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Coordination of Aggregators for Flexibility Provision: A Conceptual Framework

Cesar Diaz-Londono[1,2], Carlos Adrian Correa-Florez[2], Jose Vuelvas[2], Andrea Mazza[1], Fredy Ruiz[3], Gianfranco Chicco[1]
[1]*Dipartimento Energia "Galileo Ferraris", Politecnico di Torino, Turin, Italy*
[2]*Departamento de Electrónica, Pontificia Universidad Javeriana, Bogota, Colombia*
[3]*Dipartimento di Elettronica, Informazione e Bioingegneria, Politecnico di Milano, Milan, Italy*
Email: *cesar.diazlondono@polito.it, carlosa-correaf@javeriana.edu.co, vuelvasj@javeriana.edu.co, andrea.mazza@polito.it, fredy.ruiz@polimi.it, gianfranco.chicco@polito.it*

***Abstract*—Current trends in power systems include increasing presence of renewable intermittent energy resources and important deployment of sensing and control capabilities at the premises of end users. The latter ones become important assets to off-set potential operational problems produced by the former, and moreover, can be used to provide additional flexibility resources to be traded in energy and ancillary service markets. This paper presents a conceptual framework to bridge the gap between flexible loads and ancillary service markets by means of aggregators of particular loads, and a coordinator of these aggregators which acts as a Balancing Service Provider. This coordinator communicates with other lower level aggregators depending on the balancing service required by the System Operator. In the presented methodology, thermoelectric refrigerators, water booster pressure systems and chargers located at electric vehicle charging stations are aggregated and coordinated to provide balancing services such as frequency containment reserve, frequency restoration reserve and replacement reserves, depending on the capabilities in terms of response time, dynamics and available flexibility. The results show the ability of the coordinator and the lower level control algorithms to provide balancing services for different scenarios of power request, as well as how different loads can be managed to cope with multiple types of ancillary services.**

***Index Terms*—Aggregator, Flexibility provision, Balancing services, Smart grids.**

I. INTRODUCTION

ENERGY markets are incentivizing consumers to participate in flexibility provision with the purpose of improving the reliability of the electrical grid. Aggregators offer the opportunity to exploit the flexibility potential of small end-users by modifying their consumption through Demand Response (DR) programs. Then, DR programs allow aggregators to provide ancillary services in balancing markets as flexibility capacity in day-ahead and to provide them in real time. However, small aggregators still suffer several access barriers as they do not meet the minimum requirements to participate in balancing markets.

Demand response programs can be classified into two categories: Incentive-Based Programs (IBP) and Price-Based Programs (PBP) [1]. In the literature, different strategies for controlling aggregators can be found. Most of them focus on PBP programs. For example, [2] presents a local coordinating mechanism for strategic aggregators, in which the offered flexibility capacity depends on the price. In [3], multiple Thermally Controllable Load (TCL) aggregators regulate their load demand in response to a price signal defined by the Distribution System Operator (DSO), whereas in [4], the utility aims to optimally schedule the power consumption or production of the individual aggregators by determining the energy and ancillary services prices. Moreover, [5] proposes a game-theoretical model for an aggregator to modulate the energy demand of an EV fleet. This aggregator is price taker from the wholesale market and price designer for consumers.

On the other hand, considering IBP programs, the coordination of aggregators is usually managed by the DSO. For instance, in [6], the DSO objective is to minimize the energy cost and power losses in the network, whereas Local Aggregators (LA) intend to reduce their energy consumption cost. In that model, the DSO and LA optimization problems are solved independently, and a battery energy storage system is considered as the only flexible load. Reference [7] evaluates residential loads flexibility. Clusters of EV, TCL and water heating systems are controlled by an aggregator for providing energy regulation services at hourly intervals. In addition, coordination strategies as in [8] directly manage Plug-in EVs (PEV). There, it is proposed a methodology for calculating the optimal charging power profiles of PEV groups that are directly controlled by aggregators, coordinated by the DSO. The same approach is followed in [9], but there, the PEV aggregators only report some load boundaries to the DSO.

