OPTIMIZED DECENTRALIZED AND CENTRALIZED LOAD MANAGEMENT TECHNIQUES IN INDUSTRIAL MICROGRIDS

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ABSTRACT

This work deals with the comparison between decentralized and centralized load management techniques applied in the context of an industrial microgrid connected to the distribution network. They are used to decrease the electricity costs of the industrial companies while also considering the distribution network operator costs. This paper describes both techniques as well as their establishment in a proper microgrid short-term energy management with peer-to-microgrid exchanges and microgrid electricity pricing. Results are shown for daily and yearly applications.

INTRODUCTION

In the current electrical context, the electricity bill of industrial companies connected to the medium voltage Distribution Network (DN) may represent an important part of their expenses. Indeed, the purchasing cost of electricity includes some distribution, transmission and state taxes. Those companies may also have their own Renewable Energy Source (RES) to support a part of their need in electricity. However, this generation does not cover all the time their consumption and, at some moments, the surplus of generation must be sold to the DN, at a low sale price. In industrial areas, the complementarity of companies load profiles can be used to share the locally generated electricity and, therefore, to better exploit the RESs, leading to the concept of Industrial MicroGrids (IMGs). In the current regulatory framework, such exchanges between the IMG stakeholders are not allowed. The basic hypothesis of this work is thus to neglect the current regulatory framework and to provide pieces and guidelines for an optimized IMG framework.

The performances of microgrids have already been demonstrated in the literature [1], as well as their planning [2], [3] and their real-time energy management [4], [5]. In [6], the authors of the present paper developed a tool allowing for both the long-term planning of IMGs (the investments in RESs and Energy Storage Systems (ESSs)) and the Short-Term Energy Management (STEM) in day-ahead. Beyond the coupling between both long-term and short-term time horizons, the tool also proposes two originalities, namely: the possibility to consider the DSO as MicroGrid Energy Manager (MGEM) and the use of game theory to consider the possibly conflicting objectives of each stakeholder, including the MGEM. The present work focuses on the STEM and, more particularly, proposes to compare two Load Management (LM) techniques (inspired from [7], [8]): the Decentralized LM (DLM) individually realized by each prosumer and the Centralized LM (CLM) performed once by the MGEM. The comparison between the two LM methods will therefore be useful to better exploit the possibilities of the STEM, as well as the new needed IMG regulatory framework.

The remainder of this paper is organized as follow. The second section presents the IMG organization, including the description of the STEM. The third section describes the two LM techniques and the application of Game Theory in the decision-making process. The following section is dedicated to their application on a virtual IMG. Results are exposed for both daily and yearly simulations, with the two kinds of LM. The last section gathers the conclusion and some perspectives.

IMG ORGANIZATION

An IMG is an industrial part of the DN, geographically delimited and connected by a single point to the DN. It is composed of S_{tot} stakeholders (prosumers with their own RES and consumers) and of the MGEM. As illustrated in Fig. 1, the prosumers and consumers are not directly connected between each other. All the information is gathered by the MGEM who forecasts in day-ahead the consumption and generation profiles and performs the STEM (see next section).

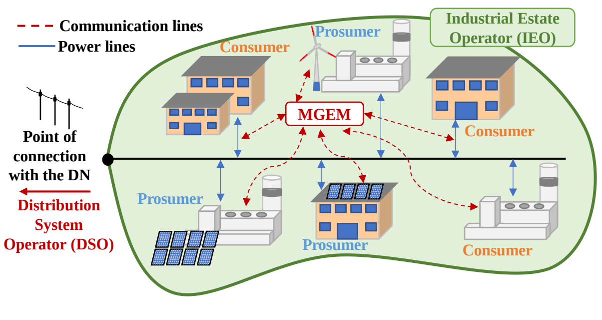

Fig. 1. Representation of an IMG connected to the DN

Regarding the electricity pricing, the prices for exchanges inside the IMG are adapted in order to make attractive the participation to the IMG. The IMG electricity purchasing price is therefore composed of a commodity part (energy and power components), a

MGEM fee and a metering cost. The IMG selling price is only composed of the commodity price only decreased by a MGEM fee.

