Optimal Contract Pricing of Distributed Generation Under a Competitive Framework

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***Abstract*—A bilevel programming approach for the optimal contract pricing of distributed generation (DG) in distribution networks is presented. The outer optimization problem corresponds to the owner of the DG who must decide the contract price that would maximize his profits. The inner optimization problem corresponds to the distribution company (DisCo), which procures the minimization of the payments incurred in attending the expected demand while satisfying network constraints. The meet the expected demand the DisCo can purchase energy either form the transmission network through the substations or form the DG units within its network. The inner optimization problem is substituted by its Karush-Kuhn-Tucker optimality conditions, turning the bilevel programming problem into an equivalent single-level nonlinear programming problem which is solved using commercially available software.**

***Index Terms*—Bilevel programming, distributed generation.**

I. Nomenclature

Indices

i,k	Bus indexes.
j	Distributed generation index.
m	Inequality constraint index.
n	Equality constraint index.

Parameters

b_{ik}	Susceptance of the line connecting nodes *i,k*.
C_{DG}	Operation cost of DG.
g_{ik}	Conductance of the line connecting nodes *i,k*.
M	Number of inequality constraints.
N	Number of equality constraints.
ndg	Number of DG units.
P_{Di}	Demand of active power in bus *i*.
$P_i(V,\theta)$	Net active power injection in bus *i*.
Q_{Di}	Demand of reactive power in bus *i*.
$Q_i(V,\theta)$	Net reactive power injection in bus *i*.
S_{ik}	Apparent power flow from bus *i* to bus *k*.
ρ_{SE}	Price of energy at the substation.

Decision variables

β_{DGj}	Contract price offered by distributed generator *j*.
P_{DGj}	Active power supplied by distributed generator *j*.
P_{SE}	Active power supplied by the substation.
P_{Gi}	Active power generated in bus *i*.
Q_{Gi}	Reactive power generated in bus *i*.
V_i	Voltage magnitude in bus *i*.
θ_i	Voltage angle in bus *i*.

II. Introduction

DISTRIBUTED generation can be broadly defined as the production of energy by typically small-size generators located near the consumers [1]. In the last decade the electric power industry has shown a renewed interest in DG. This new trend has been mainly motivated by an increasing awareness of environmental issues, along with advances in generation technologies that have rendered economic the production of small efficient generators using both conventional and renewable energy sources [2].

While it is well known that in most cases DG cannot compete with centrally dispatched generation; it is also true that it can provide benefits to the distribution utility such as reduction of power losses and improvement of voltage profile. The technical impacts of DG in electric power systems have been widely studied in the literature. Recent research includes stability [3], voltage control [4], power quality issues [5] loss reduction [6] and the potential of DG to provide ancillary services [7]. Bearing in mind that the potential benefits of DG largely depend on its location and size, many of the studies regarding DG address the problem of its optimal placement and sizing. However, since DG typically does not compete with centrally dispatched generation in wholesale electricity

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markets, an optimal bidding strategy for DG at this market level is out of the question. On the other hand, from the point of view of the DisCo, buying energy from DG units might be an attractive option, especially when these units are located in heavily loaded feeders far away from the substation [8]. This is the case addressed in this paper. It is assumed that there is a day-ahead energy market in which a DisCo must buy energy to supply the expected demand. This energy is bought at the point of interconnection with the transmission system (a substation) at the market clearing price. Depending on specific market rules, the market clearing price may be different every hour, being in general higher during peak hours. In this case the DisCo also receives a contract price offer and a declared capacity of the DG units located in its network. Consequently, the DisCo can alternatively purchase energy form independent producers (DG) or form the spot market. A more general energy acquisition market involving DG that includes bilateral contracts and load curtailment options is described in [9].

