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A Game Theory Approach for the Contract Pricing Estimation of Distributed Generation

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Abstract

This paper presents a game theory approach for the contract pricing estimation of distributed generation (DG). A scenario in which several DG units compete to sell energy to a distribution utility is considered. To meet the expected demand, the distribution utility can purchase energy from the wholesale energy market and form the DG units within its network. The distribution company determines how much energy should be bought from the DG units based on an optimal power flow analysis that takes into account not only the price bids of the GD units but also their technical impact in the network. Within the game theory approach, the players are the DG units and their strategies are the energy contract prices. The equilibrium prices are computed using the software Gambit. Several tests are performed on a 34-bus distribution system. It was found that when the number and capacity of the DG units are increased, the equilibrium prices decrease benefiting the distribution utility from competition among the DG units.

Keywords*:* Power systems, nodal indexes, transmission planning.

INTRODUCTION

In recent years, the electric industry has presented a renewed interest in Distributed Generation (DG). This has been motivated by several factors, that includes the restructuring of the electric power sector, advances in small-scale generation technologies, the availability of government incentives, and a growing awareness of environmental issues [1]. The main advantages of DG can be evaluated considering different points of view. From the standpoint of the distribution utility, DG can contribute to the reduction of power losses [2], improvement of voltage [3] and deferral of investments [3]. From the standpoint of consumers, DG units can be used as back-up in the event of interruptions of power supply and can also sell energy surplus to the distribution network [4]. Due to the potential advantages of DG, several studies have been conducted for its proper location and sizing. The methodologies adopted for the optimal location and sizing of DG include classical optimization and metaheuristic techniques. The advantage of adopting a classical optimization or analytical approach consists on finding global optimal solutions (provided that the model is convex); however, a simplified (linearized) version of the network model must be adopted and therefore dynamic studies are limited. Examples of such studies are presented in [5] and [6]. In [5], the authors present analytical expressions for finding the optimal size and power factor of different types of DG units with the aim of reducing power losses. In [6], the authors propose two analytical approaches for optimal placement of DG with the aim of alleviating network congestion.

Metaheuristic techniques allow to adopt more complex network models; nevertheless, they do not guarantee to obtain global optimal solutions. These methods include artificial bee colony [1], genetic algorithms [7] and particle swarm optimization [8] among others. Technical literature regarding the optimal operation, sizing and location of DG in distribution system is very extensive; a classification of different techniques used for the location and sizing of DG can be consulted in [9].

Most of the studies regarding DG are focused on harvesting their benefits to the network; however, very few consider the interaction of different DG owners competing to sell energy to the distribution utility. This paper adopts this last scenario. In this case, it is considered that there are several DG units within a distribution network belonging to different owners. Every DG owner is able to sell energy to the distribution utility aiming to maximize his profits. On the other hand, the distribution utility must choose the amount of energy to buy from the DG owners and the wholesale energy market. This interaction is modeled through game theory. To show the applicability of the proposed approach several tests were performed on an IEEE benchmark power system. Results show that the increasing participation of DG brings benefits to the distribution utility since it can purchase energy at lower prices given the competition among different DG owners.

METHODOLOGY

The proposed approached is based on the hypothesis that there are different DG owners in a distribution system that compete with each other to sell energy to the distribution utility. In this context, the distribution company is able to purchase energy from the DG units and/or from the wholesale energy market through long term contracts. The distribution company must decide how much energy to buy from each supplier in order to minimize the cost of meeting the expected demand. The decision over how much energy to buy from the DG units and from the wholesale energy market is carried out through an optimal power flow based dispatch that considers not only the cost of the energy but also its impact on the network. On the other hand, every DG owner must consider the fact that there are other DG owners competing to sell energy to the distribution company. In every scenario the equilibria prices are obtained through game theory. The implemented methodology is detailed below.