The previously mentioned models consider the operation of a coordinator of aggregators; however, none of them considers a coordinator of aggregators for providing several ancillary services with heterogeneous flexible loads operating as a whole. Therefore, this paper presents a conceptual operation framework for a coordinator of aggregators with heterogeneous flexible loads, considering continuous and discrete models. Moreover, each aggregator, specialized for a kind of flexible load, has a different topology, including predictive-optimal controllers and classic Proportional-Integral (PI) controllers, able to provide different ancillary services. The coordinator operates as a Balancing Service Provider (BSP) and it is responsible of providing flexibility services, aggregating and coordinating the distributed flexible loads. In particular, Water

Booster Pressure Systems (WBPS), ThermoElectric Refrigeration (TER) units, and Electric Vehicle Charging Stations (EVCS) are considered as flexible loads in this work, as it has been shown that they have the potential to provide various balancing services in the context of smart grids. Moreover, it is assumed that the aggregation decisions are purely technical, then, no market bidding [10] or price definition is assessed.

The paper is organized as follows. Section II briefly describes how the frequency restoration operates. The framework of the hierarchical coordination considering different aggregators is described in Section III. Section IV evaluates the BSP operation through simulation campaigns. Finally, Section V presents the conclusions and notes on future works.

II. FREQUENCY RESTORATION OPERATION

The System Operators (SOs) in Europe use different processes and products to balance the system and restore the frequency. In this sense, the Commission Regulation 2017/2195 of 23 November 2017 [11] sets up the requirements for the technical parameters of standard products in order to facilitate the exchange of balancing energy across borders.

A. Balancing services

Considering the guideline on electricity balancing, the balancing energy services in Europe are organised as:

- *Frequency Containment Reserves* (FCR): The active power reserves available to contain system frequency after the occurrence of an imbalance [12].
- *Frequency Restoration Reserves* (FRR): The active power reserves available to restore system frequency to the set point and, for a synchronous area consisting of more than one load-frequency control area, to restore power balance to the scheduled value. The standard FRR can by activated automatically (aFRR) [13] or manually (mFRR) [14].
- *Replacement Reserves* (RR): The active power reserves available to restore or support the required level of FRR to be prepared for possible additional system imbalances [15].

The full activation time and delivery period of these balancing services are presented in Table I.

Table I
BALANCING ENERGY SERVICES [12]–[15].

Service	Full activation time	Delivery Period
FCR	15 s (50%) - 30 s (100%)	15 min
aFRR	5 min	15 min
mFRR	12.5 min	15 min
RR	0 - 30 min	15 min - 60 min

Figure 1 depicts how the balancing services are deployed in case of a grid imbalance. Then, the use of these services is divided into four steps, i.e., FCR, aFRR, mFRR, and RR. The figure presents an idealized case, where all the services are synchronized for providing a constant energy consumption. Besides, it is shown the timings of the services after a frequency disturbance. Then, the first response is given automatically by the FCR; aFRR is activated (when necessary) to release the FCR. Later, mFRR is activated to release the aFRR. Finally, RR activation is performed.

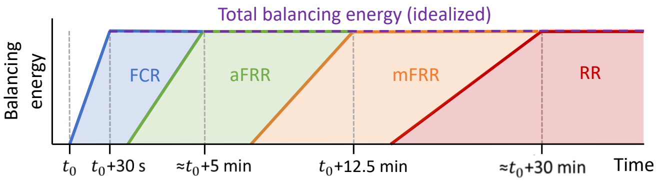

Figure 1. Balancing processes for frequency restoration.

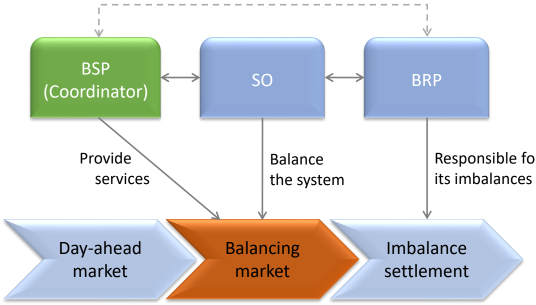

Figure 2. Electricity markets sequence and its participants.

B. Balancing operation

The balancing services are actions that the SO continuously takes to ensure constant system frequency, as well as the compliance with the required reserve amount. Therefore, the SO acts to ensure that demand and supply remain balanced by operating the system close to real-time. Figure 2 shows the electricity market sequence. The balancing market considers three main actors, i) the SO, ii) BSP, and iii) the Balancing Responsible Party (BRP).