Short-term Energy management

The STEM is performed each day for the next day and gathers three main steps [6]:

- The definition (by the MGEM) of the three possible daily evolutions of the commodity price inside the IMG according to the predicted electricity price for external exchanges. The IMG price can be constant, have the same or have the opposite trend than the electricity price for external exchanges;
- The application of the LM (by the MGEM or the prosumers) on the load predicted for the next day (see details in the next section);
- The IMG Operation, *i.e.* the management of the remaining generation and loads inside the IMG. This step is performed by the MGEM after that each prosumer has self-consumed its own generation and therefore determined its status of producer or consumer, as well as the amount of electricity to sell or to buy for each hour. Therefore, the MGEM performs first peer-to-IMG exchanges by using the remaining generation of the IMG prosumers to provide the consumers (proportionally against their needs compare to the global need). Then, exchanges with DN are authorized if there remain some uncovered loads or some surplus of generation.

For each day d and for each stakeholder $S \in S_{tot}$, a cash-flow $\rho_{S,d}^{ST}$ is computed as the difference between all incomes and outcomes. A cash-flow is also computed for the MGEM (linked to its fees as MGEM and DSO). The choice of the IMG electricity price profile and to perform LM or not are the decisions corresponding to the equilibrium of a daily non-cooperative game [6], [9] which considers all stakeholders and the MGEM (=DSO).

LOAD MANAGEMENT TECHNIQUES

This section details the principle of the two LM methods applicable inside the IMG: the Decentralized LM (DLM) method in which all prosumers/consumers realize their own optimized LM and the Centralized LM (CLM) method, in which the MGEM is performing LM for all participating stakeholders. Both LM methods rely on the same principle for the decomposition of the load. Indeed, the LM considered in this work is only valid for companies with a load decomposable in a non-shiftable base load and a shiftable process load during the working days. For an IMG with S_{tot} stakeholders, S_{tot} is equal to $N_{tot} + M_{tot}$, where N_{tot} is the number of prosumers able to perform LM and M_{tot} the others. For a company $N \in N_{tot}$ and for a working hour $h \in [6am \dots 6pm]$, the company load $l_{N,h}$ can be expressed as:

$$l_{N,h} = l_{b,N,h} + l_{pr,N,h} \quad (1)$$

where $l_{b,N,h}$ and $l_{pr,N,h}$ are the hourly base and process loads, respectively.

The optimization process consists of finding the optimal arrangement of the hourly process loads in order to increase the self-consumption rates and to decrease the electricity costs. The optimization process also takes into account the grid price weight for each hour during which LM is applicable, $\Pi_{LM} = [\pi_{LM,1}, \dots, \pi_{LM,13}]$, corresponding to the normalized electricity purchasing price compared to its average between 6am and 6pm.

The constraints are set up to keep unchanged the base load and the generation profiles. Each hourly process can only occur one time each day (with one process at each hour) to not change drastically the habits of the company. Moreover, additional constraints can be given by each prosumer regarding the succession of several processes or the available time slots for a particular process.

Decentralized LM

For DLM, each stakeholder performs its own optimization. The objective function can be expressed by minimizing the difference between the load and the generation $p_{N,h}$. Equation (2) shows the Mixed Integer Linear Programming (MILP) optimization formulation for one stakeholder $N \in N_{tot}$, with $h' \in [1 \dots 13]$:

$$\min_x \sum_{h=1}^{h=13} [|l_{b,N,h} - p_{N,h} + l_{pr,N,h'}| \times \pi_{LM,h}]^T \times x \quad (2)$$

x is the integer vector with binary decisions to activate the process shiftable load at each hour h. After the optimization, each process is no longer necessarily attached to the initial hour of occurrence, i.e. h' can be equal or different from h. As the DLM is realized individually, for each $N \in N_{tot}$, all vectors are composed of the number of hours multiplied by the number of processes (*i.e.* 13×13) elements.

The principle of the DLM is presented in Fig. 2. The MGEM communicates the individual predicted profile to each prosumer. Each prosumer performs DLM and, after the optimization, communicates his LM load profile to the MGEM. The IMG operation and the daily game are therefore computed by the MGEM. Each prosumer is a player of the ST game and, therefore, the game is composed of $S_{tot} + 1$ players. The equilibrium reflects who must do DLM or not as well as the daily IMG price profile that the MGEM has to apply. The MGEM sends the decision information to the prosumers. Note that even if the M_{tot} stakeholders that are not performing LM are taken into account in the game (through their $\rho_{S,d}^{ST}$ computed during the IMG operation), they are not taken into account in the DLM and they do not have any decision to take.