In a market structure like the one described above, a sound reasoning might point out that when the contract price supplied by the DG is lower than the market clearing price at a specific hour, the DisCo must buy all the energy available from the DG units; conversely, when the contract price supplied by the DG is higher than the market clearing price, the DisCo must buy all the energy from the substation. However, this reasoning does not consider the impact of the energy injected by the DG in the voltage profile and losses of the distribution network. This impact can only be measured using an AC power flow approach. In consequence, the DisCo must weigh the DG energy price with the impact in losses and voltage profile that the system would experience given a certain dispatch of DG. The best way to do this is by means of an AC optimal power flow model. In this case the objective function would be the minimization of the payments incurred in supplying the expected demand (buying energy form the substation and/or form the DG) subject to network constraints. If the power injected by a DG unit contributes to the enforcement of a voltage constraint and/or has a positive impact reducing power losses, then even if the DG contract price is higher than the price of energy at the substation, the DG unit is likely to be dispatched. On the other hand, if the DG unit has a negative impact in the network it might not be dispatched, even if its contract price is lower than the energy price at the substation.

In the proposed model, it is supposed that the DG does not belong to the DisCo. Then, the owner of the DG must find the optimal contract price that would maximize his profits. This two-agent relationship was modeled as a bilevel programming problem (BLPP).

A BLPP is closely related to the Stackelberg game [10]. In a Stackelberg game there are two types of agents, namely the leader and the followers. The leader makes his move first anticipating the reaction of the followers, and then the followers move sequentially knowing the move of the leader.

A BLPP is a single-round Stackelberg game. The leader in this case is the DG owner who makes his move first providing a price contract to the DisCo. Given the price at which the DG owner is willing to sell his energy, the DisCo decides over the quantity and time in which this energy will be needed to help attending the expected demand. Fig 1 shows the relationship between the two agents.

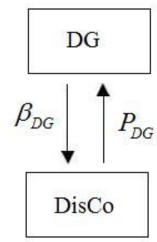

Fig 1. Bilevel programming diagram.

A BLPP is composed by an outer and an inner optimization problem. The outer problem corresponds to the optimization performed by the owner of the DG who, as stated above, procures the optimal contract price that would result in the maximization of his profits. The inner optimization problem corresponds to the DisCo which procures the minimization of the payments incurred in attending the expected demand. This last optimization problem is substituted by its Karush-Kuhn-Tucker (KKT) optimality conditions, turning the BLPP into an equivalent single-level nonlinear programming problem which is solved using commercially available software.

The rest of the document is organized as follows: section III describes the proposed BLPP model and the equivalent single-level nonlinear optimization problem. Section IV shows an example of the proposed model applied on a distribution system. Finally, the conclusions are discussed in section V.

III. Bilevel Formulation

A BLPP is a hierarchical optimization problem in which one of the constraints is also an optimization problem. In a BLPP the control of the decision variables is partitioned between two decision makers. The decision variables of the outer agent are parameterized in the inner optimization problem. A common technique for solving a BLPP is turning it into a single-level optimization problem. Such an equivalent problem can be obtained using duality properties or optimality conditions.

A. Inner optimization problem

As stated above, the inner optimization problem corresponds to the minimization of the payments incurred in attending the expected demand and is solved by the DisCo. This problem is given by (1)-(7). For simplicity, a single-period formulation is presented. However, since all decision variables are continuous, and inter-temporal constraints are not considered, a multi-period formulation is straightforward.

$$Min \quad \rho_{SE} P_{SE} + \sum_{j=1}^{ndg} \beta_{DGj} P_{DGj} \tag{1}$$

Subject to:

$$P_{Gi} - P_{Di} - P_i(V,\theta) = 0 \quad (2)$$

$$Q_{Gi} - Q_{Di} - Q_i(V,\theta) = 0 \quad (3)$$

$$P_{Gj}^{\min} \le P_{Gj} \le P_{Gj}^{\max} \quad (4)$$

$$Q_{Gj}^{\min} \le Q_{Gj} \le Q_{Gj}^{\max} \quad (5)$$

$$V_i^{\min} \le V_i \le V_i^{\max} \quad (6)$$

$$|S_{ik}| \le S_{ik}^{\max} \quad (7)$$

The objective function is divided in two terms. The first term corresponds to the power purchased at the substation, and the second one corresponds to the power purchased from the DG units. Note that the contract prices at which the DG owners are willing to sell their energy are not decision variables, but parameters for this problem. Equations (2) and (3) represent the active and reactive power balance equations respectively. Equations (4) to (7) represent the operating limits of active and reactive power; voltage magnitudes and apparent power flow respectively. The active and reactive power generated in each bus of the distribution system are represented by two vectors that include the substation and the distribution units as shown in (8) and (9). Furthermore, the net active and reactive power injected in a bus, are given by (10) and (11).

