Chapter

Reducing Power Losses in Smart Grids with Cooperative Game Theory

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Abstract

In a theoretical framework of game theory, one can distinguish between the noncooperative and the cooperative game theory. While the theory of noncooperative games is about modeling competitive behavior, cooperative game theory is dedicated to the study of cooperation among a number of players. The cooperative game theory includes mostly two branches: the Nash negotiation and the coalitional game theory. In this chapter, we restrict our attention to the latter. In recent years, the concept of efficient management of electric power has become more complex as a result of the high integration of distributed energy resources in the scenarios to be considered, mainly distributed generation, energy storage distributed, and demand management. This situation has been accentuated with the appearance of new consumption elements, such as electric vehicles, which could cause a high impact on distribution gridworks if they are not managed properly. This chapter presents an innovative approach toward an efficient energy model through the application of the theory of cooperative games with transferable utility in which the management, capacity, and control of distributed energy resources are integrated to provide optimal energy solutions that allow achieving significant savings in associated costs. This chapter presents a general description of the potential of the application of the theory to address Smart Grid, providing a systematic treatment.

Keywords: game theory, coalition, cooperative, Smart Grid, power loss

1. Introduction

Electricity consumption has grown in terms of the advances in technology, but we must bear in mind that this demand for electricity is variable at different times of the day. It is therefore possible to divide a day into two parts, namely, the maximum and minimum demand periods [1]. For 1 day, the maximum demand consists of the most active time of electricity consumption, and the maximum demand differs depending on the season. If power plants are able to consistently maintain high power generation, they can meet the maximum demand. However, the high production of electricity, especially obtained from nonrenewable energy resources (e.g., thermoelectric power plants), usually wastes a lot of energy. Therefore, we require a new type of intelligent electrical grid, which can help power plants to be more efficient, reliable, and solid, to avoid the generation of unnecessary energy and/or loss of energy in the distribution.

Microgrids (MGs) comprising distributed power generators have been introduced recently to construct smart grid to reduce power loss. MGs are able to supply electricity to the end users (i.e., homes, companies, schools, and so forth) which are linked to the corresponding MGs [2]. The MGs can exchange power with others. In addition, they are also capable of transferring power with the macro station (MS), which is the primary substation of the smart grid. In the presence of MGs, it is desirable to allow the microgrids to service some small geographical areas or group of customers based on their demand, so as to relieve the demand on the main grid [2]. We consider a power network consisting of interconnected microgrids and a macrogrid. The MGs harvest renewable energy (e.g., wind, solar, etc.), whereas the macrogrid produces energy from conventional sources. The MGs are equipped with storage devices (e.g., batteries) in which they can store energy for future usage locally. Although these resources are easily procurable and depicted as “green” energy resources, they present a significant shortcoming since they cannot guarantee stable production of electricity at all times [3]. For example [4], solar energy generation through deployed solar panels in the MGs can be seriously hampered on rainy days. When a MG needs additional power, it can buy electricity from the wholesaler (i.e., the MS) and/or from neighboring MGs.

Kantarci et al. proposed the “cost-aware smart microgrid network design,” which enables economic power transactions within the smart grid [5, 6]. The problem of power loss minimization was discussed in the work conducted by Meliopoulos et al. [7, 8] whereby a real-time and coordinated control scheme was proposed with the participation of distributed generation resources that can be coordinated with the existing infrastructure [9–11].

Kirthiga et al. proposed a detailed methodology to develop an autonomous microgrid for addressing power loss in [12]. Furthermore, some researchers have addressed power loss in the works in [13–15].

At present, game theory is an important tool for microgrid research as described in the work in [16–18]. Saad et al. presented an algorithm based on the cooperative game theory to study novel cooperative strategies between the microgrids of a distribution network [19].

The challenge of the electric companies is to determine the mechanisms that allow efficiently and quickly the equal distribution of the electric power surrendered by the electricity distribution grid as well as the distributed generation and that the clients or consumers of that energy have a common benefit.

According to the energy current pattern, the chain of the use of the energy was based on the generation stages, transport, distribution-commercialization, and consumption. This model in some countries differs basically in the form of the electric market, that is to say, in countries like Ecuador, Venezuela, and Mexico, the market structure is monopolist which has a single company constituted by subcompanies denominated as generation company, transmission company, and distribution companies. The price for the energy is fixed by the institutions of the State that regulate the electric sector. In other countries, mainly European countries, the market pattern is based on the free offer on the part of the generation companies, consumers can choose the company freely to which they want to buy the product, and the transmissions and distribution companies allow to carry out these transactions acting as intermediaries in the energy sale. From a general perspective, it is foreseen that the new smart electric grid is a cyber-physical system of a large scale that can improve the efficiency, dependability, and robustness of the electric grids, by means of the integration of advanced techniques, as control, communications, and signal processing. Intrinsically, the smart electric grid is an energy grid made up of intelligent nodes that can operate, communicate, and interact, in an autonomous way, to provide efficient electrical power to its consumers. The heterogeneous nature of the smart electric grid motivates the adoption of advanced techniques to overcome the diverse technical challenges in different levels as the design, control, and implementation.

