MARKET-ORIENTED ANALYSIS FOR ACTIVE DISTRIBUTION SYSTEMS

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ABSTRACT

Distribution networks are today the place where demand and offer are physically located and meet. Offer comes from Generation companies, through distributed generation, while demand is usually represented by simple users. Distribution company both buy and sell energy so they implement both sides. The EU promotes the free market and the renewable energy sources (RES) supported by the distributed generation technology. The technical-economical scenario in which distributed generation is thus growing is complex and comprises a large number of stakeholders. The authors, on the basis of previous studies want to analyse the problem of identifying sets of stakeholders sharing the common interest of increasing their profit in the free energy market. These analytically determined sets can be the basis for the birth of consortia among stakeholders.

The paper is organised as follows. First an introductory part on the market analysis in distribution systems in presence of distributed generation is presented. Then the mathematical formulation of the different profit functions for all the stakeholders is proposed and the algorithm for the identification of the consortia is described. Finally in the application section the algorithm is run on a system of 15 nodes taken from the literature.

INTRODUCTION

Distribution networks are today no longer simply extension of the active transmission networks with the only aim of delivering electric energy to the end-users, but have become the place where demand and offer are physically located and meet. Offer comes from generation companies, distributed generation and interruptible loads, while demand is usually represented by distribution companies and passive customers. This transformation has occurred in the last few years thanks to the actions of the European Community Parliaments carried out for promoting the free market and the use of renewable energy sources (RES). The European Directives 96/92/CE and 2003/54/CE have promoted in the last years the birth of a complex market in which operate big and small subjects and, since the 1 of July 2007, also domestic users. The European Directive 2001/77/CE has stated that all the EC Member Countries have to promote renewable energy sources (RES) in order to address precise objectives on their energy internal consumption. The use of RES has given a strong pulse for the spreading of the distributed generation.

Therefore the scenario in which distributed generation is growing is complex and comprises a large number of stakeholders. The authors want to analyse the problem of identifying sets of stakeholders sharing the common interest of increasing their profit. These sets would become the analogous of the consortia of small clients that are born with the free electricity market in order to obtain higher benefits of the new situation.

Exploiting the findings in the studies about the curse of dimensionality in multiobjective optimization, it is indeed possible to group sets of objectives together. Real world applications indeed show that multiobjective optimization or game theory are often applied to problems showing partly concurrent objectives, thus giving rise to a large and useless number of objectives. In complex problems, where heuristic search is needed, the designer does not know a priori the objective functions and cannot make reasonable assumptions about their shape in the search space. Using the approach proposed by the authors, it will be possible to identify sets of stakeholders that can co-operate for the common objective of improving their profit. The reduction of the number of stakeholders in the market simulations through game theory or other approaches is indeed a basic issue allowing computation speed and precision.

PROBLEM FORMULATION

Both generation and utilization of electrical energy can be found in modern distribution systems. Distributed generation and renewables generation are the two major news in the power distribution field. The energy market liberalization allows the identification of different stakeholders. Else than the traditional distributors (DISCOS) and customers, also interruptible loads, IL, selling a certain amount of energy and generation companies, GENCOs, can be identified. These are all actors of the energy market, each of them is characterised by a buying/selling price and by actual costs for the service they offer.

The following figure 1 shows the transactions in a distribution system.

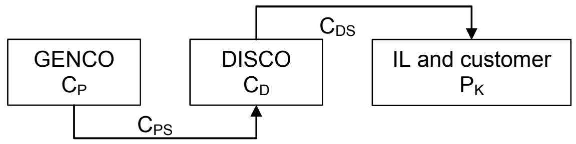

Figure 1 – Economical transactions within a distribution system with distributed generation

In figure 1, the stakeholders that are active elements in an energy market are shown. The economic transactions are also represented. The GENCOs are generation companies and they can either be small microturbines or renewables based generation units. Their concern is that to maximize the difference between the selling price and the production cost. DISCOs are the distribution companies, their main concern is that to maximize the difference between the selling price and the actual distribution cost which includes the losses. The selling prices for generation and distribution are C_{PV} an C_{DV} while the actual costs for each of these actors are C_P and C_D.

A different approach can be adopted for interruptible loads. Interruptible loads have an internal actual cost that is connected to the interruption of an industrial production or of an economic activity. The aim of the interruptible load is that to minimize the sum of the purchase price and of the above defined internal cost. They benefit from a discount rate.