$$P_G = [P_{SE} \quad P_{DG}] \quad (8)$$

$$Q_G = [Q_{SE} \quad Q_{DG}] \quad (9)$$

$$P_i(V,\theta) = V_i \sum_{k=1}^{nb} \left[V_k \left\{ g_{ik} \cos(\theta_i - \theta_k) + b_{ik}\, \mathrm{sen}(\theta_i - \theta_k) \right\} \right] \quad (10)$$

$$Q_i(V,\theta) = V_i \sum_{k=1}^{nb} \left[V_j \left\{ g_{ik}\, \mathrm{sen}(\theta_i - \theta_k) - b_{ik} \cos(\theta_i - \theta_k) \right\} \right] \quad (11)$$

The optimization problem (1)-(7) can be compactly rewritten as expressed in (12).

$$\begin{aligned} & Min \quad f(x) \\ & s.t \\ & \qquad h(x) = 0 \\ & \qquad g(x) \le 0 \end{aligned} \quad (12)$$

Where x represents a vector of optimimization variables given by (13).

$$x = [P_G \;\; Q_G \;\; V \; \theta] \quad (13)$$

B. Outer optimization problem

The outer optimization problem consists in the maximization of profits procured by the owner of the DG. The profits can be calculated as the difference between the price of the contract and the operation cost, multiplied by the power generated as expressed in (14). The power generated must be within its limits as shown in (15). Note that in this case, the power generated by the DG unit is not a decision variable, since it is decided by de DisCo in the inner problem.

$$Max \quad (\beta_{DG} - C_{DG}) P_{DG} \quad (14)$$

Subject to:

$$P_{DG}^{\min} \le P_{DG} \le P_{DG}^{\max} \quad (15)$$

In a conventional wholesale electricity market, generator agents have decision control in their bids and quantities and are paid at the market clearing price. In the market structure described in this paper, the DG agent has only control on its contract price, while the quantity is decided by the DisCo (within the generation limits and solving the optimization problem (1)-(7)). Furthermore, the DG is not paid at the market clearing price of the wholesale electricity market (the price at the substation), instead, it is paid (if dispatched by the DisCo) at the provided contract price.

C. Bilevel programming problem formulation

The optimization problems described above can be integrated into a BLPP as shown in (16). Note that the constraint represented by (15) is also implicit in the set of constraints (4) considered by the DisCo. Then, the outer optimization problem is only restricted by the inner optimization problem. For simplicity, and in order to avoid non convexity problems we have not considered line congestion constraints in the bilevel formulation.

$$\begin{aligned} & Max \quad (\beta_{DG} - C_{DG}) P_{DG} \\ & s.t \\ & \quad Min \quad f(x) \\ & \quad s.t \\ & \qquad h(x) = 0 \\ & \qquad g(x) \le 0 \end{aligned} \quad (16)$$

According to optimization theory, given a mathematical programming problem like the one described by (12), any optimal solution must satisfy the KKT optimality conditions. Consequently, under the assumption of convexity, solving the inner problem in (16) is equivalent to find a vector $\overline{x}$ that satisfies (17)-(21) which represent the KKT optimality conditions.

$$\nabla f(\overline{x}) + \sum_{n=1}^{N} \lambda_n \nabla h_n(\overline{x}) + \sum_{m=1}^{M} \mu_m \nabla g_m(\overline{x}) = 0 \quad (17)$$

$$h_n(\overline{x}) = 0 \quad n = 1 \ldots N \quad (18)$$

$$g_m(\overline{x}) \le 0 \quad m = 1 \ldots M \quad (19)$$

$$\mu_m g_m(\overline{x}) = 0 \quad m = 1 \ldots M \quad (20)$$

$$\mu_m \ge 0 \quad m = 1 \ldots M \quad (21)$$

Where (17) represents the stationary condition of the Lagrangian. Equations (18) and (19) are the primal feasibility conditions. Equation (20) is known as the complementarity condition, and equation (21) is the dual feasibility condition. In this case the problem has *N* and *M* equality and inequality constraints respectively. The dual variables λ_n and μ_m represent the Lagrange multipliers associated with the equality and inequality constraints respectively. In this case there are two sets of equality constraints, namely the active and reactive power balance equations ((2) and (3)). The dual variable λ_n

associated with the active balance equation in bus n has a special interest since it represents the price of supplying an additional MW in that bus, and it is known as the locational marginal price. Furthermore, in this marginal price the cost of active power losses are implicit [11]. Then, knowing these prices is of great interest for the DisCo since they can be used to evaluate the economic impact of the power injected by the DG units.