In this sense, it is expected that the theory of games constitutes an essential analytic tool in the design of the future smart power grid, as well as in the cyber-physical systems to a large scale. The theory of games is a formal framework as much analytic as conceptual with a group of mathematical tools that allow the study of complex interactions among rational, independent players.

2. Electric system model for a cooperative game

Considering a single macro station denominated by a transmission substation, this macro station has a group of N Smart Grid, which a certain period of time can behave as microgrids that have an energy surplus (sellers) or energy requirements (buyers). Thus, a coalition formed in the grid can have any of these two types of Smart Grid.

One of the initial hypotheses to consider the exchange pattern based on a cooperative game is that all the Smart Grid possesses the information of the grid that allows choosing one of them. Being part of a specific coalition is always know, and the link between all and each one of Smart Grid belonging to the certain Macro station is always feasible, having as a result that all the members of the electric grid can interact with each other.

A specific electric grid may be made up of a group of Smart Grid, where for the i-th Smart Grid in a particular frame of time it can be said that this microgrid has a generated total power called P_i and at the same time a power demand by a group of consumers that is shown in D_i. Therefore, the surplus power to the Smart Grid $i \in N$ is given by [20]:

$$Q_i = P_i - D_i \tag{1}$$

Depending on the power generation values and electrical demand in Smart Grid, the surplus energy can define three cases to analyze:

- Case 1: $Q_i > 0$.In this case, the Smart Grid has a surplus power which makes it able to sell this electric power (seller) and shaping coalitions with the Smart Grid or substation.

- Case 2: $Q_i = 0$. In this case, the Smart Grid supplies its consumption.

- Case 3: $Q_i < 0$.Here the Smart Grid can buy electric power (buyer) from another Smart Grid or substation.

It should be kept in mind that both the power generated P_i and the demand D_i are random; the first can rely on the wind speed, solar irradiation intensity, etc.; and the second would be determined by uses of the energy on the part of the consumers. This gives rise to the surplus Q_i that will also be a random variable in the Smart Grid. Its value in a point in time will define an agent as a seller or an energy buyer [20].

A second hypothesis might bear in mind that the energy exchange will only happen among the Smart Grid (each other) or the substation. Then it won't be deemed the energy exchange with the macrogrid, which means that an electric possible transmission system will not be considered present [20].

All energy exchange that is carried out either among the Smart Grid and the Smart Grid and the substation incurs a cost associated with the energy losses in the driver. The energy losses in the feeders or the electric lines that are connected to each other, to the Smart Grid or to the substation are a function of the driver's resistance, the distance of the line, and of the power transmitted by the line in a specific time t.

2.1 Losses of power for the exchange between a Smart Grid and the substation

If a smart grid carries out an energy exchange with the substation, the losses of power incurred can be determined through Eq. (2) [20]:

$$P_i^{loss} = R_{io} I_o^2 + \beta P_i(Q_i) \tag{2}$$

where

P_i^{loss} is the losses due to the exchange of power between the substation and the Smart Grid $i \in N$.

R_{io} is the driver's resistance that joins the substation with the Smart Grid $i \in N$.

This resistance is calculated as the product of the resistivity per unit length of the driver in [Ω/km] used to connect both Smart Grid and the distance in [km] between these elements.

I_o is the electric current in $[A]$ that flows through the driver, which joins the substation with the ith Smart Grid.

β is the coefficient that reflects the fraction of the losses in the transformer by the substation during the power exchange.

$P_i(Q_i)$ is the power flow between the substation and the i-th Smart Grid.

It can be said that the power losses associated to the power exchange are made up of a loss component in the electric line (feeder or sub-transmission line) that links the substation with the Smart Grid $i \in N$. The second component is given by the losses in the substation due to the use of the transformer to carry out the exchange of power. If it is considered that the electric current through the electric line of distribution may be calculated from:

$$I_o = \frac{P_i(Q_i)}{U_o}, \tag{3}$$

then, Eq. (2) to determine power losses can be written as an only power flow function through electric line given by Eq. (4):

$$P_i^{loss} = R_{io} \left[\frac{P_i(Q_i)}{U_o} \right]^2 + \beta P_i(Q_i) \tag{4}$$

The power flow depends on the kind of the Smart Grid $i \in N$ (buyer or seller); thus [1]:

$$P_i(Q_i) = \begin{cases} Q_i & if \quad Q_i > 0 \\ L_i & if \quad Q_i < 0 \\ 0 & other\ cases \end{cases} \tag{5}$$

Eq. (4) expresses the next; if a Smart Grid acts as a seller, the power of Q_i is completely sold to the substation; thus the flow power P_iQ_i corresponds exclusively to that power, and the power losses are determined by Eq. (4) [20].

On the other hand, if the i-th Smart Grid is a buyer, the power flow will be generated from the substation that should deliver such a power to solve the Smart Grid's power demands and its losses of power incurred for the power flow. Then the power of L_i which should be delivered by the substation is determined by [20]:

$$L_i = P_{io}^{loss} + P_i^{required} \tag{6}$$

where $P_i^{required} = -Q_i$ is the power required by the substation's load and the value of L_i the power flow through the line. When substituting these values from Eq. (4) to Eq. (6), the expression for the power which should be delivered by the substation to Smart Grid $i \in N$ is reached [1]:

$$L_i = R_{io}\left[\frac{L_i}{U_o}\right]^2 + \beta L_i - Q_i \tag{7}$$

$$\frac{R_{io}}{U_o^2}L_i^2 - (1-\beta)L_i - Q_i = 0 \tag{8}$$

Eq. (8) can present three possible solutions for the variable L_i because the same one corresponds to a quadratic equation.

If the equation presents real positive roots, the root that is the solution will be the lesser of the two, since it will cause fewer losses. Then the losses through the distribution line are determined to substitute in Eq. (4) the value of $P_iQ_i = |L_i|$.

If the equation presents negative roots or it does not have a real solution, the considered answer is:

$$L_i^* = \frac{(1-\beta)U_o^2}{2R_{io}} \tag{9}$$

Then the power losses are calculated substituting L_i^* in Eq. (7).

In either case, if N_b is the total number of buyers present in a certain time, being $N_b \subseteq N$, then it should be fulfilled with the power of the substation at a given moment that [1]:

$$\sum_{i \in N_b} L_i \le P_{subestation} \tag{10}$$

The value of L_i is the power flow which means the demanded power plus the power loss in the electric lines.

2.2 Power loss in smart grids

Suppose that the energy exchange is carried out between the Smart Grid $\boldsymbol{i \in N_b}$ denominated buyer, and another Smart Grid $\boldsymbol{j \in N_s}$ called the seller. Since $\boldsymbol{N_b}$, the group of all the Smart Grid buyers and the group of all the Smart Grid sellers with $\boldsymbol{N_b \cup N_s = N}$; the power losses will be similar to the case of the exchange with the substation, unless:

1. The energy exchange does not incur in the use of the transformer substation; consequently, the loss coefficient is $\beta = 0$.

2. The energy exchange between the Smart Grids should not necessarily be carried out with a voltage U_o but to a lower voltage U_1.

Thus, the energy losses for the power flow of a Smart Grid $i \in N_b$ y and another Smart Grid $j \in N_s$ can be determined from the equation [20]:

$$P_{ij}^{loss} = R_{ij} I_{ij}^2 \tag{11}$$

Since R_{ij} is the total resistance of the driver that joins the i-th Smart Grid buyer with the jth Smart Grid seller, their value is calculated from $R_{ij} = R \bullet d_{ij}$, something akin to an exchange case with the substation.

The current I_{ij} depends on the power flow through the electric line; therefore, as in the power exchange case with the substation and except for the different voltage level that is U_1, the power losses will be given for [20]:

$$P_{ij}^{loss} = R_{ij} \left[\frac{P_i(Q_i)}{U_1} \right]^2 \tag{12}$$

The power flow $P_i(Q_i)$ is similarly defined in Eq. (5) where the value of power L_i that supplies the Smart Grid buyer is determined by Eq. (11) with the value $\beta = 0$, getting the following equation [20]:

$$\frac{R_{ij}}{U_1^2} L_i^2 - L_i - Q_i = 0 \tag{13}$$

The solution of Eq. (13) will result once again in the cases that have been presented before where there are two different real solutions, a unique real solution, or no practical solutions. This way if:

Eq. (13) generates two values L_i, positive real and different. The lowest value is chosen since it will produce the fewest losses. The losses due to the power exchange are determined by (12) when substituting $P_i(Q_i) = |L_i|$.

On the other hand, Eq. (13) produces real roots, or there is no real solution; the value that is to be adopted for the power is:

$$L_i^* = \frac{U_1^2}{2R_{ij}} \tag{14}$$

The value L_i^* is replaced in Eq. (12) to determine the losses, since it is the power sum of the microgrid plus the power losses present during the flow power. The Smart Grid that acts at this precise point of time like seller will not necessarily cover the power Q_i required by the part of a certain Smart Grid buyer.

2.3 Algorithm for the coalition building in a cooperative game with transferable utility

To set an algorithm 1 based on [20], considerations and definitions may be carried out so that the result is a modified algorithm of [20] with the incorporation of restrictions and hypothesis that simplify the mathematical process and the calculations when carrying out its simulation.

As it was described in point (2.2), a group Smart Grid S of N is considered present in the electric grid linked to a macrogrid through a substation. Thus, a coalition game is formulated which is formed by the pair (N, v), since N is the total number of players (Smart Grid) and $v : 2^N \rightarrow \mathbb{R}$ is a function that assigns to a coalition $\subseteq N$ a real number to represent the total benefit reached by S. It must, therefore, define the value of function $v(s)$ assigned to this number or the coalition $S \subseteq N$.

The following describes the subroutines that would make up an algorithm, which will be necessary to set up the simulation that allows determining the game payment functions, the power loss of electrical grid, and power distribution in the cooperative exchange based on the resulting coalitions in the game process.

Algorithm 1 Coalition Forming Algorithm of Smart Grid

Initial State

Each coalition is one MG, which means that all MGs cannot form coalition with others. Therefore, the network is partitioned by $S = S_1, S_2, \cdots, S_N$.

Stage 1 Coalition Formation:

repeat

a) $M = Merge\ (S)$: The MGs will form coalition or merge small coalitions to big one

b) $S = Split\ (M)$: the MGs will decide to leave from coalitions to form new coalitions through the Pareto Order in (8)

until no MGs can do merge-and-split operation to get more payoffs, and the network is partitioned by S′.

Stage 2 Power transfer:

repeat for every $S_i \epsilon S'$.

The MGs $\in S_i$ will exchange power with others by the order of forming coalition.

until no local power transfer is possible.

If every $S_i \epsilon S'$, any seller or buyer, which has not meet its demand or has power surplus to sell, can exchange power with MS.

2.3.1 Subroutine for coalition formation

Once the noncooperative exchange is established, the next step is to form the coalitions which are the generation of cooperative groups to ease substation load and maximize the Smart Grid's profitability through the decrease of the losses [20].

Issues that should be considered by the time to begin to carry out the coalitions are the exchange between the Smart Grid regardless of the substation. Depending on the distance among Smart Grids in the subsets and at smaller distance minors, there will be losses; the exchange is carried out at the local level, without the necessity of the substation, except for it still existing as a surplus or lacking energy in the coalition and Smart Grid.

At the moment to start developing the coalitions, it is essential to consider that the exchange between the Smart Grid depends on the distance between the Smart Grid and the subsets S_b y S_s (at a shorter distance lower will be the losses). The exchange is carried out at the local level without the need of the substation except that an energy surplus or lack of power supply in the coalition and Smart Grid would be present.

The aim of forming coalitions inside the electric grid is to look for participation of group N, so the members of group N are creating disjoint subsets, where each subset $S_i \subset N$ is a coalition [21]. Thus, the participation established will be $\{S_1, S_2, S_3, \cdots, S_n\}$ [1]. As a coalition has a large number of possible combinations, it is necessary to introduce heuristic elements to simplify the calculations and reduce the operation number to calculate a conformed partition of a group of coalitions.

The first step is to determine the neighbors [22], defining like a neighboring coalition $S_i \subset N$ to that one with the shortest distance toward the other coalition $S_j \subset N$. In this point, the first restriction corresponding to the distance between coalitions appears. This distance is called threshold; d_{umbral} is the shortest distance that the two coalitions must have between them to be denominated neighbors, which correspond to the minimal losses of power that should be considered in such grid, so the energy quality indexes are inside the acceptable systems.

From this approach arises that large-size coalitions will hardly be formed; even a great coalition that involves all the members of the grid will be formed when the number of Smart Grid is significant.

Property: For the coalition game presented (N, v), the great coalition of all the Smart Grid rarely rises as the result of the presence of a series of expenses incurred by the power exchange, since the longer the distance, the bigger losses the grid will have. Rather, the disjoint independent coalition will be formed in the grid [22].

Observation: For the proposal of formation game coalitions (N, v), the size of any coalition $S_i \subset S$ that will be formed in the grid should satisfy the distance $d \leq d_{threshold}$.

The participation that will be carried out in the grid corresponds to merge the Smart Grid neighbors into a set of pairs in a way that each pair has a seller and a buyer that is located at the shortest reasonable distance and fulfill the distance restriction. In this first stage of coalition building, some Smart Grid can be initially isolated by the dynamics of the game. That means they do not fulfill with distance restriction, the number of Smart Grid is odd, the number of elements belonging to the set of the seller is greater or lesser than the number of the elements from the buyer set, and all the combinations are possible from these alternatives.

The next building coalition process follows the rule of coalition and division to achieve this; the following additional and necessary concepts are considered to understand the proposed algorithm.

Definition: Consider two sets of a disjoint independent coalition called $\mathcal{C} = \{C_1, C_2, C_3, \cdots, C_l\}$ and $\mathcal{K} = \{K_1, K_2, K_3, \cdots, K_m\}$ made by the same players (Smart Grid) that belong to the grid). Let $\phi_j(C_j)$ be the payment of player j in the coalition $C_j \epsilon \mathcal{C}$, and $\phi_j(K_j)$ the payment of player j in the coalition. Then, $\mathcal{C}$ is preferred for the collection $\mathcal{K}$ only if the Pareto principle is fulfilled that is shown by [1, 2]:

$$\mathcal{C} \triangleright \mathcal{K} \Longleftrightarrow \left\{ \phi_j(\mathcal{K}) \forall (\mathcal{K}) \forall j \in \mathcal{C}, \mathcal{K} \right\} \tag{15}$$

or at least just with a single player j that applies this expression.

Definition of the Pareto principle: The principle settles that the group of Smart Grid N prefers to be divided into partition or collection $\mathcal{C}$ rather than collection $\mathcal{K}$, if at least a player can improve his/her profitability when changing the structure of $\mathcal{K}$ to $\mathcal{C}$ without reducing the benefits or the payments of other players in the Grid [20]. To apply the Pareto principle, the process of coalition building will follow the coalition and division rules [23].

Definition of the coalition rule (merge): For a group of coalitions $\mathcal{S} = \{S_1, S_2, S_3, \cdots, S_n\}$, two or more coalitions decide to merge just if the profitability increases (it reduces the power losses) of at least a Smart Grid, without affecting or diminishing the profitability of the other members of the group N [23]:

$$\left\{U_{j=1}^{k} S_j\right\} \triangleright_m \{S_1, \cdots, S_k\} \tag{16}$$

Definition of the division rule (split): A coalition $\hat{\mathcal{S}} = U_{j=1}^{k} S_j$ decides to be divided into two or more disjoint coalitions if just a Smart Grid increases its profitability (reduces the power losses) without affecting or diminishing the profitability of the other members of the group.

$$\{S_1, \cdots, S_k\} \triangleright_s \left\{U_{j=1}^{k} S_j\right\}$$

2.3.2 Subroutine for the exchange of power

As in the initial subroutine the group N of the Smart Grid was classified, these were split into buyers and sellers' subsets where the coalition is expressed as $\mathcal{S} = S_s \cup S_b$. However, it may focus on several approaches to the distribution of energy for the assignment of the sellers to the buyers. The approach outlined is the preference of the buyers in the coalition.

The split $\mathcal{S}$ with k buyers in $S_b \cup \mathcal{S}$, being $S_b = \{b_1, b_2, b_3, \cdots, b_k\}$, and buyers in $S_S \subset$, being $S_S = \{s_1, s_2, s_3, \cdots, s_S\}$, these groups will act sequentially. An important consideration is the local transfer of energy made by the seller and buyer before using the substation.

Also, if a Smart Grid just buys or sells energy from or toward the substation, this Smart Grid is left out of the Grid N since it does not deliver any benefit to the coalition.

3. Simulation of the electric system based on the theory of games

The software Matlab 2017 and the data of the network of **Figure** 1 were used for the simulation.

3.1 Input data

Table 1 shows the data entered in the simulator; they include the driver resistance, link voltage, and the minimum threshold distance to build coalitions.

Table 2 shows the substation characteristics, such as, geographical location, power, meter of energy losses for the transformer of the substation, and price of the electricity in dollars per MW.

In **Table 3**, the data of 10 microgrids (MG) [24] that are composed of 6 buyers (−1) and 4 sellers (+1) are shown. Additionally, the location is given in Km by a Cartesian coordinate system, power generated by the MG, energy demand by each MG, and the price of electricity.

3.2 Analysis of the results

3.2.1 Noncooperative model

Table 4 shows the algorithm results for the noncooperative model. The energy surplus is higher than zero (Q_i>0), in which the Smart Grid has an energy surplus

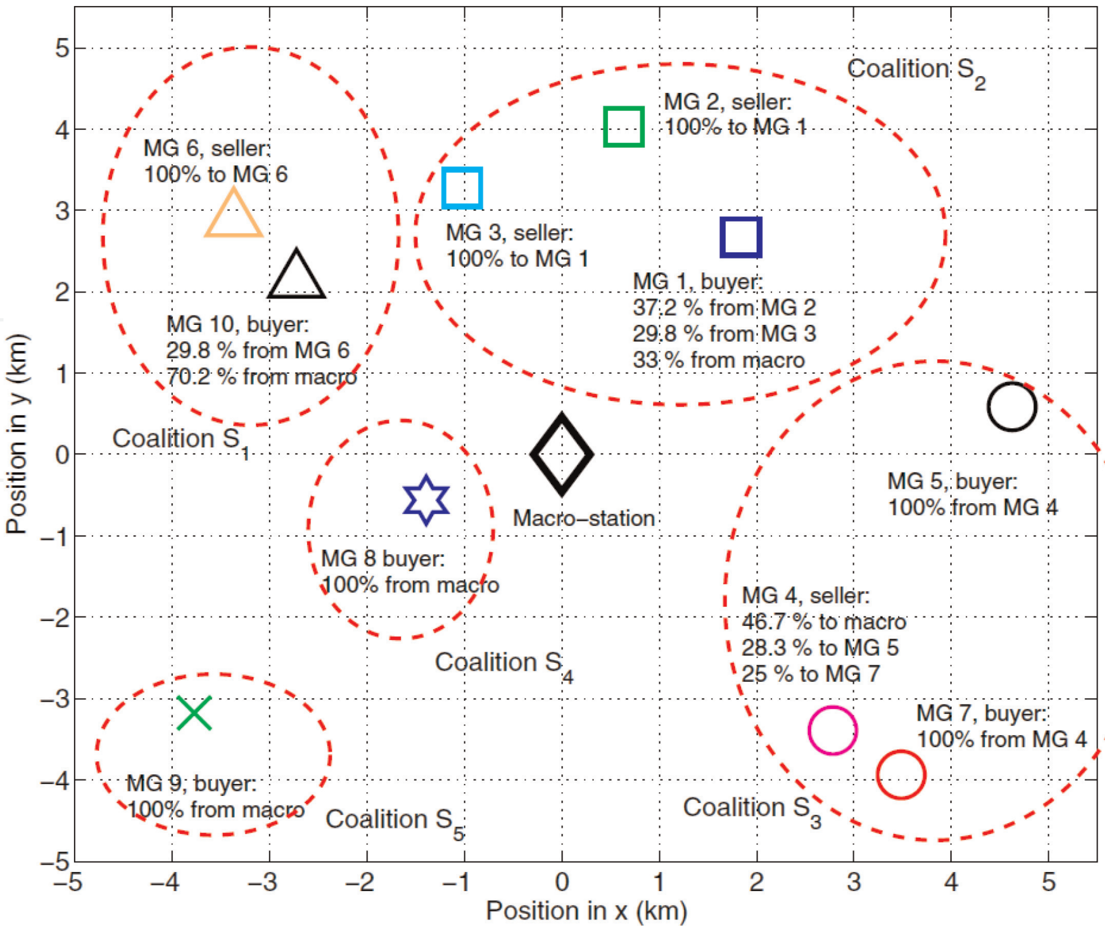

Figure 1.
Base model.

Resistance [Ω/km]	MT voltage [kV]	BT voltage [kV]	Threshold distance [km]
R	Uo	U1	Du
0.0147523	22	22	5

Table 1.
Data feeder.

N°	Location [km]		Power [MW]	Loss constant	Cost of energy [$/MW]
	X	Y			
0	0	0	100	0.02	1

Table 2.
Macro station or substation data.

so that it can sell that power (seller). Likewise, it is observed that there are other values of de $Q_i < 0$; consequently, in this case, some MGs need to buy energy from another MG or directly from the substation. The value of L_i is the power flow, that is, the demanded power plus the power loss in the electric lines. Finally, there are values of the power losses P_{i0}, and the individual payments P_{i0}.

3.2.2 Coalition building

When Smart Grids decide to build coalitions with its neighbors, the merger processes and the application Pareto principle generate a stable coalition where the

N°	Location [km]		Power [MW]	Demand [MW]	Energy price [$/MW]	State buyer: (−1) seller: (1)
	X	Y				
1	1.8	2.6	0	152.2	1	−1
2	1.6	4	56.6	0	1	1
3	−1	3	45.4	0	1	1
4	2.8	−3.3	134.3	0	1	1
5	4.7	0.4	0	35.4	1	−1
6	−3.4	2.8	42	0	1	1
7	3.5	−4	0	33.2	1	−1
8	−1.4	−0.6	0	60	1	−1
9	−3.8	−3.2	0	68	1	−1
10	−2.8	2.2	0	140.9	1	−1

Table 3.
Smart grid data.

N°	Q_i [MW]	L_{i_optimo} [MW]	P_{io} [MW]	U_{ii}
1	−152.2000	162.0883	9.8883	−9.8883
2	56.6000	54.5463	2.1686	−2.1686
3	45.4000	44.0290	1.4294	−1.4294
4	134.3000	126.2559	8.9307	−8.9307
5	−35.4000	36.6394	1.2394	−1.2394
6	42.0000	40.6068	1.4616	−1.4616
7	−33.2000	34.3907	1.1907	−1.1907
8	−60.0000	61.6978	1.6978	−1.6978
9	−68.0000	71.4586	3.4586	−3.4586
10	−140.9000	150.3462	9.4462	−9.4462
Average of power losses for the noncooperative case is 4091 [MW].				

Table 4.
Noncooperative state.

members of each coalition can improve their payments. The evolution of the payments can also be observed and compared with the case presented in [24]. The payments are shown in **Table 5**. In analyzing the payments concerning pattern [24], these improve when the Smart Grids decide to build coalitions like those shown in **Figure 2**.

It is noteworthy that like [24], it was not possible to improve the payment of the Smart Grid 9, which was left isolated for the cooperative game and Pareto principle. It would not represent any problem since it does not contribute any benefit to the coalition's members nor does it worsen the payments.

3.2.3 Power exchange in a cooperative game

Power exchange in a cooperative game incorporates the restrictions in the coalition building, improving the algorithm presented for [24]. It carries an

−9.8883	−5.7107
−2.1686	−1.2524
−1.4294	−1.4254
−8.9307	−5.2128
−1.2394	−1.2394
−1.4616	−0.7797
−1.1907	−0.6950
−1.6978	−1.6930
−3.4586	−3.4586
−9.4462	−5.0395

Table 5.
Vector payment evolution.