The operation of the BSP i.e., the coordinator, is guided by the SO with the purpose of ensuring the balance between demand and generation in the real-time dispatch, through the activation of the flexibility services. The balancing market normally considers the SO, the BSP, and the BRP (see Figure 2), and consist of two phases:

1) *Balancing planning phase*: performed in a Day-Ahead (DA) market. The main actions are:
   - The BRP reports the scheduled demand and generation per time step. In addition, the BRP computes the energy imbalances and sends them to the SO.
   - The BSP informs the SO about the power demand baseline, which is defined as the sum of all the aggregators (AGGs) power demand. This can be based on forecast or historical data.
   - The BSP offers to the SO upward and downward flexibility capacities. This is based on the sum of all the AGGs flexibility. Notice that each AGG is responsible for its own flexibility forecast and baseline.

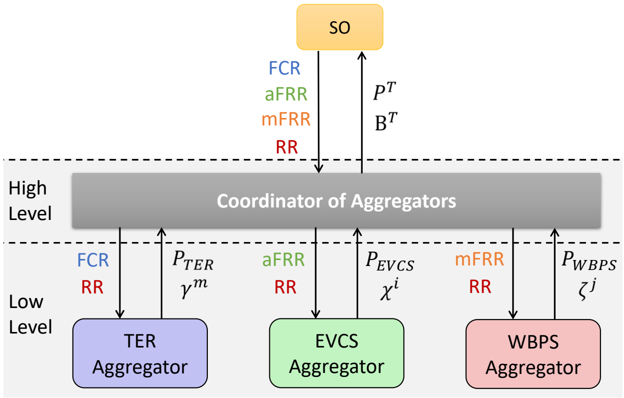

Figure 3. Two-level BSP structure.

2) *Balance settlement phase*: performed in a Real-Time (RT) market. The main actions are:
   - The SO guides the BSP for activating the balancing service based on the BRP imbalances information.
   - The coordination within the BSP allocates the SO energy request among the AGGs.
   - Each AGG manages its loads and generation resources providing upward or downward power variations to follow the coordination requests.

III. UNIFIED AGGREGATION FRAMEWORK

In this section, a hierarchical structure for a BSP is proposed, taking into account the coordination level, the aggregators, and flexible load models. In fact, the challenge of the BSP consists in integrating various AGGs with different load characteristics and response times. Therefore, a conceptual framework is formulated by proposing a two-level BSP structure (see Figure 3): i) the coordination level (high-level), and ii) the AGGs level (low-level). The high-level logic is developed considering the SO requirements and the availability of flexible resources provided by each AGG, in order to provide balance services such as FCR, aFRR, mFRR, and RR.

A. Flexible Loads Aggregators

The flexible load aggregators considered in the low level are presented in this subsection. In this work, three loads with different characteristics and aggregation strategies are considered. However, the framework can be applied to any other flexible load, provided that an automatic control strategy for power regulation is available and the response time of the closed-loop system fits into any of the services described in section II-A.

1) ThermoElectric Refrigeration AGG: A TER is a solid-state energy-conversion technology that exploits the Peltier effect to convert electricity into thermal energy for heating or cooling. Reference [16] proposes an aggregator for large populations of TERs, providing both upward and downward power deviations. The flexibility is achieved by changing the temperature set-point to the highest or lowest limit of each TER. The aggregated dynamic response is represented by linear transfer functions.

The aggregator (TER-AGG) is a proportional-integral (PI) feedback controller. The TER-AGG decides the amount of TER systems that must modify the temperature set-point β_{TER} (nominal, high, or low) based on the high-level coordination request r_{TER} and current power consumption P_{TER} of the population. It is designed to avoid any rebound effect after providing any balancing service, leading to a long recovery time; however, this is not desirable when coordinating several aggregators. Therefore, the TER-AGG controller is here improved for achieving faster changes when providing different services and interacting with several aggregators. In fact, due to the fast response of the TERs (few seconds), it is possible to consider instantaneous changes after the activation of a service. A block diagram of the TER-AGG and TER set interaction is depicted in the purple blocks of Figure 4.

2) WBPS-AGG: Water Booster Pressure Systems (WBPS) are responsible of supplying water and maintaining adequate pressure levels in a building pipeline. Reference [17] proposes an aggregator for large populations of WBPS, providing downward power deviations. The flexibility is achieved by changing the pressure set-point for each pressure tank. The aggregated dynamics are represented as a discrete time model with sampling time of 3 min.

The aggregator (WBPS-AGG) is a discrete-time PI controller with gain-scheduling. The WBPS-AGG offers downward flexibility by deciding the amount of WBPS whose pressure set-point must be modified (β_{WBPS}), based on the high-level coordination request r_{WBPS} and current power consumption P_{WBPS}. A block diagram of the WBPS-AGG and WBPS set interaction is depicted in the red blocks of Figure 4.