The equivalent single-level optimization problem is given by (22). The KKT optimality conditions are parametric in β_{DG} since it is a decision variable of the DG owner.

$$\begin{aligned} &Max \quad (\beta_{DG} - C_{DG})P_{DG} \\ &s.t \\ &\quad Equations\ (17)-(21) \end{aligned} \tag{22}$$

The nonlinear optimization problem given by (22) is equivalent to a MPEC (Mathematical Problem with Equilibrium Constraints) and can be solved using commercially available software. In this case, the equivalent single-level nonlinear programming problem described by (22) was implemented in GAMS [12].

IV. Test and Results

The proposed methodology was tested using the 34 bus distribution system shown in Fig 2. This system is similar in topology with the IEEE 34 bus distribution system; however, a single-phase modified version has been used. The line data are provided in the appendix. The aggregated load curve is shown in Fig 3. For simplicity this load is equally divided among the 34 nodes. A constant power factor of 0.94 lagging is considered. Fig 4 shows the energy prices at the substation.

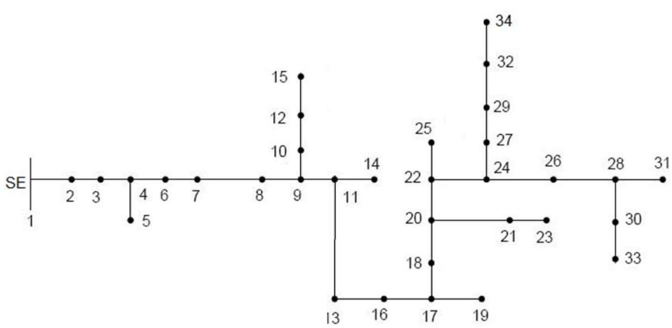

Fig. 2. 34 bus distribution system.

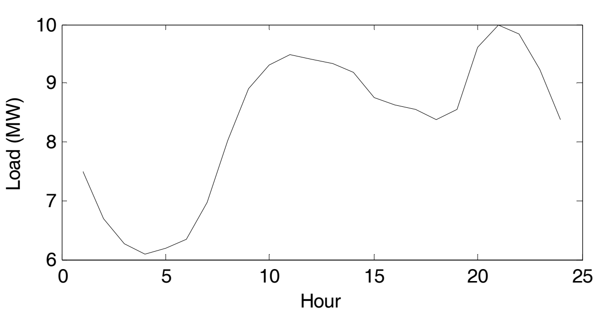

Fig. 3. Aggregated load curve.

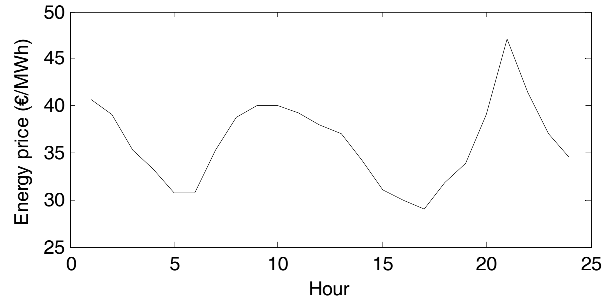

Fig. 4. Energy prices at the substation.

A. *Distributed generation units*

There is a number of different technologies that can be used for small-scale electricity generation. Furthermore, DG technologies can be divided in renewable and no renewable. Technologies that utilize conventional energy resources include reciprocating engines, gas turbines, fuel cells and microturbines. On the other hand, technologies that use renewable energy resources include wind turbines, photovoltaic arrays, biomass systems and geothermal generation. A detail discussion of the current status of these technologies is beyond the scope of this paper. A more in depth discussion of the technical features of the different DG technologies can be found in [2] and [13].

