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Two-stage algorithm for the management of distributed energy resources included in an aggregator's activities

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Abstract

The growing number of distributed energy resources in power systems, leads to the appearance of new entities and roles for the existing ones that affect the operation of the network. One of these entities with more relevance, is the aggregator, either independent or represented by public organizations. An aggregator manages small-size distributed energy resources, creating a virtual amount of energy flexibility that can be used by it, to enable participation in energy markets and capitalize the integration of distributed energy resources. This paper proposes a two-stage optimization methodology for the operation of an aggregator regarding distributed energy resources. In a first stage, the network part managed by the aggregator is scheduled, meaning at a macro perspective, while in the second stage, it is assumed that the distributed energy resources are also scheduled considering their operation. It is assumed that this second stage is enabled due to an aggregator's communication infrastructure and interconnected management systems.

Keywords: aggregator; demand response; distributed generation; optimization

1. Introduction

In Europe, renewable energy sources have been installed by several consumers at their location, in response to promoting schemes implemented by the national entities of each country. This represents a goal of the European Union to reduce greenhouse gases emission in a global consideration of 20% by 2020 [1]. In 2014, much of greenhouse gases emission, comes from fuel combustion and fugitive emissions from fuels (without transportation), namely, 55.1% [2]. The use of fossil fuels in electricity generation greatly contributes for this percentage, and thus, efforts must be made towards a more sustainable future using other generation sources. In this way, renewable energy sources were the main solution considered by the European Union, and since then, promoting schemes have been implemented to support the installation of these resources, both in a small and large scale in terms of capacity [3], [4]. In the first approach, legislation was made to enable the installation of renewable energy sources of small capacity by consumers or individuals, being implemented a business case that clearly benefits the installer in a way that remuneration is attractive considering the energy consumption price. These consumers that besides their consumption, have also generation, are named prosumers [5], [6]. In the latter case, auctions and tenders of large wind and photovoltaic farms are implemented to obtain a responsible entity for its construction. These farms consider several units of renewable energy sources to obtain a large amount of energy generation with a high level of operation flexibility [7]. Renewable energy sources provide flexibility to the system in a less expensive way, since it is cheaper to stop a wind turbine than a traditional power station.

The number of prosumers in nowadays power systems, reflects a growth of interest in distributed energy resources (DERs), and represents a trend regarding a sustainable future of energy consumption [8]. The average consumer does not take much interest in its consumption, however, it is known through several studies that the existing potential of energy savings is high and can avoid the continuous construction of new generation facilities [9]. This can be achieved through an elastic demand that can adjust to the current operation of the power system, instead of the classical model where generation adjusts to an inelastic demand. Both prosumers and consumers can provide flexibility to the power system through their consumption profile, namely, by adopting demand response measures [10]. Demand response is defined as the modification of load profile in exchange for monetary incentives or in response to price signals. The demand response concept is associated to the elastic demand, in a way that can be adjusted to the operation context. Additionally, this strategy has been gained popularity in recent years by being associated with the terms: energy management systems, energy efficiency, smart grids, and intelligent consumption.

All concepts referred above, are interconnected by their complementarity between each other and between them and the smart grid implementation. In this scope, new tools must be developed so that a more facilitated integration of these DERs and related concepts can be achieved, considering both technical and social environments. In the first feature, these tools must comprehend the necessary concepts for the management of electricity consumption, considering the adequate exhibition of the information that is more relevant for this action. In the second feature, these tools must be capable of being adjusted to different operation contexts and consumer behaviors, implementing the best strategies that are in line with the interests of the user. In a more legal approach, it must be considered that these tools are developed accounted for the current legislation, data privacy, and data security.

In addition to the appearance of new tools that facilitate the integration of DERs, new managing entities and/or roles to existing entities, must be implemented in power systems to complement the progress made by the tools. In this case, the role of aggregators is focused. Aggregators are entities capable of grouping several small-size DERs, such that a virtual energy amount is obtained that enables market participation and the uncovering of flexibility potential [11], [12].