3) EVCS-AGG: An Electric Vehicle Charging Station (EVCS) is composed of various chargers, to which electric vehicles (EVs) connect with the aim of being charged. Reference [18] proposes an aggregator to manage the charging profiles of the EVs served by the EVCS. The model considers a switching behavior of the chargers, caused by the arrival and departure of EVs. The EV charger flexibility is defined as the maximum power deviations, given a nominal charging profile, that guarantee a proper charge level at the end of the charging period.

The aggregator (EVCS-AGG) is based on a Model Predictive Control (MPC) strategy that aims following the aggregated power scheduled in DA and the high-level coordination request r_{EVCS}, i.e., looking for minimizing the DA tracking error considering a penalty cost, subject to the charger state of charge dynamics (SoC_i) and technical limits. The decision variables are the power P_i delivered by each charger i and the flexibility capacity. Moreover, the AGG has the capability to schedule a DA power demand based on the expected EV chargers request. The DA power schedule is formulated as an optimal control problem that aims to minimize the operation cost while maximizing the flexibility capacity, subject to the battery dynamics and technical limits. This aggregator can

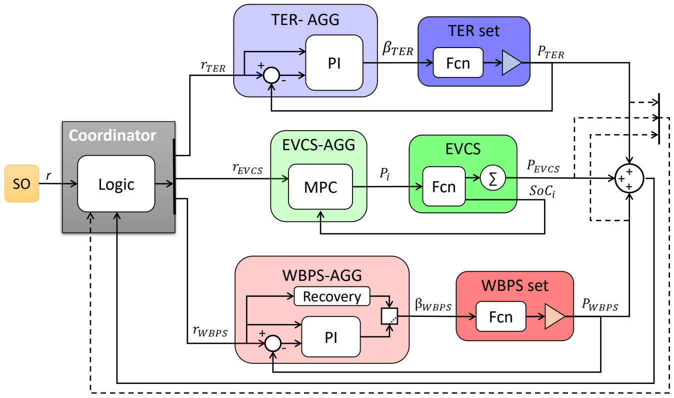

Figure 4. BSP operation scheme.

provide upward and downward flexibility. A block diagram of the EVCS-AGG and EVCS is presented in the green blocks of Figure 4.

B. Hierarchical Coordination

The two-level structure is presented in Figure 3. Notice that the communication between the BSP and the SO considers few parameters, the same can be observed for the interaction between the high-level and low-level coordination layers. In fact, the exchanged information is the power (P_{TER}, P_{EVCS}, and P_{WBPS}), the flexibility of the AGGs (γ^m, χ^i, and ζ^j), and the balancing services requests (FRC, FRR, and RR). Then, the dispatching is carried out by the BSP.

The main responsibilities of the BSP high-level coordination are:

- Understand the capacity and time response of each AGG.
- Assign the balancing services that each AGG can provide.
- Offer the complete flexibility of the structure to the SO.
- Manage the SO requests, i.e., if some AGG has variations following its requested power, the high-level coordination can compensate the overall power with another AGG.

The high-level coordination manages the provision of the balancing services by assigning them to the AGGs considering their time response, i.e.:

- the TER-AGG can provide FCR with a response time within seconds;
- the EVCS-AGG can provide aFRR with activation time within 5 min;
- the WBPS-AGG can provide mFRR with activation time within 12.5 min; and,
- the RR service can be provided by all the AGGs.

Therefore, the high-level coordination decides the energy service each AGG must provide (considering that all AGGs have different response times), by defining the power that each AGGs should follow. It is worth noticing that the BSP operates with a sample time equal to the one on the fastest AGG, i.e., is 1 s in the TER-AGG.

The decision of the provision of the services starts with the computation of the DA baseline and flexibility capacity offered by each AGG. Then, the BSP evaluates and calculates the services to offer to the SO, e.g., for the FCR service only the TER-AGG flexibility can be considered, whereas, for the RR service, the flexibility of all AGGs can be offered. Besides, when a request from the SO arrives, the high-level coordination calculates and reports the power that each AGG should follow at a specific period. However, if an AGG is experimenting large power deviations, the high-level coordination slightly modifies the power requested to other AGGs with the purpose to avoid a general error in the service provision.

It is worth noting that the two-level structure is scalable by varying number and characteristics of AGGs. In fact, if more AGGs participate in the framework, better performance of the balancing service can be reached.