Since the proposed model requires the DisCo to decide over the quantity and the hour in which DG units must run, then, the model is restricted to dispatchable DG technologies.

B. *Case 1. A single DG unit*

Let us consider a 2MW DG unit with an operating cost of 35€/MWh located in bus 24. The equivalent objective function of the optimization problem described by (22) for a horizon planning of 24 hours is represented by (23).

$$Max \quad \sum_{t=1}^{24} (\beta_{DG} - 35) P_{DG,t} \tag{23}$$

Fig 5 shows the locational marginal prices at peak hour (hour 21) obtained by the DisCo when solving the OPF given by (12) in the absence of DG. Despite of the fact that the energy price at the substation at the peak hour is 47€/MWh, supplying an additional MW to bus 24 at this hour will cost 58.5€/MWh. This happens because all the power required in bus 24 will have to pass though the main feeder which will cause an increase in power losses. Then, if the DG unit located in this bus is willing to sell energy at a price below 58.5€/MWh, it will represent savings for the DisCo. However, the DG owner has to consider the whole time horizon to decide the price contract that maximizes his profits.

Solving the optimization problem given by (22) it is found that the best price contract for this DG unit is 42.745€/MWh which will result in a profit of 171.785€. Fig 6 shows the profits for different contract prices. It can be observed that the highest contract price does not guarantee the highest profits, since they depend on the energy contracted by the DisCo. Fig 7 shows the dispatch of the DG unit for the 24 hours of the horizon planning, it can be seen that the DG unit is dispatched during the high load periods in which the price of energy at the substation is also high.

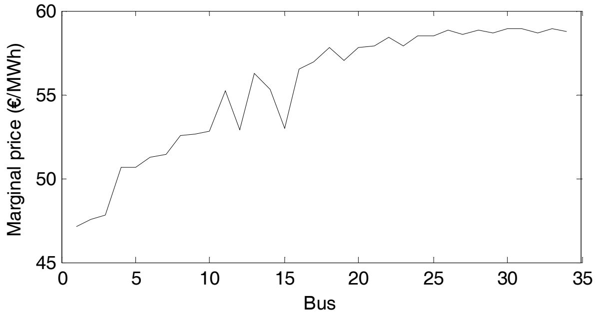

Fig. 5. Locational marginal prices at peak hour.

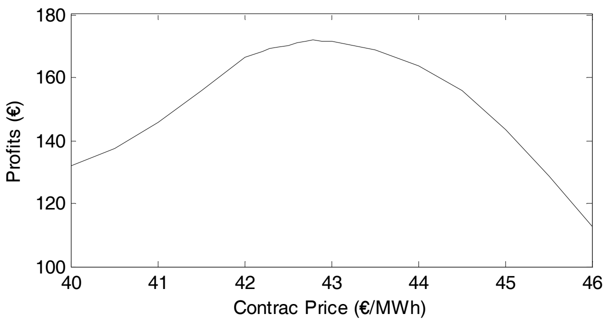

Fig. 6. Profits for different contract prices.

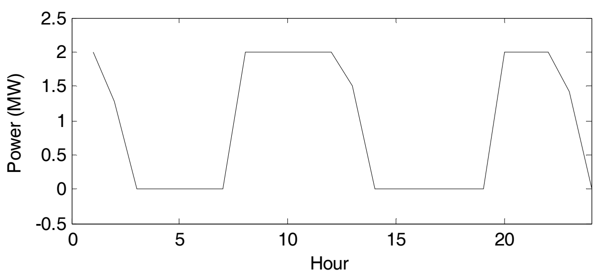

Fig. 7. Hourly Dispatch of the DG unit located in bus 24.

C. Case 2. Multiple DG units

Let us consider two DG units (DG1 and DG2) belonging to different owners with a generation capacity of 2MW and operating cost of 35€/MWh located in buses 11 and 24 respectively. Furthermore, let us consider that the contract price of DG1 (located in bus 11) is 40€/MWh. Under this new scenario, the optimal contract price of DG2 will be 41.0€/MWh with a profit of 142.58€. It was found that DG2 had to change its contract price due to the presence of DG1. Furthermore, the new profits of DG2 are lower when compared with the former case when it was the only DG unit in the network. Fig 8 shows the new relationship between contract prices and profits. In this case the contract price of DG1 was given as a parameter; in general, to consider several DG units belonging to different owners with a BLPP approach it is necessary to freeze the contract price of all units but one. A mathematical problem considering the variation of all contract prices at the same time will result in an EPEC (Equilibrium Problem with Equilibrium Constraints) approach which is out of the scope of this paper.

