Centralized flexibility services for distribution system operators through distributed flexible resources

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Centralized flexibility services for distribution system operators through distributed flexible resources

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Abstract. Under the context of smart grids within smart cities, increasing distributed generation, consumer empowerment and emerging flexibility services, distribution system operators could benefit by activating flexibility in distribution grids to avoid deploying new infrastructures and grid overloading. The solution offered by this work is an energy management system algorithm capable of activating flexibility behind the prosumer main meter during constrained periods. Therefore, the distribution system operator could compensate grid congestion during high consumption or production periods and increase their renewable generation hosting capacity by using behind-the-meter flexibility during peak production periods.

Keywords: smart grids, smart cities, distribution grid, flexibility, energy management system, centralized optimization

1 Introduction

The presence of more intermittent distributed generation and the empowerment of consumers are forcing the power system to evolve and adapt its operation to these changes. Past electrical system was mainly based on centralized, dispatchable and predictable generation that provided flexibility at transmission level to the electrical system to balance generation and demand. However, the increasing installation of distributed renewable generation is transforming the generation side in a more variable and intermittent source of energy. At the same time, the European Commission has presented a package of measures to ensure that consumers are active and central players on the energy markets of the future [1]. In this sense, the use of flexibility from the demand side can boost the involvement of prosumers in the energy system and make them a valuable asset in the electrical market. The proper management of available flexibility, both in generation and demand side, can help to compensate the lack of certainty of renewable sources.

In addition, electric vehicles (EV) and heat pumps have a strategic role in reducing greenhouse gas emissions and they are a key component of the transition to a low carbon economy [2]. However, its widespread use is increasing the demand of electricity, which may cause the need to upgrade the electricity infrastructure. The introduction of flexibility services can also be used as a more efficient alternative to reinforce the distribution grid, reducing or postponing infrastructure investment needs [3].

The use of flexibility for congestion management in the distribution grid is currently being widely investigated and there are some undergoing initiatives trying to standardize and provide common understanding of flexibility usage in the distribution grid. As an example, Universal Smart Energy Framework (USEF) Foundation created a detailed framework to provide an integral market design for the trading of flexible energy use [4]. However, optimization strategies are not covered as they can be different for each flexibility operator based on its own requirements and characteristics. Regarding optimization strategies, [5] proposes a method to employ the flexibility service from EV and heat pumps for real-time congestion management through an optimal power flow. In contrast, authors in [6] presented an optimization framework for the use of customers flexibility aggregation participating in the wholesale power market and the regulation capacity market. Moreover, in [7] an optimization problem is formulated considering battery degradation cost and using a decomposed solution approach with the alternating direction method of multipliers (ADMM) instead of commonly adopted centralised optimization to reduce the computational burden and time, and then reduce scalability limitations.

This paper presents a centralized energy management system algorithm that provides flexibility from prosumers to distribution system operators (DSOs) during constrained periods in order to avoid grid congestion or other related grid failures. The suggested approach has been developed under the INVADE project [8], which aims to design a flexibility management system using batteries that supports the distribution grid and electricity market while coping with grid limitations, high penetration of renewable energy and EV. The main contribution of this paper is the development of a robust algorithm capable of activating the maximum flexibility available to meet the DSO flexibility request (FR) at minimum cost behind the prosumer main meter when needed to avoid grid congestion during high consumption or production periods at distribution level.

The remainder of the paper is organized as follows: Section 2 describes the developed framework. The mathematical formulation problem is outlined in Section 3. The case study and its results are presented in Section 4. Ultimately, conclusions are presented in Section 5.

2 System description

The optimization problem description and the architecture implemented is based on the INVADE H2020 [8] project. The result of this project will be an integrated platform enabling flexible management algorithms. It will be applied to public and private EV charging stations, households and mid-size customers to offer flexibility services to DSOs, BRPs and prosumers.

The three main actors involved in the present work and what role each one of them play is described below:

Distribution system operator : requests and purchases flexibility to the aggregator in order to avoid grid congestion and gives the corresponding financial compensation to the aggregator.

Aggregator : receives flexibility requests from the DSO and flexibility offers from the prosumers that are part of its portfolio. It is responsible for activating the flexibility requested by the DSO at minimum cost.