Finally the simple end customers who want to maximize their own profit given by the difference between benefit and cost. Their demand curve is assumed to be elastic. The problem formulation includes hourly changes in the consumer response according to the load level, the price of electricity, and also depending on the elasticity at every hour. The linear demand function is one of the simplest and more widely used models [1]. In order to illustrate this case, a utility or profit function for the use of the electricity, correspondent to the linear demand model, is presented in the following equation:

$$d_{hi} = d_{hi0} *(1+\beta(t)*(S_{Di}(t)- S_{D0})/ S_{D0}) \quad (1)$$

Where d_{hi} is the energy demand of the i-th customer at hour h, d_{hi} is the energy demand of the i-th customer at hour h at the rated price of energy S_{D0}, while S_{Dih} is the price at hour h. The elasticity parameter $\beta(t)$ characterizes the daily period. Larger elasticity values (near −1) will take place during the peak period since the consumers have a very high activity and more loads connected, therefore they have more options to reduce the demand if high prices are present. Figure 2 shows the linear dependency between the hourly demand and the price functions in monetary unit, m.u.. The aggregated benefit can be then calculated as:

$$Bk[d_{hi}]= B_0+S_{D0}*(d_{hi}-d_{hi0})*(1+(S_{Dih}-S_{D0})/ (2*\beta(t)*S_{D0})) \quad (2)$$

Where $Bk[d_{hi}]$ is the benefit of the i-th customer for the demand d_{hi} at hour h and B_0 is the benefit for rated load.

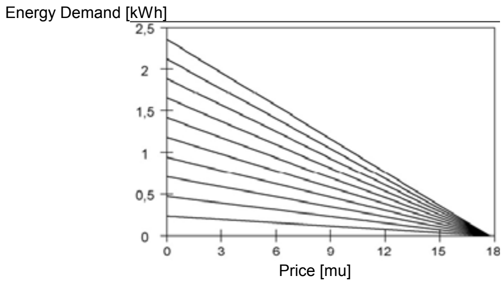

Figure 2 - Hourly demand vs. price functions in monetary unit, m.u.

The variables are the powers of the ILs within the admissible contract ranges as well as the energy prices (from generation to distribution and from distribution to customers).

In what follows, the analysis is carried out considering a given time interval of H hours. In the following subsections describe the analytical formulation of the profit for each actor.

GENCOs

Generation companies have a production cost that is connected to the generation technology. Micro-turbines, as an example, have a generation cost curve that decreases as the produced power approaches the rated value, they can slightly modulate the power injection according to the energy price hour by hour. Photovoltaic or wind generation have a fixed production cost and must inject all the power produced. For the k-th unit the following cost term can be written:

$$C_{Pk} = \Sigma_h G_{Pk}(P_{hk})* E_{hk} \quad (3)$$

Where G_{Pk} is the power production unitary cost for the k-th unit, P_{hk} is the power produced from the k-th unit at hour h. E_{hk} is the energy produced at hour h from unit k (the power produced is considered constant in the time interval h, thus $E_{hk} = P_{hk}*h$). The earning for the same amount of energy can be written as:

$$C_{PSk} = \Sigma_h K_{Pkh}* E_{hk} \quad (4)$$

Where K_{Pkh} is the selling unitary price at hour h for the k-th unit. The objective for the k-th unit is that to maximize the operating margin expressed by the following difference.

$$o_k = \max\{C_{PSk} - C_{Pk}\} \quad (5)$$

DISCOs

Distribution companies are characterised by the purchase from GENCOs and the selling to consumers. Consumers can either be interruptible loads or normal loads. In both cases, the latter generate a losses term, $\Delta E'_{hi\_joule}$, that can be computed using the circuit-based losses allocation algorithm described in [2]. In this case, the Distribution company buys from the GENCOs a given amount of energy but can only sell a lower amount due to the losses in the system. Therefore the actual cost term for the distributor can be expressed as follows:

$$C_D = \Sigma_k \Sigma_h ((C_{RD} + K_{Pkh})^* E_{hk}+C_F{}^*R_i{}^*\lambda_i{}^* E_{hk}) \quad (6)$$