DERs are often spread geographically from each other, although their characteristics may be similar. In this way, the aggregator can either manage these individuals without considering the network operation, or act as a system operator, and manage a given region of the network. The interaction between the aggregator and the other upper-level entities responsible for the network operation, is essential for the successful implementation of DERs to complement the operation of power systems in a benefic way [13], [14]. Nowadays, most aggregators focus their activities in the ancillary services market, providing operation flexibility to the power systems by using DERs, both distributed generation (composed of prosumers and/or other small generating units) and demand response (composed of prosumers and/or consumers) [15]. Also, in Europe, the interruptible load programs are the most popular, while in the United States, emergency demand response programs are most often available for load participation. The activities developed by the aggregator can cover several levels of actuation, in Figure 1 and as follows:

- **Upper Level** – stage where the aggregator manages resources considering a global perspective of grid operation, providing them a scheduling that these can adopt, that benefits both the aggregator and the resource in their operation;
- **Lower Level** – stage where the aggregator can provide management systems that complement its global scheduling, and reflects the resource's assets and interests.

This two-stage approach is representative of the real business models implemented by aggregators operating in Europe or United States, and has been the subject of some literature [16]. These consider that the aggregator, besides managing their resources to enable market participation in an upper level perspective, often provide energy management systems to allow a facilitated communication structure from their control center to the resource's assets and location. This process is sequential, since the lower-level adjusts to what is obtained in the upper-level, considering the resource's constraints and interests. These management systems provide real-time information for the aggregator, that can help support its scheduling decisions and better evaluate possible operation scenarios. This paper presents a methodology that implements the activities of an aggregator, implementing distributed generation and demand response resources.

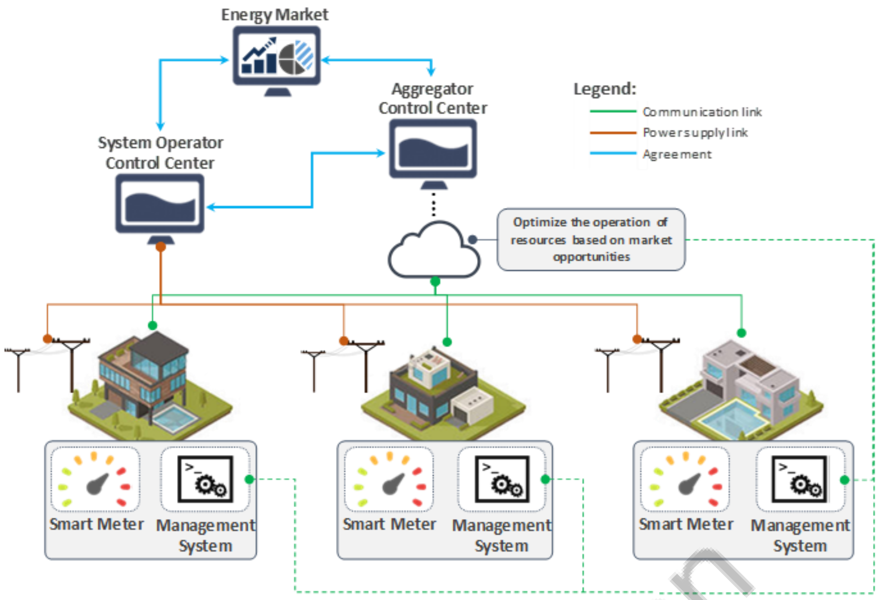

Fig. 1: Action levels of an aggregator.

This is performed using a two-stage algorithm, where in the first stage the resources are scheduled in an upper-level approach, and the in the second stage, an individual scheduling of the resource's assets is made. This allows the aggregator to unveil opportunities to improve energy efficiency of the resource's operation, and consequently, provide the aggregator more negotiation capacity in the energy market. The present paper is structured in the following way. After this introductory Section, the next Section details the main components of energy management systems, approaching their advantages, concepts, and opportunities that these can provide. In section 3, the methodology is explained and its considerations that represent the aggregator's activities. Section 4 presents the case study and results obtained to verify the usefulness of the proposed methodology, while finally, Section 5 shows the main conclusions.