IV. BALANCING SERVICE PROVIDER OPERATION

In this section, the operation of the BSP is proposed. Likewise, simulation campaigns are performed in order to evaluate the capability to provide FCR, FRR, and RR services. The simulations compare the DA power schedule with the actual power consumption considering the balancing services provision.

The AGGs DA power schedule or baseline are defined as: i) nominal power consumption for the TER-AGG and the WBPS-AGG; and ii) the day-ahead scheduling for the EVCS.

The flexibility offered by each low-level aggregator is fixed as the capacity found by the proposers of the aggregators:

- TER-AGG: considering the flexibility for RR service, the upward and downward capacities are 85% and 53% of the baseline, respectively.
- WBPS-AGG: the downward flexibility capacity of 27% of the baseline is considered.
- EVCS-AGG: upward and downward flexibility capacities based on the chargers flexibility definition provided in [18] are considered.

Figure 5 presents the flexibility offered by each aggregator as well as the aggregated capacity offered by the BSP to the SO. It is shown that the total flexibility is always higher than ±100 kW; however, with the purpose of providing all the balancing services, i.e., FCR, FRR, and RR, it is not possible to offer this capacity. In fact, only the TER-AGG can provide fast services such as FCR. Then, following the frequency restoration process presented in Figure 1, the maximum capacity is defined by the aggregator with the fastest response, i.e., TER-AGG.

It is worth noticing that for long-lasting services such as RR, the flexibility offered by the BSP can be the complete capacity depicted in Figure 5.

In order to evaluate the BSP performance in RT, two different service provisions are evaluated:

- *Case 1*: Each AGG provides a specific service (15 min).
- *Case 2*: The services are provided by overlapping the AGG power requests by following an idealized provision case.

Both cases are evaluated in MATLAB/Simulink simulations. These cases provide different power capacities due to the

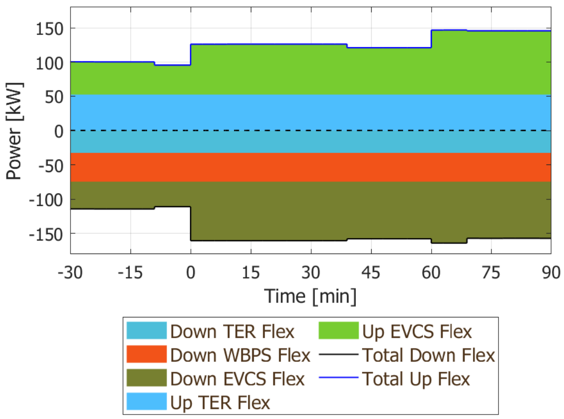

Figure 5. Flexibility of the BSP.

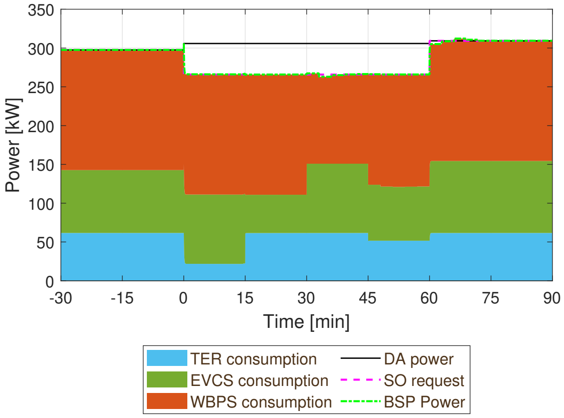

Figure 6. BSP performance in balancing services (*Case 1*).

maximum power the TER (fast service) can provide to the grid in each case. The high-level coordination defines and reports to the AGGs the power deviation they should follow. Moreover, in the simulations, only reduction power requests by the SO are analysed due to the WBPS response that only considers reduction flexibility.

In Figure 4 the two-level structure operation is depicted, presenting the two-level BSP. The TER and WBPS sets are represented by linear transfer functions. These functions allow the simulation to be computationally lightweight. Besides, the MPC and EV chargers dynamics are run in MATLAB.

1) Case 1: The case study evaluates a frequency restoration process where all the aggregators participate in providing balancing services. In this case, the FCR, the aFRR, and the mFRR services are provided by a single AGG considering the time response of each one.

Figure 6 depicts how the BSP performs the services when the SO requests a power reduction of r=40 kW from minute 0 to 60. The DA power is 305.82 kW, the ideal RT power is 265.82 kW, while the BSP RT average power is 265.88 kW, achieving an average error of 22.6 W and standard deviation of 0.78 kW.