Prosumer : is the flexibility provider. Each prosumer aims to minimize its electricity bill by optimizing the used of batteries and photo-voltaic (PV) generation, but this optimized baseline consumption can be altered if the DSO needs to avoid a failure in the distribution grid in a certain period. The aggregator will economically reward the prosumer for modifying his optimized baseline.

The relationship and how these 3 main actors interrelate among each others is shown in Fig. 1.

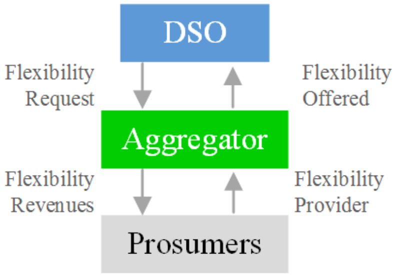

Fig. 1. Local flexibility market agents outline

Decisions are taken centrally. The aggregator will try to satisfy the DSO flexibility request at the lowest possible cost within its portfolio. This approach has a two way communication, which means that local data is available as an input to the optimization algorithm and the central system has direct control on the local flexible electric devices [9].

2.1 Flexibility Services

Flexibility services can be classified in function of the flexibility customer. The three main flexibility customers are listed in Table 1 along with what kind of

Flexibility customer	**Flexibility Service**
Distribution system operator	Congestion management Voltage / Reactive power control Controlled islanding
Balance responsible party	Day-ahead portfolio optimization Self-balancing portfolio optimization
Prosumer	Hourly tariff optimization kW max control Self-balancing

Table 1. Main flexibility customers and their flexibility services.

flexibility services they can demand. In order to describe the flexibility services, the INVADE project [10] and article [11] are used as reference.

The present study focuses on the DSO and prosumer flexibility service. Prosumers aim to minimize their electricity bill, while the DSO requests then flexibility needed to operate properly the distribution grid, within the safe operation zone.

2.2 DSO flexibility requests

The DSO flexibility requests are the minimum required amount of active energy variation with respect to the aggregated prosumer baseline optimization to avoid grid overloading. Negative flexibility request values mean decreasing generation or increasing demand while positive flexibility request is defined as increasing generation or decreasing demand. Table 2 summarizes these definitions.

FR <0	**FR >0**
↓ *generation*	↑ *generation*
↑ *consumption*	↓ *consumption*
Charge batteries	Discharge batteries

Table 2. Description of the DSO flexibility requests

The proposed flexibility algorithm flow chart is described in Fig. 2 and it is based on [7]. The algorithm starts by minimizing each prosumer electricity bill using their flexibility devices: distributed batteries and PV generation. The optimization result is the aggregated baseline optimized, which is the sum of each of the optimized consumption prosumer sites. The following step is to check whether the portfolio has enough flexibility to meet the DSO requests: the aggregator executes the aggregated level flexibility offer (ALFO) optimization problem. In case the flexibility requested could not be activated, it would deliver as much as possible. The aggregator sends to the DSO a flexibility offer and if the DSO accepts it, the aggregated level flexibility management (ALFM) optimization problem is then carried out, which will provide the flexibility asked to the DSO at minimum cost.

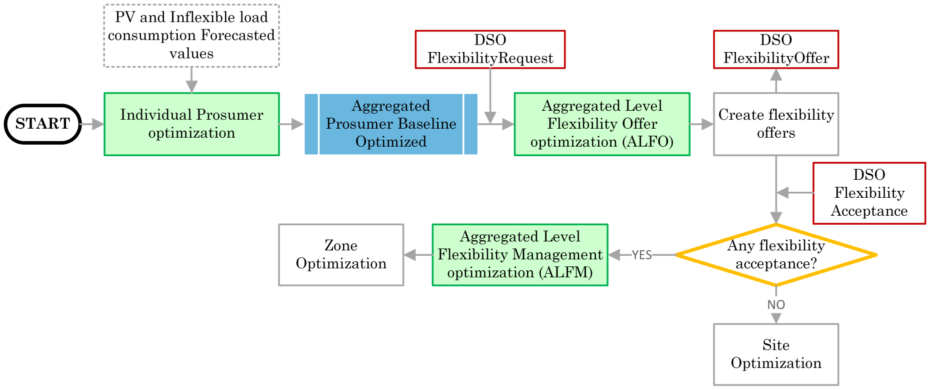

Fig. 2. DSO flexibility service flowchart

2.3 Flexibility Sources

Flexibility in the distribution grid can come from different distributed energy sources, mainly grouped by three types: loads, storage units, and renewable generation. All these flexible sources that can provide the amount of flexibility requested by the DSO are listed and described below:

Demand-side response: prosumers are provided with a financial incentive to turn down or turn off non-essential processes at times of peak demand or high energy prices, depending on what you want to minimize or maximize, helping the grid to balance supply and demand without the need for additional generation to be used.