2. Proposed Methodology

The proposed methodology is detailed in this section, considering its overall structure and sequence. It is important to notice that the second stage receives a data that is an output of the first stage, namely, the energy schedule. Based on this data, the second stage can complement the aggregator's activities with an adequate schedule of a consumer's inner operation, regarding the schedule obtained in the first stage. The first scheduling, due to the complexity that involves, is adequate to be in a day-ahead approach. This provides enough time for the aggregator to perform and analyze the operation optimization of the network. As for the second scheduling, the consumer's processes are adjusted in real-time, based on the signals transmitted by the aggregator related to what is obtained from the first scheduling.

The aggregator can perform the optimization of its activities given certain operating conditions, based on its interests in a first stage, and in the consumer's interests in a second stage. It is assumed that the resources belonging to the aggregator's portfolio, have a communication structure and the necessary equipment for the interconnection between the first and second stage of the proposed methodology. The second stage is related to the operation of three types of distributed energy resources, namely, generators, consumer, and prosumers. In this way, being one of these three types, a resource belonging to the aggregator's network and portfolio, can participate in the aggregator's market participations, by providing generation or load reduction/shifting.

3. First Stage – Aggregator's Resource Scheduling

In this section, it is presented the first stage of the proposed methodology, addressing a macro perspective for the resources scheduling. The aggregator considers the technical constraints imposed by the network, simulating the aggregator's role when acting as an operator. Additionally to considering the operation costs for the usage of resources to network balance, the objective function, demonstrated in equation (1), includes the revenues obtained from the sale of energy supply to consumers, and the remuneration obtained from market participation with the flexibility scheduled. In this way, the objective function addresses the interests of the aggregator whether in terms of reducing the operation costs of the usage of resources, and the capitalization of revenues obtained from consumer's supply and market participation.

$$
\begin{aligned}
&Minimize = Cs - (R^{load} + R^{market}) \\
&= \sum_{t=1}^{T} \left[\begin{array}{l}
\sum_{p=1}^{P} P_{(p,t)}^{DG} \cdot C_{(p,t)}^{DG} + \sum_{s=1}^{S} P_{(s,t)}^{sup} \cdot C_{(s,t)}^{sup} \\
+\sum_{c=1}^{C} \left(P_{(c,t)}^{red} \cdot C_{(c,t)}^{red} + P_{(c,t,d)}^{shift} \cdot C_{(c,t,d)}^{shift} \right) \\
-\sum_{c=1}^{C} \left(\begin{array}{l} P_{(c,t)}^{load} - P_{(c,t)}^{red} \\ -\sum_{d=1}^{T} \left[P_{(c,t,d)}^{shift} - P_{(c,d,t)}^{shift} \right] \end{array} \right) \cdot C_{(c,t)}^{load} \\
-\left(\sum_{p=1}^{P} P_{(p,t)}^{DG} + \sum_{c=1}^{C} P_{(c,t)}^{red} \right) \cdot C_{(t)}^{market}
\end{array} \right]
\end{aligned} \tag{1}
$$

As mentioned before, the aggregator must perform the analysis of the network when acting as an operator. Moreover, the aggregator performs the resource's scheduling/dispatch based on this approach. In this paper, it is considered the AC power flow model with only active power to guarantee that the optimization reflects the technical limitations of the network. In this way, equation (2) demonstrates the AC power flow method for active power based on the injected power of each bus, represented by equation (3).