Optimal power flow based dispatch model

Equations (1)-(8) describe the decision making process of the distribution company. Equation (1) is the objective function that consists on minimizing the cost of attending the forecasted demand. The first term corresponds to the cost of the energy bought from the wholesale market and provided to the network through substation. Equations (2) and (3) represent the active and reactive power balance constraints, respectively. Equations (4) and (5) represent the minimum and maximum limits of active and reactive power supplied by every substation. Equation (6) represents the active power limits of every distributed generator. Finally, equations (7) and (8) are the minimum and maximum limits of voltage magnitudes and apparent power flow in buses and lines, respectively.

$$\underset{P_{DGj}(t),P_{SEj}(t)}{Min} \sum_{t\in T}\sum_{k\in K}\Delta_t \rho_{SEk}(t)P_{SEk}(t)+\sum_{t\in T}\sum_{j\in J}\Delta_t \delta_{GDj}P_{GDj}(t) \tag{1}$$

$$P_{Gn}(t)-P_{Dn}(t)-P_n(t)=0; \quad \forall n\in N,\forall t\in T \tag{2}$$

$$Q_{Gn}(t)-Q_{Dn}(t)-Q_n(t)=0; \quad \forall n\in N,\forall t\in T \tag{3}$$

$$P_{SEk}^{Min}\le P_{SEk}(t)\le P_{SEk}^{Max}; \quad \forall k\in K,\forall t\in T \tag{4}$$

$$Q_{SEk}^{Min}\le Q_{SEk}(t)\le Q_{SEk}^{Max}; \quad \forall k\in K,\forall t\in T \tag{5}$$

$$P_{GDj}^{Min}\le P_{GDj}(t)\le P_{GDj}^{Max}; \quad \forall j\in J,\forall t\in T \tag{6}$$

$$V_n^{Min}\le V_n(t)\le V_n^{Max}; \quad \forall n\in N,\forall t\in T \tag{7}$$

$$-S_{lmn}^{Max}\le S_{lmn}(t)\le S_{lmn}^{Max}; \quad \forall l_{mn}\in L,\forall t\in T \tag{8}$$

In this case *J, K, L, N* and *T* are the set of DG units, substations, lines, nodes, and time intervals, respectively. Δ_t corresponds to the length of the time intervals, ρ_{SEk} and P_{SEk} are the wholesale market price and power supplied by the substation k, respectively. δ_{GDj} and P_{GDj} are the price offer and the active power supplied of the j^{th} DG unit, respectively. P_{SEk} and Q_{SEk} are the active and reactive power supplied by substation k, respectively. Finally, S_{lmm} is the apparent power flow of line *lmn*. The active and reactive power injections expressed in (2) and (3) are given by (9) and (10), respectively. Finally, the apparent power and its active and reactive power components are given by (11), (12) and (13), respectively. In this case g_{mn} and b_{mn} are the real and imaginary parts of the Admittance matrix in position *mn*. Finally, θ_{mn} is the phase angle between nodes *m* and *n*.

$$P_n = V_n\sum_{n\in N} V_m\left[g_{nm}\cos(\theta_{nm})+b_{nm}sen(\theta_{nm})\right] \tag{9}$$

$$Q_n = V_n\sum_{n\in N} V_m\left[g_{nm}sen(\theta_{nm})+b_{nm}\cos(\theta_{nm})\right] \tag{10}$$

$$S_{lmn}=P_{lmn}+jQ_{lmn} \tag{11}$$

$$P_{lmn}=V_n^2 g_{nm}-V_nV_m g_{nm}\cos(\theta_{nm})-V_nV_m b_{nm}sen(\theta_{nm}) \tag{12}$$

$$Q_{lmn}=-V_n^2 b_{nm}+V_nV_m b_{nm}\cos(\theta_{nm})-V_nV_m g_{nm}sen(\theta_{nm}) \tag{13}$$

Once a dispatch is performed, the profits of the DG units can be calculated using equation (14), where δ_{DGj} is the production cost of the j[th] DG unit and CP is its corresponding contract price.