Energy storage systems: electricity systems face an increased need for flexibility and a fundamental pillar in terms of flexibility are batteries, whose main potential is to help to deal with the high volatility of distributed renewable energy resources. Energy can be stored when there is a surplus of renewable energy generation. This energy can then be used at a time when its needed.

Distributed Energy Resources: they are electric generation units located within the electric distribution system at or near the end user. Electricity is generated locally, minimizing transportation losses.

3 Mathematical problem formulation

This problem is executed in three main steps: first, an individual optimization of each of the prosumers is carried out. The aggregated prosumer baseline optimized is used as an input to the ALFO optimization problem. Once the flexibility offer is calculated by the aggregator and accepted by the DSO, the ALFM optimization problem is carried out and it will provide the flexibility service to the DSO.

3.1 Individual prosumer flexibility service optimization problem

Prosumer objective function and constraints are defined as follows: The prosumer optimization function (1a) aims to reduce the electricity bill by minimizing the amount of energy purchased to the grid χ_t^{buy}, taking into account the revenues for injecting electricity to the grid χ_t^{sell}, maximizing the generation of renewable energy resources and minimizing the flexibility cost ζ_t^{flex}, which is the minimum amount of money that the prosumer is willing to save in order to activate a flexibility source (1b).

Equation (1c) represents the internal energy balance behind each prosumer smart meter: the total electricity imported from the grid, the optimized production from PV generation units $\psi_t^{gen,r}$ and the energy discharged by batteries σ_t^{dis} must be equal to the electricity exported to the grid, the consumption from inflexible load units W_t^{inflex} and the energy charged in batteries σ_t^{ch} for each period of time.

Binary variables δ_t^{buy} and δ_t^{sell} are introduced in equation (1d) in order to ensure that it is not possible to sell and buy electricity in the same period. They are set to 1 if the customer is buying (importing) or selling (exporting); else 0.

The amount of electricity bought (1e) and sold (1f) in each period of time must be less or equal to the maximum energy export capacity of each site per period, according to the terms stipulated in the retail contract.

$$
\begin{aligned}
\min_{\chi,\zeta} \quad & \sum_{t\in T} (P_t^{retail,buy} \chi_t^{buy} P_t^{VAT} - P_t^{retail,sell} \chi_t^{sell} + \zeta_t^{flex}) && \text{(1a)}\\
\text{s.t.} \quad & \zeta_t^{flex} = P_t^{gen,r} (W_t^{gen,r} - \psi_t^{gen,r}) + P_t^{b,ch} \sigma_t^{ch} + P_t^{b,dis} \sigma_t^{dis}, && \text{(1b)}\\
& \psi_t^{gen,r} + \sigma_t^{dis} + \chi_t^{buy} = \chi_t^{sell} + \sigma_t^{ch} + W_t^{inflex}, && \text{(1c)}\\
& \delta_t^{buy} + \delta_t^{sell} \leq 1, && \text{(1d)}\\
& \chi_t^{buy} \leq \delta_t^{buy} X^{max,import}, && \text{(1e)}\\
& \chi_t^{sell} \leq \delta_t^{sell} X^{max,export} && \text{(1f)}
\end{aligned}
$$

3.2 DSO flexibility service optimization problem

The aggregator has to ensure that there is enough flexibility available in his portfolio to meet the DSO flexibility request. The DSO purchases this available flexibility and gives the corresponding economic compensation to the prosumer through the aggregator. Once the flexibility offer sent by the aggregator is accepted by the DSO, the ALFM optimization problem is be executed.