$$
\begin{aligned}
&P_{(i,t)}^{inj} = \sum_{j=1}^{B} V_{(i,t)} \cdot V_{(j,t)} \cdot \left[\begin{array}{l} G_{(i,j)} \cdot \cos\left(\theta_{(i,t)} - \theta_{(j,t)}\right) \\ +B_{(i,j)} \cdot \sin\left(\theta_{(i,t)} - \theta_{(j,t)}\right) \end{array} \right] \\
&\forall i \in \{1,\dots,B\},\ \forall t \in \{1,\dots,T\}
\end{aligned} \tag{2}
$$

$$
\begin{aligned}
&P_{(i,t)}^{inj} = \sum_{p=1 \in i}^{P} P_{(p,t)}^{DG} + \sum_{s=1 \in i}^{S} P_{(s,t)}^{sup} \\
&+\sum_{c=1 \in i}^{C} \left[P_{(c,t)}^{red} + \sum_{d=1}^{T} \left(P_{(c,t,d)}^{shift} - P_{(c,d,t)}^{shift} \right) - P_{(c,t)}^{load} \right] \\
&\forall i \in \{1,\dots,B\},\ \forall t \in \{1,\dots,T\}
\end{aligned} \tag{3}
$$

Moreover, the technical limits imposed by the power flow equations shown before, are reflected by the levels of voltage magnitude and angle, expressed in equation (4). These variables may change over time and by bus of the network, according to the balance of energy. In this way, the aggregator guarantees the security of operation to both the network's equipment and resources regarding energy quality.

$$
\begin{aligned}
&V_{(i,t)}^{min} \le V_{(i,t)} \le V_{(i,t)}^{max} \\
&\theta_{(i,t)}^{min} \le \theta_{(i,t)} \le \theta_{(i,t)}^{max} \\
&\forall i \in \{1,\dots,B\},\ \forall t \in \{1,\dots,T\}
\end{aligned} \tag{4}
$$

Previous equations are related to the physical limitations of the network. The resources that belong to that network also possess operation constraints, namely, in terms of output generation (in the case of generation units) and load reduction (in the case of consumers and prosumers) capacity – equations (5) and (6), respectively.

$$P_{(t)}^{\min sup} \leq P_{(t)}^{sup} \leq P_{(t)}^{\max sup} \quad \forall t \in \{1, \ldots, T\} \tag{5}$$

$$P_{(p,t)}^{\min DG} \leq P_{(p,t)}^{DG} \leq P_{(p,t)}^{\max DG} \quad \forall p \in \{1, \ldots, P\}, \forall t \in \{1, \ldots, T\} \tag{6}$$

Regarding demand response programs, two are considered in this stage by aggregator to be applied to consumers: load reduction and load shifting. These two programs allow the aggregator to obtain more energy flexibility from the resources, in this case, consumers. The limit of each consumer in each time step, for the load reduction program, is expressed by equation (7). This program reflects the capacity of a consumer or prosumer, in a continuous form, reduce load of their operation.

As for the load shifting program, it considers that load can be shifted between periods for either benefit the aggregator or the consumer in their operation. In a similar way to the load reduction program, equation (8) represents the limits of load transfer amongst periods for the consumers and prosumers. Moreover, equations (9) and (10) limit the total amount of load shifted to or from other periods, by a given consumer.

$$P_{(c,t)}^{red} \leq P_{(c,t)}^{max\_red} \quad \forall c \in \{1, \ldots, C\}, \forall t \in \{1, \ldots, T\} \tag{7}$$

$$P_{(c,t,d)}^{min\_shift} \leq P_{(c,t,d)}^{shift} \leq P_{(c,t,d)}^{max\_shift} \quad \forall c \in \{1, \ldots, C\}, \forall t \in \{1, \ldots, T\} \tag{8}$$

$$\sum_{d=1}^{T} P_{(c,t,d)}^{shift} \leq P_{(c,t)}^{max\_shift-out} \quad \forall c \in \{1, \ldots, C\}, \forall t \in \{1, \ldots, T\} \tag{9}$$

$$\sum_{d=1}^{T} P_{(c,d,t)}^{shift} \leq P_{(c,t)}^{max\_shift-in} \quad \forall c \in \{1, \ldots, C\}, \forall t \in \{1, \ldots, T\} \tag{10}$$

This section presents the mathematical formulation of the first stage of the optimization model, representing the macro perspective of the aggregator. The resource's scheduling is based on the grid's constraints and limits, insuring the adequate technical operation of the network and resources. In the next section, it is detailed the second stage of the proposed methodology regarding the operation of a given prosumer that belongs to the network managed by the aggregator.