$$Profit_{DGj}=\sum_{t\in T}(\delta_{DGj}-CP)\Delta_t\, P_{DGj}(t) \tag{14}$$

Computing equilibria prices through game theory

Game theory is the study of strategic interaction between rational decision-makers. This theory studies scenarios in which various agents are interested in maximizing their own gains, which often conflict with each other. In this theory, a *game* is a situation in which there are two or more agents in which the actions of one interfere in the results of another. A *player* is every agent who participates and has goals in the game. A *strategy* is the action that a player performs to achieve his goal. A player always looks for a strategy that increases their winnings (or lessens his losses). The main problem is to choose a strategy trying to predict the potential gains and losses that it can bring. In this case, every player must predict what the other participants will do or are doing.

In this work, the players are the DG owners and their strategies are the energy contract prices. The goal of every DG owner is to maximize his profits. It is also considered that players have complete information about the network and wholesale market prices. The game is played simultaneously (only one round), meaning that the players act without knowing the bid of the competitors. DG owners should consider several factors in determining the contract price offer, these factors include:

• *The allocation of DG units in the network:* DG units that are strategically allocated (for example, at the end of heavily loaded feeders) can benefit from this situation since the power injected by such units alleviates congestion in the network.

• *Wholesale energy market prices*: if wholesale energy market prices are high; the DG owners can benefit from this fact by also offering their energy at a high price. Conversely, if these prices are low, DG owners must bid at a lower price.

• *Price offers of other DG owners*: in general, the distribution company would prefer to buy energy from the cheapest source. However, the DG impacts are evaluated by the distribution company through the multi-period economic dispatch given by equations (1)-(13). Therefore, it might be the case that even if a DG unit has a low energy price offer it is not dispatched if the power injected by such unit causes technical problems (such as congestion or deterioration of voltage profile). Conversely, if a DG unit offers a high price but it brings additional benefits to the network, the distribution company might purchase energy from this unit.

The solution to a game is the prediction of its outcome. In this case, to solve the game, the pay-off matrix is calculated. This matrix consists on the players' profits for each combination of strategies. After calculating the pay-off matrix, the Nash equilibrium (or equilibria) is calculated using the GAMBIT software [10]. The Nash equilibrium of a game is a point where each player has no incentive to change his strategy unilaterally, if the other players do not change their strategies.

TEST AND RESULTS

Several tests were performed on the IEEE 34-bus power system illustrated in Figure 1. The data of this system can be consulted in [7]. For all tests a period of one year is considered. Figure 2 shows the load and price duration curves used in all tests. Note that wholesale energy market prices are expected to be higher in periods of high demand and vice versa. To solve the game a pay-off matrix is calculated evaluating all possible combination of strategies (contract price offers) of the DG units. For every set of contract price offers, the optimal dispatch given by (1)-(13) is computed with the software Matpower [11] and the profits of the DG owners are calculated using equation (14). For all tests, an operative cost of 60$/MWh was considered for all DG units. The contract price offers of every DG owner were discretized from 65,1 $/MWh to 80$/MWh at intervals of 0,1 $/MWh. Note that the combination of strategies increases exponentially with the number of players (DG owners).