The objective function (2a) is to minimize the aggregator operational cost of meeting DSO flexibility request. $W_{p,t}^{baseline,opt}$ is the aggregated baseline consumption after the individual prosumer optimization. Constraints (2b) (2c) ensure that the activated amount of flexibility is less or equal to the positive and negative FR, respectively. Constraints (2d) and (2e) avoid the rebound effect, which can cause new load peaks before or after the FR activation.

$$\min_{\chi,\zeta} \quad \sum_{t\in T}\sum_{p\in P}(P_t^{retail,buy}\chi_{p,t}^{buy}P_t^{VAT} - P_t^{retail,sell}\chi_{p,t}^{sell} + \zeta_{p,t}^{flex}) \tag{2a}$$

$$\text{s.t.} \quad \chi_{p,t}^{buy} - \chi_{p,t}^{sell} \leq W_{p,t}^{baseline,opt} - FR_t \qquad \forall FR_t > 0, \tag{2b}$$

$$\chi_{p,t}^{buy} - \chi_{p,t}^{sell} \geq W_{p,t}^{baseline,opt} - FR_t \qquad \forall FR_t < 0, \tag{2c}$$

$$\chi_{p,t}^{buy} \leq max(W_{p,t}^{baseline,opt}), \tag{2d}$$

$$\chi_{p,t}^{sell} \leq max(W_{p,t}^{baseline,opt}) \tag{2e}$$

3.3 Distributed Flexible Resources constraints

Energy Storage System constraints Distributed storage units can provide flexibility to the electrical grid by charging or discharging batteries to meet a flexibility request made by the DSO in a given period of time.

The behaviour of the battery is then formulated. The variable σ_t^{soc} in (3) indicates the current battery state of charge (SOC). With the aim to represent a more accurate battery model, the mathematical formulation has into account efficiency factors for storing η^{ch} and delivering electricity η^{dis}. Energy storage units can meet both, negative and positive DSO flexibility requests by charging σ_t^{ch} or discharging σ_t^{dis} the batteries, respectively. Both are variables in this problem.

$$\sigma_t^{soc} = \sigma_{t-1}^{soc} + \sigma_t^{ch} \cdot \eta^{ch} - \frac{\sigma_t^{dis}}{\eta^{dis}} \qquad \forall t \in T \tag{3}$$

In order to preserve and extend the battery life-time, σ_t^{soc} must be between a minimum O^{min} and a maximum O^{max} energy limit value (4):

$$O^{min} \leq \sigma_t^{soc} \leq O^{max} \qquad \forall t \in T \tag{4}$$

Equations (5)(6) limit the maximum energy charged Q^{ch} and discharged Q^{dis} by battery per period .

$$\sigma_t^{ch} \leq \frac{Q^{ch}}{N^{hour}} \qquad \forall t \in T \tag{5}$$

$$\sigma_t^{dis} \leq \frac{Q^{dis}}{N^{hour}} \qquad \forall t \in T \tag{6}$$

Equation (7) makes sure that the energy charged σ_t^{ch} is linearly decreased.S_b^{ch} is the threshold in charging process. The same happens with the discharging energy σ_t^{dis} (8).The lower threshold to limit the energy output is S_b^{dis}.

$$\sigma_t^{ch} \leq \frac{-Q^{ch}}{1-S^{ch}}\left(\frac{\sigma_t^{soc}}{O^{max}}-1\right) \qquad \forall t \in T \tag{7}$$

$$\sigma_t^{dis} \leq \frac{Q^{dis}}{S^{dis}} \frac{\sigma_t^{soc}}{O^{max}} \qquad \forall t \in T \tag{8}$$

The total battery degradation cost ζ^{bat} is taken into account (9). $P^{b,ch}$ is the degradation price for charging 1 kWh. The discharging degradation cost has been already included in the charging cost.

$$\zeta^{bat} = \sum_{t \in T} P^{b,ch} \cdot \sigma_t^{ch} \qquad \forall t \in T \tag{9}$$

Photo-voltaic reducible generation constraints The optimized PV scheduled production $\psi_t^{gen,r}$ must be between 0 and the PV baseline electricity generation $W_t^{gen,r}$. The price for reducing the PV generation is set high to maximize the renewable generation.

$$0 \leq \psi_t^{gen,r} \leq W_t^{gen,r} \qquad \forall \ t \in T \tag{10}$$

The total cost for reducing the PV generation is given by $\zeta^{gen,r}$. $P^{gen,r}$ is the price for disconnecting a PV generation unit.

$$\zeta^{gen,r} = \sum_{t \in T} P^{gen,r} \cdot (W_t^{gen,r} - \psi_t^{gen,r}) \qquad \forall \ t \in T \tag{11}$$

4 Case Study

A case study where the aggregator provides a flexibility service to the DSO and prosumer in the Spanish energy market is proposed. The aggregator controls the flexible energy sources of its portfolio, which is formed by 31 prosumers located in Austin, Texas. Real load consumption and PV generation data from different households have been provided by DataPort Inc. Street [12].