4. Second Stage – Prosumer Scheduling

In the second stage of the optimization methodology, it is considered the operation of a consumer given the received schedule from the aggregator in an upper level. In this way, the objective function, equation (11), defines the interests of the consumer which are the minimization of operation costs. This objective function considers the use of on-site generation and of the demand-side management capabilities of the prosumer or consumer.

$$Minimize\ Costs = Cs - R^{agg} = \sum_{t=1}^{T} \left[\begin{array}{l} P_{(t)}^{Agg} \cdot C_{(t)}^{load} + \sum_{g=1}^{G} P_{(g,t)}^{DG} \cdot C_{(g,t)}^{DG} \\ + \sum_{a=1}^{A} \left(P_{(a,t)}^{red} \cdot W_{(a,t)}^{red} + P_{(a,t,d)}^{shift} \cdot W_{(a,t,d)}^{shift} \right) \\ - \sum_{a=1}^{A} \left(P_{(a,t)}^{red} \cdot C_{(a,t)}^{red} + P_{(a,t,d)}^{shift} \cdot C_{(a,t,d)}^{shift} \right) \end{array} \right] \quad (11)$$

The prosumer needs to maintain the balance of operation based on the request of the aggregator for a certain level of load, obtained in the first stage of the proposed methodology, expressed by (12). The balance of the consumer's operation is based on the usage of on-site generation and, load reduction and shifting of appliances. The consumer has an energy contract with the aggregator, being him the one that supplies the consumer, expressed by (12).

$$\begin{array}{l} P_{(t)}^{Agg} + \sum_{g=1}^{G} P_{(g,t)}^{DG} - P_{(a,t)}^{red} \\ - \sum_{d=1}^{T} \left[P_{(a,t,d)}^{shift} - P_{(a,d,t)}^{shift} \right] = P_{(a,t)}^{loadStage1} \\ \forall t \in \{1,...,T\} \end{array} \quad (12)$$

As in the first stage, and because of the energy contract with the consumer, this second stage consider the technical limits of the resources, both for the aggregator supply and the use of on-site generation. This is represented by equations (13) and (14), respectively. It is also considered that the prosumer may have multiple on-site generators, being this implemented in the mathematical formulation.

$$\begin{array}{l} P_{(t)}^{\min Agg} \le P_{(t)}^{Agg} \le P_{(t)}^{\max Agg} \\ \forall t \in \{1,...,T\} \end{array} \quad (13)$$

$$\begin{array}{l} P_{(g,t)}^{\min DG} \le P_{(g,t)}^{DG} \le P_{(g,t)}^{\max DG} \\ \forall t \in \{1,...,T\}, \forall g \in \{1,...,G\} \end{array} \quad (14)$$

The demand response programs that the consumer can adopt are the same as the ones considered in the first stage for the macro perspective of the aggregator. The limits of their implementation are modelled by equations (15) and (16). The demand response differs from the first stage, only in terms of costs, that are replaced by the consumer preferences through weights.

$$\begin{array}{l} P_{(a,t)}^{\min red} \le P_{(a,t)}^{red} \le P_{(a,t)}^{\max red} \\ \forall t \in \{1,...,T\}, \forall a \in \{1,...,A\} \end{array} \quad (15)$$

$$\begin{array}{l} P_{(a,t,d)}^{\min shift} \le P_{(a,t,d)}^{shift} \le P_{(a,t,d)}^{\max shift} \\ \forall t,d \in \{1,...,T\}, \forall a \in \{1,...,A\} \end{array} \quad (16)$$

The second stage considers the scheduling of the consumer's operation, using demand response programs and on-site generators. The consumer's scheduling intends to minimize the costs and raise the revenues, accomplishing the objective of load set by the first stage of the proposed methodology.

5. Conclusions

This paper has proposed and discussed a methodology for an aggregator to manage the existing distributed energy resources. This method is divided in two phases for an improved accuracy of the consumers response to demand response events. Further work will include a large scale case study in order to demonstrate the effectiveness of the proposed methodology.

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