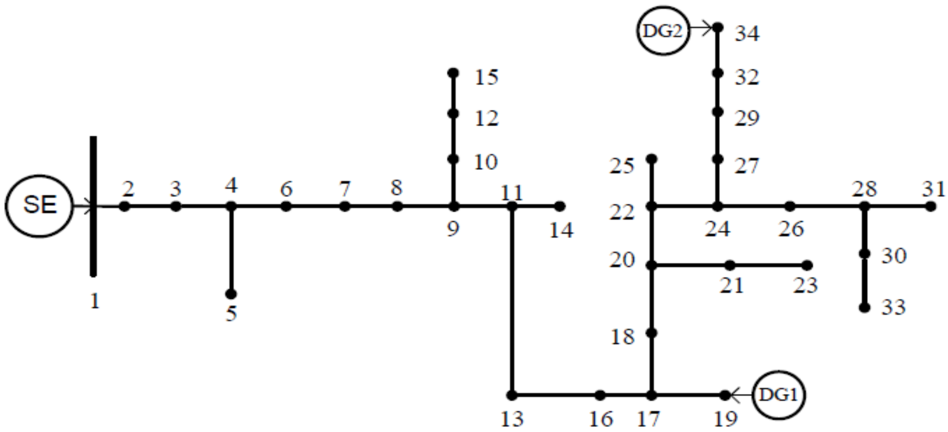


Figure 1. IEEE 34-bus distribution system with two DG units.

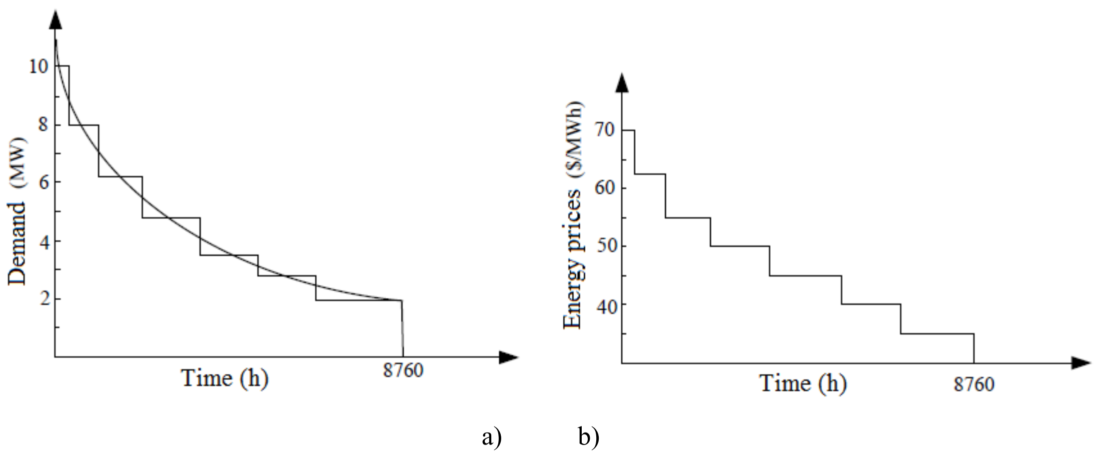


Figure 2. a) Load duration curve and b) Price duration curve

Scenario 1: Considering two DG owners

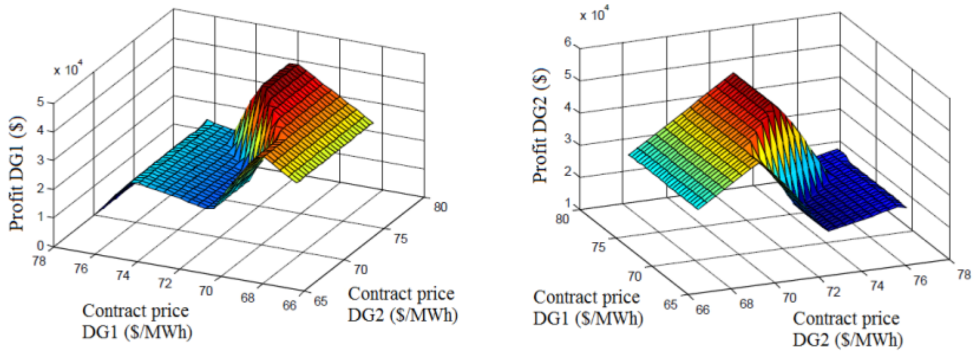
Initially, two DG units were considered. These units were labeled as DG1 and DG2 and allocated in buses 19 and 34, respectively, as illustrated in figure 1. To show the impact of DG sizing in the resulting equilibrium contract prices, four different DG sizes were considered ranging from 0,5MW up to 2,0MW at intervals of 0,5MW. Table 1 illustrates the equilibrium contract prices obtained with the software Gambit for different tests. Note that when the DG size increases the equilibrium contract prices decrease. Table 2 presents the corresponding profits of the DG owners for the same tests. The combination of contract price offers and their corresponding profits for both DG units is illustrated in figure 2 (pay-off matriz); in this case two DG units of 2.0 MW each are considered. The interdependency of profits is evident since the maximum profits of one DG owner depends on the contract price offer of the other GD owner.