On the other hand, the DisCo can benefit from the DG units since they can help reducing the energy losses and the payment incurred in attending the expected demand. Table I presents the energy losses and the total payment of the DisCo for the cases presented in this paper. In case 1 there was a reduction of 28% in the total energy losses, while in case 2 the reduction in energy losses was nearly 40%. It is worth mentioning that such a reduction in losses might not always be the case, since these results depend on the location of DG as well as its size and the characteristics of the network.

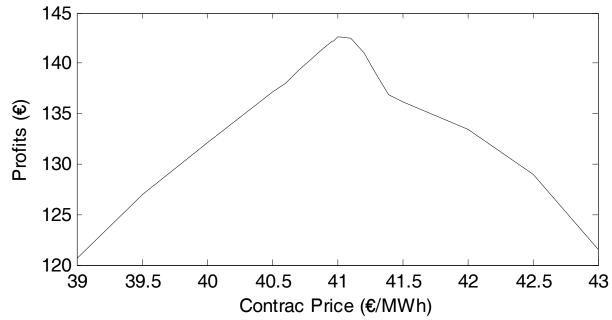

Fig. 8. Profits of DG2 for different contract prices.

TABLE I
IMPACT OF DG IN ENERGY LOSSES AND PAYMENT OF THE DISCO

Case	Energy Losses (MWh)	Total Payment (€)
Without DG	14.306	7791.1
Case 1	10.26	7662.4
Case 2	8.53	7592.6

V. CONCLUSIONS

A bilevel optimization model for the optimal contract pricing of DG in distribution networks was presented. The proposed approach encompasses in a single optimization problem the maximization of the profits procured by the owner of the DG and the minimization of the payments incurred by the DisCo in attending the expected demand. The inner problem of the bilevel model was substituted by its KKT optimality conditions, turning the problem into a single-level optimization problem (MPEC) that can be solved using commercially available software. To properly account for the impact of the DG in voltage profile and power losses, an AC model of the distribution network was considered.

The model was tested in a 34 bus distribution system for two different cases: with a single DG unit, and with two DG units. It the last case it was found that the profits of the DG are reduced due to competition. It was also found that when properly dispatched by the DisCo, the DG can help reducing energy losses as well as the payments incurred in attending the expected demand.

Further work will include non dispatchable technologies as well as the search for the most suitable node where to allocate the DG units.

VI. Appendix

The line data of the 34 bus distribution system used in section IV is provided below. Data are given in per unit using a 10MW base.

TABLE II
LINE DATA OF THE DISTRIBUTION SYSTEM SHOWN IN FIG 2.

Line	r	x	Line	r	x
1-2	0.0043	0.0040	17-18	0.0128	0.0106
2-3	0.0029	0.0021	18-20	0.0006	0.0006
3-4	0.0280	0.0228	20-21	0.0087	0.0062
4-5	0.0006	0.0005	20-22	0.0117	0.0117
4-6	0.0060	0.0060	21-23	0.0012	0.0006
6-7	0.0016	0.0015	22-25	0.0006	0.0005
7-8	0.0126	0.0094	22-24	0.0012	0.0007
8-9	0.0005	0.0005	24-26	0.0173	0.0107
9-10	0.0122	0.0122	24-27	0.0061	0.0061
9-11	0.0312	0.0283	26-28	0.0006	0.0005
10-12	0.0143	0.0108	28-30	0.0007	0.0006
12-15	0.0157	0.0107	30-33	0.0061	0.0055
11-14	0.0061	0.0062	28-31	0.0116	0.0076
11-13	0.0126	0.0106	27-29	0.0022	0.0022
13-16	0.0028	0.0018	29-32	0.0062	0.0067
16-17	0.0062	0.0061	32-34	0.0078	0.0056
17-19	0.0170	0.0171			

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VIII. Biographies

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