The summation is here extended to all the G generation units (k=1,…G). C_{RD} is the retail and distribution cost, while C_F is the cost of non supplied energy, R_i is the duration of the contingencies and λ_i is their frequency. The selling term for the distributor is thus expressed as:

$$C_{DS} = \Sigma_i \Sigma_h S_{Dih}{}^* (E'_{hi} +\Delta E'_{hi\_joule}) \quad (7)$$

Where E'_{hi} is the energy provided to the i-th customer. The summation is extended to all the L loads (i=1,…L), S_{Dih} is the selling price at hour h applied to the i-th customer. This price can be reduced when the load allows a curtailment (interruptible load).
The objective for the distributor is that to maximize the operating margin expressed by the following difference.

$$o_k = \max\{C_{DS} – C_D\} \quad (8)$$

Interruptible loads and loads

In an Interruptible loads management program, the customer enters into a contract with the system operator (DISCO) to reduce its demand as and when requested. The DISCO benefits in having additional reserve for its security management services, while the customer benefits from reduction in energy costs and from incentives provided by the contract. In this case, the consumer does not have control over the demand and we have thus assumed that the demand is in this case controlled by the DISCO within the admissible range. The IL profit the IL attains is expressed by the following expression:

$$P_k = B_{0kh}\text{-}S'_{D0}{}^*(E'_{hi} +\Delta E'_{hi\_joule}) - \Sigma_h T_{ih}{}^*(E_{Rated,ih}\text{-}E'_{hi}) \quad (9)$$

Where $E_{Rated,ih}$ is the rated value for the energy demand at the i-th IL, T_{ih} is the cost of unserved energy at hour h for load i, S'_{D0} is the discounted price for the IL. In order to model the consumer response [1], consider the consumer demand for electricity E'_{hi} and assume that it depends on price that he must pay for electricity, S_{Dih}. Then, the profit or utility obtained from the electricity is to be maximized by the consumer:

$$P_k = Bk[E'_{hi}] − S_{Dih}{}^*(E'_{hi} +\Delta E'_{hi\_joule}) \quad (10)$$

Where $Bk[E'_{hi}]$ is the aggregated benefit of consumer k at time h. For a given value of S_{Dih} varying in a given range $[S_{D0};S_{Dx}]$, the demand can be calculated as:

$$E'_{hi} = E'_{hi0}{}^*(1+\beta(t)^*(S_{Dih}\text{- }S_{D0})/ S_{D0}) \quad (11)$$

Where $\beta(t)$ is the demand elasticity. Then the benefit can be calculated as:

$$Pk = Bk[E'_{hi}]=$$
$$B_0+S_{D0}{}^*(E'_{hi}\text{-}E'_{hi0})^*(1+(S_{Dih}\text{-}S_{D0})/ (2^*\beta(t)^*S_{D0})) \quad (12)$$

Where $\Delta E'_{hi\_joule}$ is the losses term deduced from [X] for the i-th load at hour h; T_{ih} is the cost of unserved energy at hour h for load i and $E_{Rated,ih}$ is the rated energy for load i at hour h. In the following section, the reference scenario is more clearly illustrated and the clustering procedure is defined.

$$o_k = \max (Pk) \quad (13)$$

THE CLUSTERING PROCEDURE

Finding the optimal operating point or pricing for a system with one distribution company, NP producers and NIL interruptible loads is a multiobjective optimization problem with a large number of objectives.
In this frame, it is possible to find clusters of stakeholders showing concurrent interests. In particular, in this paper it is proposed a methodology for identifying these clusters in order to reduce the dimensionality of the multiobjective optimization problem or of any market simulation. In this aim, a random perturbation procedure is implemented.
In the Interruptible Loads management operation mode, the DISCO can modulate within a prescribed range the ILs demand. Also the selling prices fron GENCO to DISCO and from DISCO to consumers can vary. The optimization variables are then the sets of loading values at the ILs within the prescribed range and the hourly prices. In this frame, in order to identify the sets of stakeholders sharing a common interest it is possible to build a Perturbation_matrix having n_cycles rows and n_obj (number of objectives) columns, these being calculated using the expressions (5), (8) and (13) calculated over the given time interval. At every cycle, a random perturbation is applied to the ILs string and to the prices and the objectives are calculated. In this way for each objective three options are possible:
- increase
- decrease
- unchanged.