Table 1. Equilibrium contract prices for scenario 1

	0,5MW	1,0MW	1,5MW	2,0MW
DG1	71,6	70,6	69,6	68,7
DG2	73,0	71,8	70,6	69,5

Table 2. Profits of the DG owners for scenario 1

	0,5MW	1,0MW	1,5MW	2,0MW
DG1	12702	23214	31536	37821,4
DG2	14235	25842	34821	41161,7



a) b)

Figure 3. Profits of DG owners for different combinations of strategies.

Scenario 2. Considering 3 DG owners

A second scenario was considered with 3 DG owners. The new DG unit is allocated in bus 14 with the same operative costs of the previous DG units. The same procedure of scenario 1 is performed and the new equilibrium contract prices and profits of the DG owners are presented in Table 3 and Table 4, respectively. Note that there is a tendency of the contract prices to reduce with the inclusion of a new competitor, which as expected would result in benefits to the distribution company.

Table 3. Equilibrium contract prices for scenario 2

	0,5MW	1,0MW	1,5MW	2,0MW
DG1	71,0	69,8	68,6	67,3
DG2	72,5	71,0	69,5	68,2
DG3	70,0	69,0	68,0	67,1

Table 4. Profits of the DG owners for scenario 2

	0,5MW	1,0MW	1,5MW	2,0MW
DG1	12045	21462	28251	31974
DG2	13687,5	24090	31207,5	35916
DG3	10950	18898,2	24811,2	30673,5

Scenario 3. Considering 4 DG owners

As mentioned before, the combination of strategies increases exponentially with the number of players. Therefore, in the case of 4 DG owners, the discretization of strategies was performed from 65,1 $/MWh to 73$/MWh at intervals of 0,1 $/MWh. This new range was considered taking into account that maximum contract prices for 3 DG owners were lower than 73$/MWh (see table 3). The new DG unit was allocated in bus 24. Tables 5 and 6 show the equilibrium contract prices and profits of the DG units for this scenario, respectively. Note that there is a tendency of contract prices and prices and profits to reduce when a greater number of DG units is introduced in the network.

Table 5. Equilibrium contract prices for scenario 3

	0,5MW	1,0MW	1,5MW	2,0MW
DG1	70,8	68,6	67,2	66,5
DG2	71,3	70,9	68,3	67,2
DG3	69,6	68,8	67,5	66,3
DG4	70,2	70,2	67,8	67,1

Table 6. Profits of the DG owners for scenario 3

	0,5MW	1,0MW	1,5MW	2,0MW
DG1	11525	20212	27452	29974
DG2	12963,5	22904	25219,5	30478,5
DG3	12635,5	20485	28562,5	32318,5
DG4	12645	22312	26584,5	33453,5

CONCLUSIONS

This paper presented a methodology to calculate DG energy prices by means of game theory. A scenario in which different DG units compete to sell energy to the distribution utility was considered. It was observed that when the capacity and / or the number of DG units increases, the equilibrium contract prices decrease. It is concluded that the competition between the DG owners, benefits the distribution utility since it allows it to buy energy from DG units at a lower price. In a future work, the allocation of DG units will also be included as a strategy, which will allow the analysis of the impact of competition on both prices and allocation of DG units; also, the impact of DG technology and its variability will be taken into account.

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