with other agents to maximise their profits. A Competitive Coevolutionary Algorithm is used as a simulation platform of strategic interactions among market agents, and calculates the optimal strategies of each agent. Coevolution offers the possibility to model interactions among agents (individuals or populations), in the same way as based-agent approaches. An individual in coevolutionary algorithm is evaluated based on his interactions with other individuals of other populations.

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2. Equilibrium calculation

Game theory is a mathematical discipline which studies the situation of strategic interactions (games) of two or more agents (players). In strategic games, the payoff of each agent depends on his decision (strategy) and the decisions of the other players.

The concept of Nash Equilibrium is the main tool for predicting the outcome of a non cooperative game. Nash Equilibrium is, by definition, "a strategic profile with the property that no player can improve his profit by choosing a strategy other than the equilibrium strategy, given that, all other players choose their equilibrium strategies" [9–11].

Let G be a game with a set of N players:

- Each player has a set of strategies $S_i = (s_1, \ldots, s_n)$.
- $s = (s_1, \ldots, s_n) \forall s_i \in S_i$ is a strategies profile of players $i = 1, \ldots, N$.
- $\pi_i \in \Re$ is the profit function of player i, associates to each player i a payoff $\pi_i(s)$.
- Let s_i be the player i strategy and s_{-i} the strategies of all players except i.

A strategies profile $s^* \in S$ is Nash Equilibrium if and only if:

$$\pi(s_i^*, s_{-i}^*) \geq \pi(s_i, s_{-i}^*), \quad \forall s_i \in S_i, s_i \neq s_i^*, \quad i = 1, \ldots, N. \tag{1}$$

Another way to describe the Nash Equilibrium is as follows:

$$s_i^* = \arg\max \pi_i(s_i, s_{-i}^*), \forall s_i \in S_i \quad i = 1, \ldots, N. \tag{2}$$

When reaching the Nash Equilibrium, no player has the incentive to deviate from it, since Nash strategy ensures a maximum of profit to a player, considering that all other players play their Nash strategies.

3. Electricity market modeling

The role of electricity market is to establish a fair trading platform to exchange electrical energy between suppliers, consumers and other financial entities for both short and long-term. Several entities participate to the transactions and the most important are:

- *Suppliers*: productive companies, neighbour systems or intermediaries can participate as suppliers and try to sell their energy in the market.
- *Consumers*: cities, distribution companies or intermediaries can participate to the transactions and buy energy from the market or from the suppliers directly.
- *Independent System Operator* (ISO): is an independent and non profitable organism. The ISO has to ensure a reliable and secure functioning of the power system and to maximise the social welfare from the market transactions.

A typical electricity market consists at least of two markets: forward market for long time delivery, and spot market for day ahead delivery. An agent can take part in one or in both markets. In this section; first, we expose the basic models of the forward and the Spot markets. Later, we model a two settlement model of the electricity market where market agents take into account the outcome of the forward market when dealing with the spot market and vice versa.

3.1. Basic electricity market models

Here, the suppliers' models in both forward and spot markets are presented; we assume that market agents are interested in one transaction at time, and do not take into account the outcome of the forward transactions when biding in the spot market (single settlement).

In order to formulate the market models, we consider that:

- N_g suppliers acting strategically by choosing the quantity of Energy to be sold to consumers in order to maximise their profit. A supplier cost function is as follows:

$$Cst_i = 0.5\alpha_i q_i^2 + \beta_i q_i + \gamma_i \quad i = 1, \ldots, N_g \tag{3}$$

- N_d consumers have no strategic behaviour: they can only affect the forward market price by their forward demand function. Consumers demand functions are of the form:

$$D_j^f(p_j^f) = D_j^0 - e_j p_j^f \quad j = 1, \ldots, N_d \tag{4}$$

- The ISO is primarily concerned with the preservation of system constraints and has to reject any transaction affecting the system integrity.

3.1.1. Forward market model

The forward market takes place several months prior to the delivery. Forward market is purely financial: there is no energy exchange between suppliers and consumers, all the contracted energy has to be produced and delivered in real time. Due to this characteristic, forward market transactions are not conditioned of the power system constraints and conditions [25,26].

This market is commonly analyzed using Cournot model:

- Suppliers compete in term of quantities to be sold to consumers

$$q_i^f = \{q_{i1}^f, \ldots, q_{ij}^f, \ldots, q_{iN_d}^f\} \quad i = 1, \ldots, N_g \tag{5}$$

- Consumers are defined by their demand function where the energy demand is inversely proportional to the price.

$$D_j^f(p_j^f) = D_j^0 - e_j p_j^f = \sum_{i=1}^{N_d} q_{ij} \quad j = 1, \ldots, N_d \tag{6}$$

Where:

- e_j is the price elasticity of the demand function.
- D_j^0: the maximum consumer demand.
- p_j^f: the forward market price.
- N_d: the number of consumers in the market.

The market clearing price is established when production meets demand, and is therefore formulated as follows:

$$p_j^f = \frac{1}{e_j}\left(D_j^0 - \sum_{i=1}^{N_g} q_{ij}^f\right) \quad j = 1, \ldots, N_d \tag{7}$$

Thus, the profit of a supplier from forward transaction can be formulated as: