ON THE USE OF GAME THEORY TO STUDY THE PLANNING AND PROFITABILITY OF INDUSTRIAL MICROGRIDS CONNECTED TO THE DISTRIBUTION NETWORK

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ABSTRACT

This paper deals with the long-term planning of industrial microgrids in order to decrease the electricity bill (compared to the current situation) for participating companies. In such industrial microgrids, the distribution system operator, the industrial estate operator and prosumers' objectives, which can be conflicting, need to be taken into account at the same time. The planning problem is formulated as a multi-agent and multi-objective problem which is solved by computing a Nash equilibrium of an extensive game from Game Theory. Different time horizons of the decision process are taken into account. In this paper, the planning tool principle is presented and some applications are provided.

INTRODUCTION

In Belgium, even though the energy cost itself is more or less stable, the electricity prices are increasing because of networks costs and taxes. Indeed, an industrial company connected to the Medium Voltage (MV) Distribution Network (DN) has to buy its electricity at a high fixed price including taxes, distribution and transmission costs. Therefore, investing in decentralized generation such as small wind turbines or photovoltaic panels (PV) may seem interesting for such companies. However, with such installations, the excess of generation is sold at a very low price (price of energy only). This difference between purchasing and selling prices of electricity represents a shortfall for those companies. In that context, a special attention is currently devoted among the community to the setting up of industrial microgrids (MGs), in order to limit these losses. According to our general definition, such industrial MGs have to be managed by an entity called aggregator and involve several stakeholders: the distribution system operator (DSO), the companies (which are consumers or prosumers) and the industrial estate operator (IEO). As detailed in a previous work [1], each one of them can be put alternately as aggregator which leads to the definition of different management strategies. By doing so, the different roles and potential benefits for each stakeholder are taken into account.

In order to convince companies, DSO and IEO to take part into industrial MGs, the long-term profitability for each one of them needs to be demonstrated. However, no regulatory framework currently exists in Belgium for such industrial MGs. In this work, the problem is therefore taken in the reverse way: a long-term planning tool of industrial MGs connected to the DN is developed in order to define its own regulatory framework and to find the set of rules which leads to the best equilibrium among actors. Some planning models have already been developed in the literature [2], but the planning procedure proposed here is established in order to take into account, at the same time, the objectives of the different stakeholders and the different time horizons of the decision process with alternately different aggregators. The developed tool is intended to ultimately provide guidelines to all stakeholders about, in particular, the regulatory framework and investments needed to tailor an industrial estate to a MG connected to the DN.

This paper is organized as follows. In section II, the complexity of the planning procedure and the use of game theory are described. Then, the principle of the tool with the combination of both long-term and short-term decisions is presented. In section III, some applications of the tool are shown. Finally, conclusions are drawn and perspectives for future work are given.

PLANNING PROCEDURE

As detailed in [1], according to their specific activities, the stakeholders of the MG have each their own objectives. Those objectives are often different and even conflicting. Hence, the problem to solve is multi-agent and multi-objective. An interaction model is defined for ruling the exchanges between stakeholders inside the MG, such as flexibility exchanges. Among the different management strategies presented in [1], this paper focuses on the one considering the DSO as aggregator.

Multi-agent multi-objective problem

The DSO's objectives are to decrease its costs thanks to a reduction of the transmission and losses costs and a proper schedule of its operation [3]. Its role is also to ensure a sufficient electricity power quality on the DN. As aggregator of a MG, it also has to manage the electricity exchanges inside the MG and between the MG and the DN while ensuring the quality of electricity supply inside the MG. Of course, in order to make worthwhile the MG operation, the electricity purchasing and selling prices have to be attractive compared to the current situation without MG.

As mentioned above, the main goal of the prosumers is to reduce their electricity bill. This is possible in three different ways. First, prosumers and traditional consumers can try to regulate their consumption thanks to, *e.g.*, load management (LM) techniques [4] or prosumers can improve their self-consumption using energy storage systems (ESSs). Possibly simultaneously, they can also purchase and sell electricity at more attractive prices thanks to their operation within the MG and a proper management of the electricity exchanges by the aggregator. As the last possibility, the IEO can provide investment aids in renewable energy systems (RESs) and ESSs by filling its own objective of developing the industrial estate [1] and therefore accepting possible net financial losses.

Use of the game theory

Game theory is a concept which allows for describing and analyzing different dealings among agents who need to take decisions to fulfill their own objectives. It involves using the interaction between them to optimize their respective objectives. Nowadays, game theory is more and more used in various fields such as economics and politics. Game theory is based on different game models which allow to represent at best the context of the problem and to solve it [5]. Among those games, an extensive game [6] consists in building a tree of combination of decisions that takes into account the time notion in terms of actions succession. In Fig.1, ρ_{ij} is the payoff of each player. Subscript i is the index of the combination of decisions while the subscript j refers to the j-th player. For example, ρ_{11} is the payoff for the first combination of decisions for player 1, ρ_{12} is the payoff for the first combination of decisions for player 2, and so on. This game can be either with perfect information, when the player who has to make a decision knows the choice of the previous player(s), or with imperfect information otherwise. In this work, the use of game theory, and more particularly of extensive games, can be doubly justified. On the one hand, the problem as formulated above involves several actors with several possibilities of actions and different objectives. On the other hand, the tree form is really representative of the different combinations of possible decisions available to each player alternately. As explained in more details in [6], it is possible to go from an extensive tree to a normal form [5] in order to compute a Nash equilibrium. The latter denotes a global solution such that, if any players would change its decision, the risk of weakening the global solution would increase.

METHODOLOGY OF THE TOOL

As the time horizons of the possible decisions can be different and, besides, each decision has an influence on

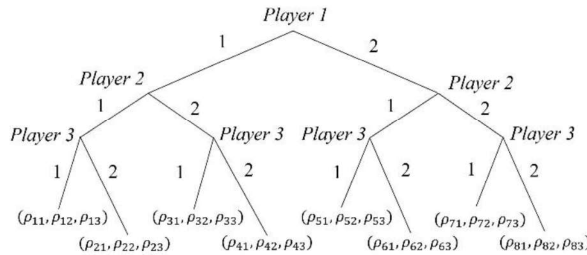

Figure 1 - Extensive game with 3-players, 2-decisions

the other ones, the planning problem has to be split into several time horizons with a dependence between them (as suggested in [2], [7]). Of course, the cost objective function pertaining to each stakeholder also takes into account those time horizons. The combination of long-term and short-term decisions into the extensive game is described hereunder and illustrated in Fig.2.

Long-term decisions

Among the possibilities available to the DSO as aggregator, it can propose more attractive prices inside the MG by, *e.g.*, decreasing some price components linked to the DN. Its long-term decisions are then different levels of electricity prices from the more attractive one for its own revenues to the more attractive one for the prosumers expenses. For the prosumers, long-term decisions are investments which will take several years to be written off and to provide benefits. For example, for companies with a significant consumption or with interesting consumption profiles (daily bell-curve), a PV installation can be an investment. For those who already have PV, ESSs may be a long-term choice in order to improve their self-consumption. In this paper, the long-term decisions are taken initially, at the year $Y = 0$, and a single long-term tree is created for the Y_{tot} years (typically 20 years).

Short-term decisions

The short-term planning horizon is one hour ahead. For each hour, the prosumers define a quantity of electricity that they will have to buy or sell (according to the short-term prediction of their consumption and generation and, if possible, after some LM). The aggregator receives all the offers and performs MG operation which means that exchanges inside the MG are privileged. The aggregator can then define the quantity of electricity purchased and sold by each prosumer at the MG price and at the regular price, through a supplier. In order to make decisions, a short-term tree is created for each hour of the Y_{tot} years. An equilibrium is computed for each one, taking into account the choices made at the previous hour.

Cost objective function

The objective function of this planning procedure is a cost objective function with technical constraints. It consists in the computation of a Net Present Value (NPV) in order to evaluate the profitability of the MG investments and operation.

$$NPV_{CA} = \rho_{CA}^{LT} + \sum_{Y=1}^{Y_{tot}} \frac{1}{(1+r)^Y} \left(\sum_{h=1}^{8760} \rho_{CA}^{ST}(h,Y) \right) \quad (1)$$

In (1), ρ_{CA}^{LT} and ρ_{CA}^{ST} are differences between incomes and outcomes for the long-term and the short-term time horizons, respectively. Subscript C is the index of the combination of decisions and A is the corresponding stakeholder. Such an expression has to be written for each stakeholder for each combination of decision of the created long-term tree. The first right-hand side term ρ_{CA}^{LT} takes into account investment initially chosen as a whole (it is a negative term) for each stakeholder. The second term ρ_{CA}^{ST} corresponds to the decisions which are taken at each hour of each year (*i.e.* after the computation of each hourly short-term tree and taking into account the decision of the previous hour) for each terminal node of the long-term tree. It is composed of the different components related to the purchase or sale of electricity (which are respectively outcomes and incomes) inside the MG or to the DN, as well as the LM. Indeed, LM is realized in order to decrease the demand for electricity during peak usage times and so the electricity bill, but it also represents a small cost for the company to shift its consumption. This term also potentially takes into account the yearly maintenance costs of the long-term installations (according to the combination of decisions). For the aggregator, it also takes into account several fees linked to its role of manager of the internal and external exchanges (in addition to the distribution costs in this particular case). Note that the expenditures of each future year are updated through the discount rate r.

Constraints

Overall, exchanges with the DN are decreased. A load flow is executed initially for each long-term combination of decisions and then at the end of the planning horizon in order to verify the proper operation of the MG in terms of voltage and power flows.

Computation of a global solution

The NPV is computed for each stakeholder for each combination of decisions in the long-term tree. The Nash Equilibrium can then be found by adopting a normal form representation [6]. The equilibrium is not the optimal solution for each stakeholder but rather a solution through which each stakeholder is satisfied. If anyone changes his decision, others will also change their choices. However, none of those other solutions would provide a better profit to them so that they will lose in comparison with the equilibrium solution.

Results' analysis

In this paper, the profitability of the MG is defined by comparing the NPV when the equilibrium is reached with the NPV computed if no MG would have been created (see (2)). Both are computed over 20 years and their evolutions as well as their final values will be compared.

$$NPV_{0A} = \sum_{Y=1}^{Y_{tot}} \frac{1}{(1+r)^Y} \left(\sum_{h=1}^{8760} \rho_{0A}^{ST}(h,Y) \right) \quad (2)$$

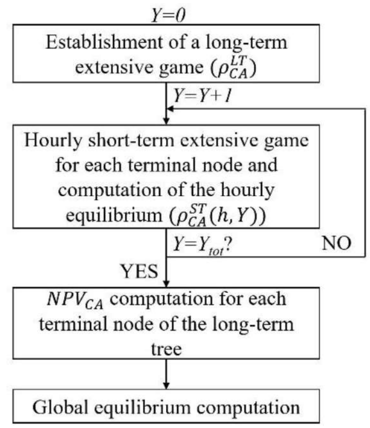

Figure 2 - Principle of the planning procedure

APPLICATION ON A VIRTUAL INDUSTRIAL ESTATE

In this section, some applications of the tool are exposed. The planning horizon is chosen to be 20 years. The considered industrial estate is simplified in two companies: P1 (consumer) and P2 (prosumer, with its own PV installation). The management strategy is still the one with the DSO as aggregator and actions of the IEO are neglected in a first approach. Moreover,in this paper, the MG aggregator is also the electricity supplier inside the MG.

Data modelling

In this long-term planning tool, hourly data are used. Consumption profiles can be divided into two classes: industrial companies and office hours companies. The first class has neither a seasonal nor a weekly and daily profile. The consumption only depends on the industrial activity (during night and day) over several weeks or months. The second one has a daily profile and it can be relevant to take into account its seasonality. In this paper, results are exposed for two combinations of classes: firstly, P1 and P2 are both from class 2 (Test case 1). Secondly, P2 still belongs to class 2 but P1 is now from class 1 (Test case 2). In order to predict the consumption of each company over the long-term time horizon, the following two methods were applied according to the class they belong to. In the first method, each year of data is divided into twelve months. Each monthly data block is then randomly chosen in order to rebuild a full year [8]. The second method, inspired from [9], makes use of cumulative distribution functions (CDF). For instance, in this work, seven typical days (Monday to Sunday) are created and used to rebuild a whole year of consumption. The following steps are processed:

1. Definition of a mean daily profile (mean value of consumption for each hour);
2. Construction of 24 hourly CDFs based on the difference between each mean hourly value and the real observed one (use of the database). For a given CDF, it is built thanks to $52*y$ values (with y the number of years in the database);
3. Sampling on the CDFs and addition with the mean profile.

The seasonality can be taken into account by subtracting the polynomial approximation of the trend of the yearly consumption's profile, applying the CDF principle and adding the seasonal annual trend to the rebuild yearly consumption profile. For the production, CDF principle is directly applied for each year. The uncertainty due to RESs and ESSs prices evolution over the years is here neglected. The uncertainty about the long-term evolution of the companies consumption and electricity prices is considered through a linear increase, each year. Each combination of evolution is called a scenario. Results are presented by considering four scenarios:

1. Constant consumption and prices (S1);
2. P1 and P2 consumptions increase of 2% per year with constant prices (S2);
3. Prices increase with 2% per year with constant consumptions evolution (S3);
4. Consumptions and prices both increase by 2% per year (S4).

Decisions

In this paper, two long-term decisions, called Medium Prices (MP) and Low Prices (LP), are possible for the aggregator (Fig.3). In the two test cases, prices for prosumers are attractive for external exchanges and even more attractive for internal exchanges (decrease in the difference between purchasing and selling prices compared to the situation without MG and so decrease of the aggregator's fee). Note that two kinds of prices are considered in this work: the peak time prices (between 8am and 10pm) and the off-peak time prices for the remaining time of the day. For the prosumers, PV installation of 250 kWp or ESS are the long-term decisions (Fig. 3). For the short-term decisions, the only possibility considered in this paper for P1 and P2 is to do some LM (Fig.4). In Fig.3 and 4, N is the choice of doing nothing except the MG operation. Moreover, ρ_{CA}^{LT} and ρ_{CA}^{ST} from the objective function (1) are the payoffs of the long-term and short-term trees, respectively.

Results

The goal of the MG operation is to decrease the electricity cost for P1 and P2 without penalizing the DSO. The global NPVs (over 20 years) for the different scenarios with the two Test cases are presented in Tables 1 and 2. The percentages won for the DSO and saved for P1 and P2 are shown in the last row. Simulations are realized with an Intel Core i7-6700 HQ, 2.6 GHZ, 16 Go RAM computer and each scenario is computed in about

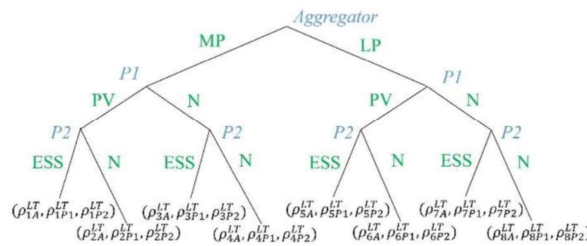

Figure 3 - 3-players, 2-decisions long-term extensive game

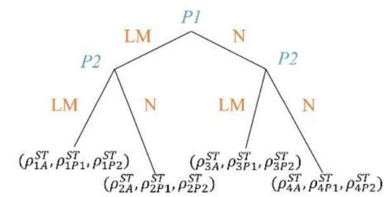

Figure 4 - 2-players 2-decisions short-term extensive game

	S1	S2	S3	S4
NPV_{0A} (k€)	(484.17, -1767.3, -1054.1)	(602.98, -2236.0, -1327.4)	(590.66, -2118.4, -1249.0)	(748.85, -2704.3, -1607.5)
Equilibrium	(MP, PV, N)	(MP, PV, N)	(MP, PV, N)	(MP, PV, N)
NPV_{CA} (k€)	(562.32, -1515.3, -994.72)	(725.97, -1937.7, -1256.6)	(670.69, -1753.5, -1178.2)	(879.04, -2282.9, -1521.8)
$\frac{(NPV_{CA} - NPV_{0A})}{NPV_{0A}}$ (%)	(16.14, -14.26, -5.64)	(20.4, -13.34, -5.33)	(13.55, -17.23, -5.67)	(17.39, -15.58, -5.33)