The present case study covers a planning horizon of 3 days, divided into 15-minutes time intervals and starting at April 1st of 2019 at 00:00h. All the distributed storage units in the aggregator's portfolio begin and end at half their maximum capacity. The Spanish tariff market is applied in the present optimization problem and the elecricity tariff chosen for buying electricity from the grid is the PVPC (Precio Voluntario para el Pequeño Consumidor), because price changes hourly. There is no economic remuneration for selling electricity to the grid. All prosumers have a contract power equal to 10 kW.

This work seeks to decide the optimal usage and scheduling for the utilization of the households's flexible devices in order to offer a flexibility service to the DSO when requested, for which they will be remunerated financially, while minimizing their individual electricity bill.

This section demonstrates the applicability of the developed DSO flexibility service algorithm for a zone level optimization, using the prosumer aggregated flexibility.

4.1 Prosumer optimization results

The aggregated result of each individual prosumer optimization is shown in Fig. 3. The lower horizontal axis shows the number of periods of the optimization horizon while the upper axis gathers these intervals in 3 days, for a better visual understanding. A negative energy value represents an electricity input to the system, such as PV generation and batteries discharging. A positive energy value refers to consumption as inflexible loads and batteries charging. Both, generation and consumption, must have the same amount of energy in order to meet the energy balance (1c).

Batteries charge when there is an excess of PV generation and discharge mainly in periods with no solar production and more expensive electricity prices (see periods 30 and 125 for example). The accumulated battery state of charge (SOC) is 155 kWh at the beginning and at the end of the time horizon, as indicated by the restriction imposed. The SOC helps to better understand the inertia of the batteries behaviour. The baseline is defined as the energy purchased minus the energy sold to the grid. Looking at the aggregated baseline optimized, it can be seen that there is an excess of generation injected to the grid between the intervals 159-163 and a high consumption during periods 216-223 and 284-288. The DSO will ask for flexibility in those time intervals in order to avoid grid congestion during high consumption or production periods. The execution time of the 31 individual optimizations in series was 31.19 seconds with an Intel(R) Core(TM) i5-7400 processor and 8GB of RAM.

4.2 Zone maximum flexibility available

The result obtained after the individualized optimization of each prosumer is the aggregated optimized baseline demand. Immediately, the DSO receives a notification of this aggregated optimized baseline demand of all its customers per zone [7] and based on this information, the DSO generates the FR with the aim of maintaining the electrical grid within the safe operation zone. Fig. 4 shows the aggregated optimized baseline demand and the DSO flexibility requests. The DSO needs to increase consumption (sends a negative FR) from periods 157 to 163 due to an excess of generation in the grid caused by the PV production. In periods 216 to 223 and 283 to 287, the DSO asks to reduce consumption (sends a positive FR) to avoid a grid overload. FRs are sent to the aggregator and

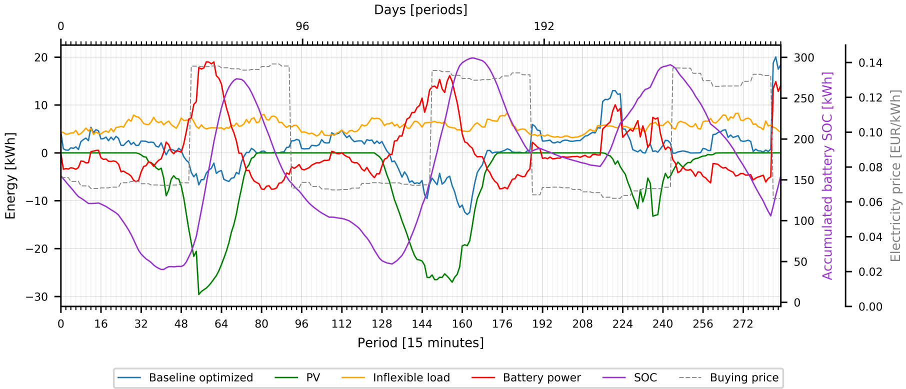

Fig. 3. Aggregated individual prosumer optimization results. Source: Pecan Street Inc. Dataport 2019.

then executes the ALFO optimization problem as it is formulated in [7]. It is verified that there is enough flexibility in the aggregator's portfolio, therefore it is possible to offer all the flexibility requested by the DSO. Following the scheme in Fig. 2, the aggregator creates and sends a flexibility offer to the DSO, which accepts.