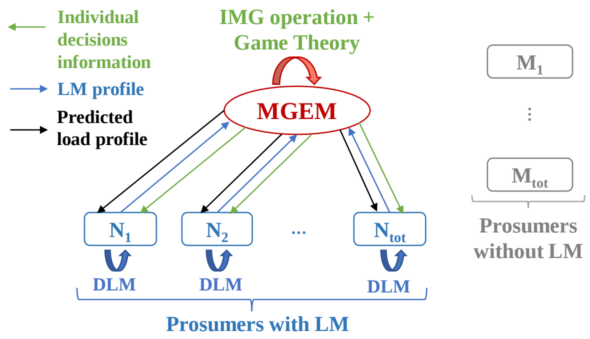

Fig. 2. DLM principle

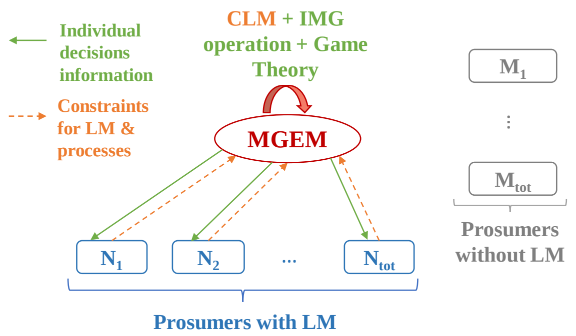

Fig. 3. CLM principle

Centralized LM

For CLM, each prosumer wishing to make LM allows the MGEM to use its predicted load and generation profiles for the next day. The global optimization (3) is realized once by the MGEM in order to fit the global IMG load profile to the global IMG generation profile.

$$\min_{x} \sum_{h=1}^{h=13} \left[\left| \sum_{S=1}^{S_{tot}} l_{b,S,h} - \sum_{S=1}^{S_{tot}} p_{S,h} + \sum_{N=1}^{N_{tot}} l_{pr,N,h'} \right| \times \pi_{LM,h} \right]^{T} \times x \tag{3}$$

The dimension of the vectors of the optimization is therefore $13 \times 13^{N_{tot}}$ elements (in order to consider the $13^{N_{tot}}$ process loads combinations of the N_{tot} stakeholders). With this formulation, both N_{tot} and M_{tot} stakeholders are taken into account, which means that the load and generation of the M_{tot} stakeholders that are not performing LM are considered (without being changed) to determine the optimized repartition of the process loads of the N_{tot} stakeholders that are performing CLM. The CLM principle is presented in Fig. 3. This kind of LM allows to reduce the communication needs (depending on the technology used) between the MGEM and the prosumers as well as the complexity and the amount of information to transmit. Indeed, the prosumers only have to transmit the constraints linked to their process loads and the MGEM has only to send them the final results of the IMG operation and the daily game.

Regarding this daily game, two players are considered: the MGEM (for the choice of the daily IMG price profile) and the S_{tot} companies as a whole. Therefore, regarding those last ones, the equilibrium reveals if the N_{tot} stakeholders have to apply CLM or not.

APPLICATION ON A VIRTUAL IMG AND RESULTS

The simulated IMG is composed of 6 stakeholders: the MGEM and 5 prosumers ($S_{tot} = 5$). Prosumers 1, 2 and 4 can perform LM ($N_{tot} = 3$ and $M_{tot} = 2$). The IMG is connected to the 10.5 kV DN. The IMG was simulated over 1 year once with DLM and once with CLM in order to observe their influence on the IMG costs. The results are exposed in two parts: the first one is dedicated to the analysis of two specific days. The second one is presenting the results over one year.

Daily Analysis

In this section, two days are analyzed: days 72 and 134. In both cases, we can see that the global IMG load profiles with CLM ($L_{tot,CLM}$) and DLM ($L_{tot,DLM}$) better fit the production (P_{tot}) than the load profile without LM ($L_{tot,noLM}$).

For day 72 (see Fig. 4), the global Self-Consumption Rate (SCR) is almost unchanged with DLM but clearly increased with CLM (from 80% to 85%). For this day, after the application of the IMG operation, the daily game leads to a constant IMG price for both kinds of LM. For DLM, only the prosumers S_1 and S_2 have to perform LM. Regarding the costs for this day, the CLM allows a decrease of the global expenses of the IMG compared to the DLM (because the DLM profile presents a load peak at hour 6 and leads to a lower global SCR).

Regarding day 134 (see Fig. 5), without LM, a peak of consumption occurs in hour 11. With both LM techniques, this peak is smoothed. For this day, the IMG

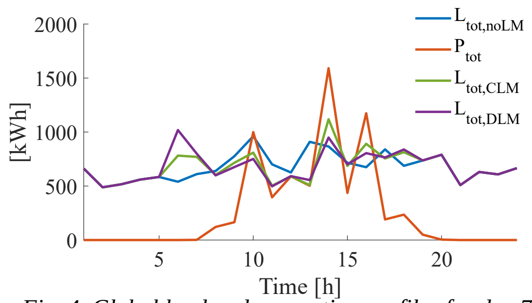

Fig. 4. Global load and generation profiles for day 72.