Table 2 - Results and savings for Test case 1

	S1	S2	S3	S4
NPV_{0A} (k€)	(1138.3, -6288.2, -1048.4)	(1364.2, -7483.8, -1319.6)	(1450.6, -7833.9, -1249.0)	(1762.0, -9396.6, -1595.3)
Equilibrium	(MP, PV, N)	(MP, PV, N)	(MP, PV, N)	(MP, PV, N)
NPV_{CA} (k€)	(1633.1, -5810.6, -979.83)	(1971.6, -6943.2, -1240.2)	(2022.2, -7175.9, -1167.6)	(2464.7, -8665.9, -1500.4)
$\frac{(NPV_{CA} - NPV_{0A})}{NPV_{0A}}$ (%)	(43.47, -7.60, -6.54)	(44.52, -7.22, -6.02)	(39.40, -8.40, -6.52)	(39.88, -7.78, -5.95)

Table 1 - Results and savings for test case 2

33 minutes. For all simulated scenarios, each stakeholder makes benefits with the following combination of decisions: make MP for the aggregator, install PV for P1 and do nothing for P2. P2 makes benefits thanks to the MG operation (direct exchanges between P1 and P2) and advantageous electricity prices. As P1 decision is PV installation, it is interesting to look at the progress of NPV_{0A} and NPV_{CA} over the years in order to observe the time of return on investment. As presented in Fig. 5 for Test case 1 and Fig. 6 for Test case 2, for the scenario S4,

the time of return of investment for P1 is about 6.5 years and 4.5 years, respectively. This time is slightly longer for the other scenarios (as the consumption and/or the prices are lower).

The DSO considered as an aggregator to the proposed model always makes benefits because when electricity is exchanged inside the MG, it wins the difference between MG purchasing and selling prices. So, even if the incomes related to its DSO status are decreased with the setting up of the MG (because the energy exchanges with the DN are overall reduced), those are widely compensated by its incomes as aggregator. For Test case 2, as the consumption profile of P1 is more irregular, globally high and with a shape totally different from P2 profile (see Fig. 6), the benefit linked to the MG operation is more pronounced for the aggregator and also slightly increased for P2.

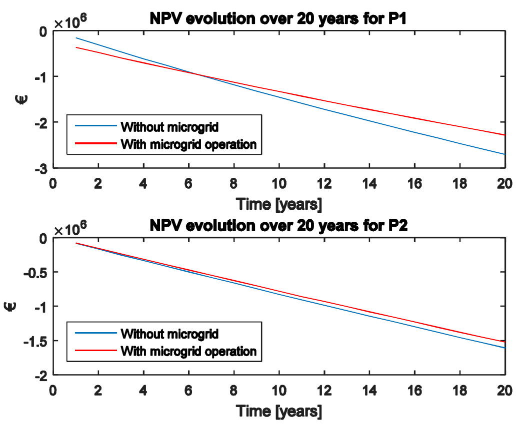

Figure 5 - Evolution of P1 and P2's NPV (Test case 1 - S4)

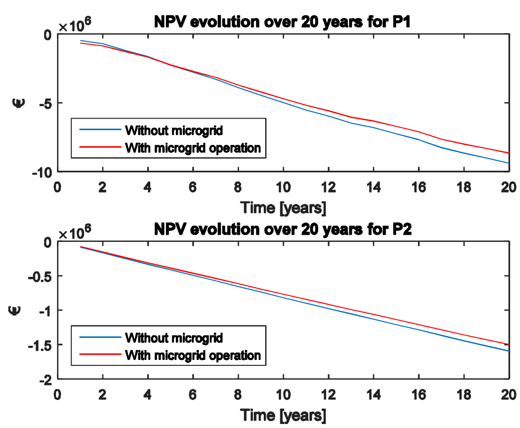

Figure 6 - Evolution of P1 and P2's NPV (Test case 2 - S4)

CONCLUSION AND PERSPECTIVES

A long-term planning tool using Game Theory has been presented in this paper. The goal of this work is to encourage stakeholders (DSO, IEO, consumers and prosumers) to take part into industrial MGs. This tool takes into account the objectives of each stakeholder and the proposed global solution is computed so that anyone can make benefits. The MG operation favours exchanges between prosumers and consumers inside the MG. In this paper, since the DSO is taken as MG aggregator, prices are more attractive inside the MG by reducing some component linked to the distribution network. Moreover, the combination of hourly and multi-yearly decisions is implemented. There are many perspectives to this work such as the dynamic choice of the year for undertaking long-term investments (with a proper sizing of RESs and ESSs) as well as the development of a regulatory framework with different time horizon contracts.

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