In the three cases, a different index is written in the Perturbation_matrix. As an example, it is possible to adopt the indices 0 for unchanged, 1 for increase and 2 for decrease. At the end of the algorithm, the Perturbation is full and it is possible to build a Concurrence matrix, having n_obj rows and n_obj columns. Each entry contains the number of different results found in the perturbation_matrix for two different objectives. The following example shows the process for 4 objectives and 10 cycles.

Perturbation matrix

Cycles/Objectives	O1	O2	O3	O4
1	1	1	2	2
2	1	1	2	2
3	1	1	2	2
4	0	0	2	2
5	0	0	2	2
6	0	0	1	1
7	0	0	0	0
8	0	0	1	1
9	2	2	1	1
10	0	0	0	0

Concurrence matrix:

0	**0**	8	8
-	0	8	8
-	-	0	**0**
-	-	-	0

In the example above, two sets have been identified, one comprises the stakeholder for whom objectives 1 and 2 have been calculated, the second comprises the stakeholder for whom objectives 3 and 4 have been calculated. These situations are evidenced by the zeros of the entries (1,2) and (3,4).
The following figure 2 shows the pseudo-code of the analysis procedure.

```
Procedure Find_sets
Begin
 For i:=1 To Maxcycles Do
      Mutate(Solution)
      Evaluate(Solution)
      Update(Perturbation_Matrix)
Build(Concurrent_matrix)
End
```

Figure 2 : Pseudo code of the procedure

APPLICATION

The clustering procedure has been applied to identify clusters of stakeholders in a small distribution system sharing common interests. The distribution system has electrical features described in [3], but loads and generation units have been added for simulation purposes. The modified system is depicted in figure 3.

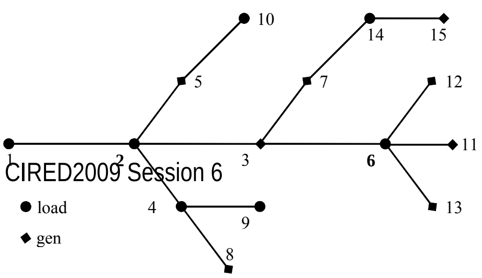

Figure 3 – The test distribution system

Table 1 reports the concurrence matrix for the cited application. It is evident that in the given hypotheses a large cluster of stakeholders can be identified. It comprises GENcos 3, 7, 8, 11, 12, 13 and 15, Customers 9, 10 and 14. The DISCO instead does not share its interests with no one else, as well as IL 2 and IL6. therefore if a multiobjective optimization or a market simulation is carried out four actors instead than 15 can be considered.

Table I – concurrence matrix for the system in figure 3

	D	SL(1)	IL(2)	G(3)	C(4)	G(5)	IL(6)	G(7)	G(8)	C(9)	C(10)	G(11)	G(12)	G(13)	C(14)	G(15)
D	0	1000	704	1000	1000	1000	722	1000	1000	1000	1000	1000	1000	1000	1000	1000
SL(1)	0	0	999	999	1000	999	999	999	1000	999	999	999	1000	999	999	999
IL(2)	0	0	0	296	297	296	366	296	297	296	296	296	297	296	296	296
G(3)	0	0	0	0	1	0	278	**0**	**1**	**0**	**0**	**0**	**1**	**0**	**0**	**0**
C(4)	0	0	0	0	0	1	279	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
G(5)	0	0	0	0	0	0	278	**0**	**1**	**0**	**0**	**0**	**1**	**0**	**0**	**0**
IL(6)	0	0	0	0	0	0	0	278	279	278	278	278	279	278	278	278
G(7)	0	0	0	0	0	0	0	0	**1**	**0**	**0**	**0**	**1**	**0**	**0**	**0**
G(8)	0	0	0	0	0	0	0	0	0	**1**	**1**	**1**	**1**	**1**	**1**	**1**
C(9)	0	0	0	0	0	0	0	0	0	0	**0**	**0**	**1**	**0**	**0**	**0**
C(10)	0	0	0	0	0	0	0	0	0	0	0	**0**	**1**	**0**	**0**	**0**
G(11)	0	0	0	0	0	0	0	0	0	0	0	0	**1**	**0**	**0**	**0**
G(12)	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**	**1**	**1**
G(13)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**	**0**
C(14)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
G(15)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Further studies will be addressed towards the analysis of the attained results and towards the implementation of other demand curves. Moreover, the effectiveness of the proposed analytical method for data pre-processing in multi-objective optimization and game theory must be proved by suitable test experiments.

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