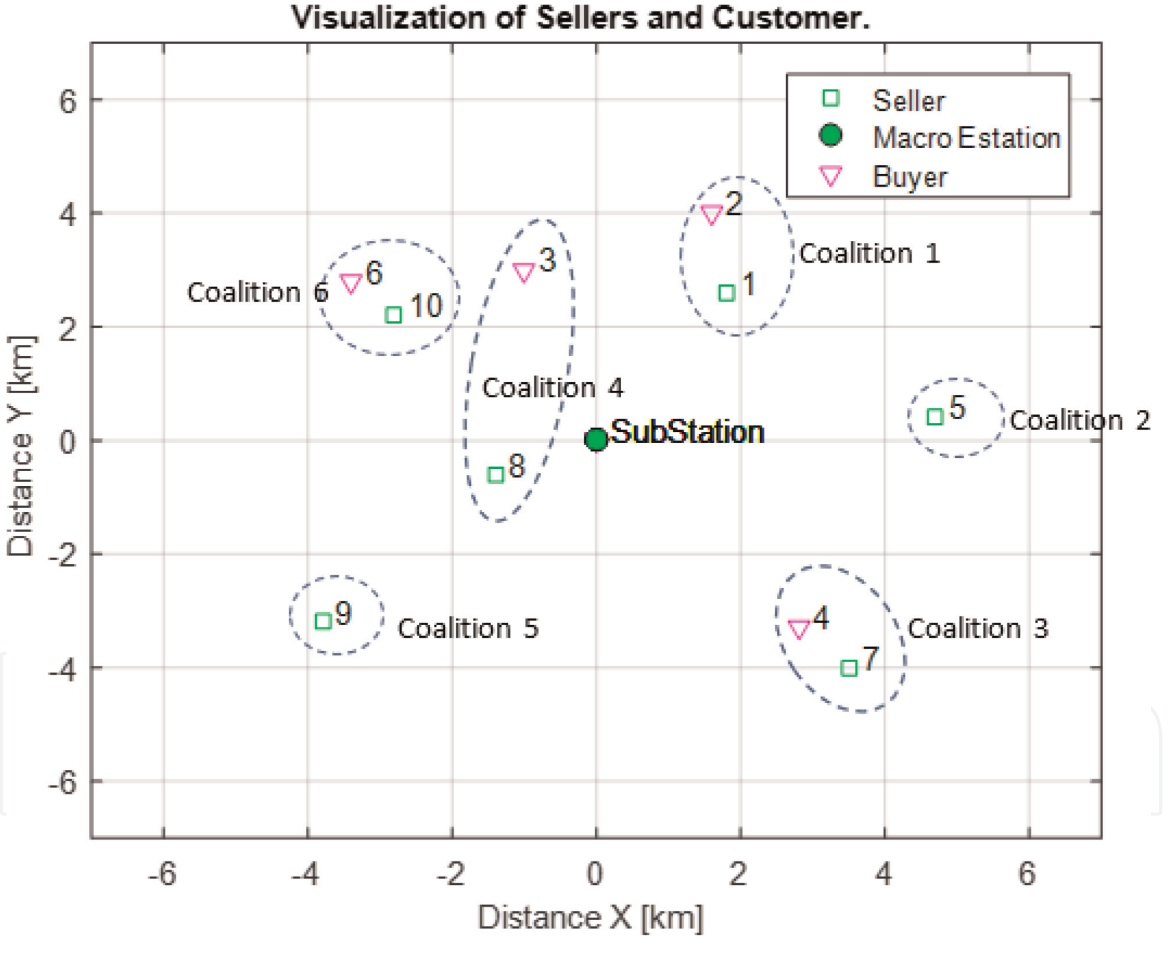

Figure 2.
The coalition formed for the cooperative game in the energy exchange.

improvement of the reduced power losses. **Table 6** shows the increases in the payments of the members belonging to the grid.

3.2.4 Energy exchange in the grid

Finally, **Table 7** shows the power bought to each MG and substation during the process of energy exchange in the grid.

Seller i	Buyer j	Transferred power [MW] $MG_i - MG_j$ P_{ij}	Power purchased from the substation [MW] P_{j0}	Power sold to the substation [MW] P_{i0}
		Coalition $S_1\{1,2\}$		
2	1	2.2507	—	—
Substation	1	—	4.7124	—
		Coalition $S_2\{5\}$		
Substation	5	—	—	1.2394
		Coalition $S_3\{4,7\}$		
4	7	0.4390	—	—
4	Substation	—	—	5.4688
		Coalition $S_4\{3,8\}$		
3	8	2.7257	—	—
Substation	8	—	0.3926	—
		Coalition $S_5\{9\}$		
Substation	9	—	—	3.4586
		Coalition $S_6\{6,10\}$		
6	10	0.6009	—	—
Substation	10	—	5.2183	—

Table 6.
Power exchange in the distribution grid.

	Purchase to	MW	Losses	Transferred power
		Coalition $\boldsymbol{S_1\{1,2\}}$		
MG_1	MG_2	164.339	2.2507	162.0883
MG_1	Substation	61.3124	4.7124	56.6000
		Coalition $\boldsymbol{S_2\{5\}}$		
MG_5	Substation	46.6394	1.2394	45.4000
		Coalition $\boldsymbol{S_3\{4,7\}}$		
MG_7	MG_4	134.739	0.4390	134.3000
MG_4	Substation	42.1082	5.4688	36.6394
		Coalition $\boldsymbol{S_4\{3,8\}}$		
MG_8	MG_3	44.7257	2.7257	42.0000
MG_8	Substation	34.7833	0.3926	34.3907
		Coalition $\boldsymbol{S_5\{9\}}$		
MG_9	Substation	65.1564	3.4586	61.6978
		Coalition $\boldsymbol{S_6\{6,10\}}$		
MG_{10}	MG_6	72.0595	0.6009	71.4586
MG_{10}	Substation	155.5645	5.2183	150.3462

Table 7.
Energy exchange in the distribution grid.