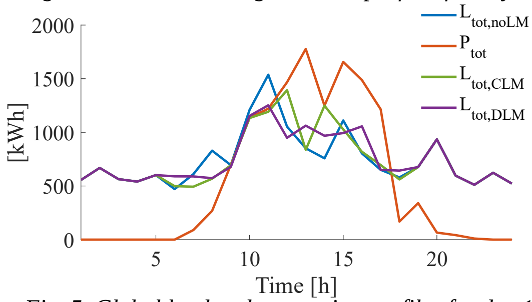

Fig. 5. Global load and generation profiles for day 134.

daily price profile is variable (with the same trend than grid price profile) with CLM and constant with DLM. Note that the load profile with DLM is well smoothed. Therefore, if both price profiles were variable, CLM would be more interesting. However, as the daily game with DLM leads to the decision to apply a constant price, the global IMG costs is lower with DLM than with CLM.

Yearly Analysis

Fig. 6 shows, after 1 year, the percentage saved by each prosumer and the small losses that LM entails for the MGEM compared to the situation of the IMG without any LM techniques. Note that, for S_3 and S_5, which are not doing LM, the application of LM by the other prosumers does not have an important impact.

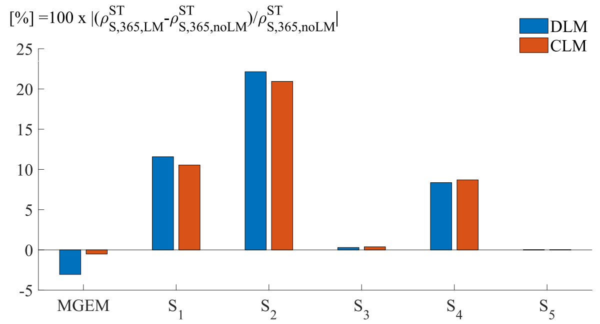

Fig. 6. Saving percentage for the MGEM and all prosumers

DLM leads to little higher savings for S_1 and S_2, because their individual SCRs are higher with DLM. For S_4, both techniques lead to almost equivalent results. Regarding the MGEM, its loss is reduced thanks to CLM because there are more exchanges inside the IMG than with DLM (with the associated MGEM and DSO fees). Moreover, globally, the difference between the aggregated load and generation profiles is slightly smoother with CLM than DLM, which is beneficial for the MGEM, as it also is the DSO. Therefore, if we observe the IMG as a whole, including the MGEM, it seems fairer to consider CLM.

Moreover, currently, zero costs are assumed for the communication installations, the LM optimization computations, the data management and the loads shifting. With CLM, the three first costs would be decreased because, as explained in the CLM principle, there would be less connections to establish and less operation costs between the MGEM and the prosumers. The information to transmit and to manage is also reduced and less complex. Besides, the LM optimization is realized only once by the MGEM instead of N_{tot} times which represents a decrease of the computation costs for the prosumers. So, the small differences presented for S_1 and S_2 could be compensated by these other savings.

Note that, the combination of both techniques, *i.e.* the possibility of choosing, each day, between CLM and DLM has also been tested and leads to intermediate results. In practice, this solution would be difficult to establish (more decisions possibilities and so more information to exchange and to manage) and could be less interesting given the required communication installations (for both DLM and CLM).

CONCLUSION AND PERSPECTIVES

The presented work allows to observe the influence of DLM and CLM inside an IMG managed by a MGEM (=DSO) and with its original STEM (allowing peer-to-microgrid and microgrid-to-DN exchanges and daily IMG pricing). The DLM is performed individually by each prosumer while CLM is performed only once by the MGEM for all prosumers. The daily analysis has shown the benefits of each technique. Over one year, both techniques lead to savings between 8% and 20% for the prosumers performing LM. CLM presents slightly lower savings for them but allows a reduction of the MGEM loss. This solution could therefore be fairer from the point of view of the IMG as a whole. Moreover, the presented results do not consider the costs linked to the communication needs and operation as well as those linked to the information management. Those last would also be reduced thanks to the CLM principle. In future work, the same comparison inside a bigger IMG (with more prosumers and consumers load profiles) could be carried out for further analysis.

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