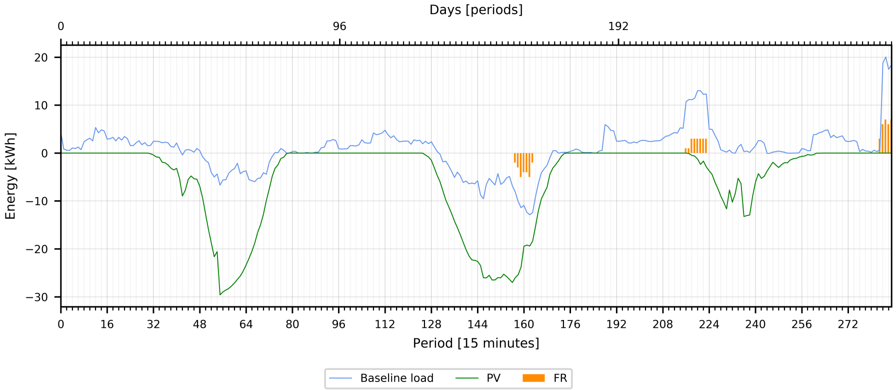

Fig. 4. Zone level optimization flexibility requests. Source: Pecan Street Inc. Dataport 2019.

4.3 Zone optimization results

The aggregated prosumer baseline optimization and the optimized battery power obtained in the previous individual prosumer optimization are the input of the ALFM optimization problem.

The result of the minimum cost centralized optimization is shown in Fig. 5. The activated flexibility is the same as the requested, since the portfolio has enough available flexibility. The only flexibility source are distributed batteries, as the reduction of PV production is severely penalised. It is observed that in periods where the DSO requests to increase the consumption due to an excess of PV generation (see 159-163 periods), the ALFM battery power increases regarding the baseline battery power. The opposite happens when the DSO requests a baseline load reduction: the ALFM battery power decreases in contrast to the battery power baseline because batteries charge has been reduced. The total cost for activating the flexibility is 64.72 €. The execution time of the centralized optimization problem was 33.21 seconds with an Intel(R) Cotre(TM) i5-7400 processor and 8GB of RAM.

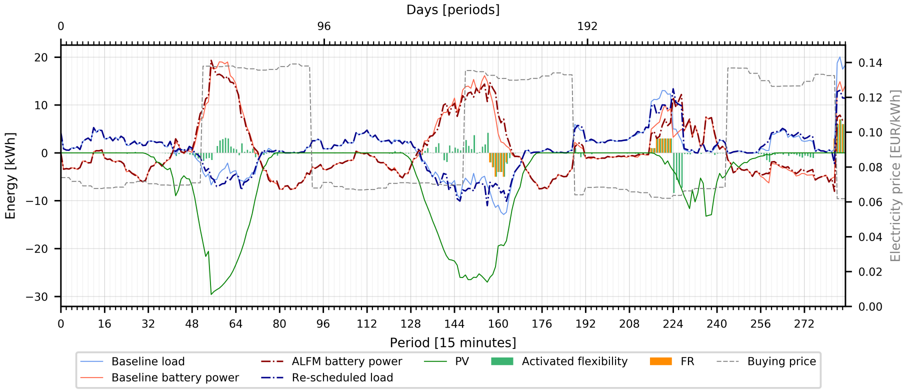

Fig. 5. ALFM optimization problem results under the DSO flexibility requests. Source: Pecan Street Inc. Dataport 2019.

5 Conclusions

It can be concluded that the centralized optimization algorithm proposed performs as it is expected: when the DSO requests a negative FR, this means increase consumption or reduce production, distributed batteries take advantage to charge during these time intervals. On the other hand, when the distribution grid is overloaded and a positive FR is required, some distributed storage units discharge to increase the generation in the grid to match the demand.

6 Acknowledgment

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