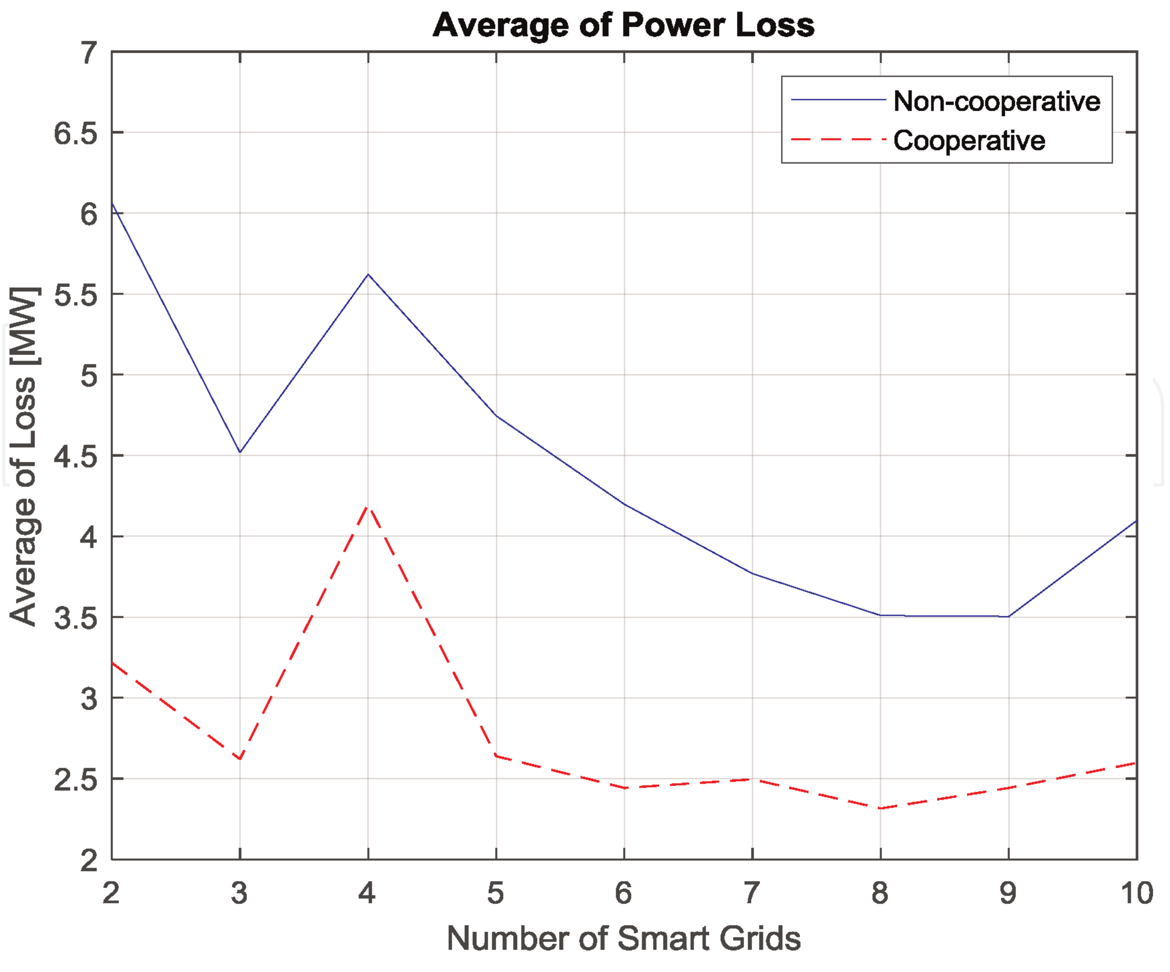

Figure 3.
Average power losses in a cooperative system vs. noncooperative.

3.2.5 Average loss

Figure 3 shows that as *N increases*, the power losses tend to reduce. When *N* is big in a smart grid, it has higher possibilities to find neighboring nodes to develop the coalition process for cooperative exchange of energy.

Table 8 shows a significant power loss in the cooperative model compared to the noncooperative. Thus, the study concludes that the average losses decrease by 38.62 when they join the MGs.

N° MG	Noncooperative	Cooperative	[%]
2	6.0622	3.2160	46.95
3	4.5179	2.6205	42.00
4	5.6211	3.6968	34.23
5	4.7448	2.6382	44.40
6	4.1976	2.4421	41.82
7	3.7680	2.4953	33.78
8	3.5092	2.3150	34.03
9	3.5036	2.4420	30.30
10	4.0979	2.4542	40.11

Table 8.
Payment evolution.

4. Conclusions

The most outstanding conclusion in this chapter is the development of a coalition building algorithm through the game theory to reduce energy losses in smart grids, which are based on a conceptual new model within the same ones that concentrate on the consumers and benefits if they decide to use the flexibility of distributed generation grids.

The coalitions built between MGs could be very profitable if they were truly allowed, and it they will encourage the consumers to participate and to take the next step as prosumers, that is, to produce and consume energy at the same time.

The proposal presented allows the MG building coalitions to minimize the power loss when the power is transmitted from an MG to another MG, to the macro station, or to the nearest substation.

This study simplifies numeric calculations, by introducing certain heuristics to the algorithm, through the approximation of the data that belongs to an ideal or practical system. That is, a great coalition. among all the participants is not possible.

It can be seen that for similar distances between a buyer and a seller, and a buyer and the substation, the power losses can end up being lower in the second case than the first. This is because it is in the voltage level between the interconnection, which is lower when two MGs are connected, instead that an MG and the substation: U_1<U_2.

Concerning the theoretical pattern, the losses significantly decrease by introducing into the coalition building the right restrictions such as the correct selection of neighbors (threshold distances), load priorities (distribution of power in the coalitions), power flow, and limitation of the energy in Smart Grid.

About the theoretical pattern, the losses significantly decrease by introducing appropriate restrictions into the coalition building, such as the correct selection of neighbors (threshold distances), load priorities (distribution of power in the coalitions), power flow, and limitation of the energy in Smart Grid.

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