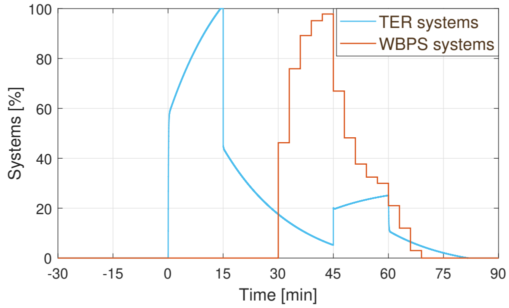

Figure 7. Population of TER and WBPS systems changing the set-point (*Case 1*).

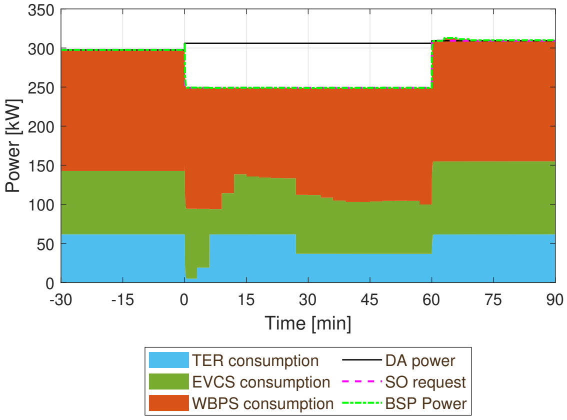

Figure 8. BSP performance in balancing services (*Case 2*).

Figure 7 shows the percentage of TER and WBPS systems with active flexibility required to follow the power request. Notice that the maximum power deviation of the BSP is computed as the maximum power the TER-AGG can provide, in this case for 15 min. In addition, the ramp-down is considered at the end of the service to avoid a rebound effect of the BSP.

Regarding the performance of the EVCS-AGG (see Figure 6), it can be seen that between the minutes 45 and 60, the power is not constant, this is due to the fact that the high-level coordination modifies the EVCS consumption depending on the other AGG consumption. In particular, the WBPS-AGG has small variations when following its request; then, the EVCS is operated to maintain the balance. Notice that the DA power schedule varies at each hour.

2) Case 2: In this case, the high-level coordination manages the aggregators with an strategy similar to the one presented by [12], considering ramps rates and times per service (see Figure 1).

Figure 8 presents the power response of the BSP when aggregating the AGGs power. The SO requests a power reduction of r=57 kW, 17 kW higher than in *Case 1*. The DA power is 305.82 kW (the same as *Case 1*), the ideal RT power is 248.82 kW, while the BSP RT average power is 249.00 kW achieving an average error of 71.5 W and standard deviation of 0.10 kW (lower than in *Case 1*).

The TER-AGG is the first AGG commanded to modify consumption, it is the only one that can provide the FCR

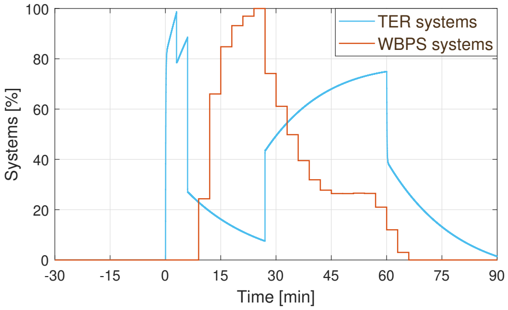

Figure 9. Population of TER and WBPS systems changing the set-point (*Case 2*).

energy service. Therefore, the maximum power is defined by the maximum capacity of this AGG in the specific time window (3 min in this case). Moreover, it can be seen that the high-level coordination is constantly changing the requested EVCS-AGG power due to the variations of the WBPS-AGG.

The percentage of systems changing temperature set-point (TERs) as well as the percentage of systems changing pressure set-point (WBPS) are depicted in Figure 9. Besides, the ramp-down is considered to avoid a rebound effect at the end of the BSP energy provision.

Finally, Table II summarises the main differences between *Case 1* and *Case 2*. It can be seen that *Case 2* considers a higher power reduction due to the duration of the first interval when the TER-AGG is activated (3 min). Likewise, in *Case 2* the standard deviation is lower because the EVCS-AGG is constantly correcting the WBPS-AGG power deviations. In addition, the tracking average error is higher in *Case 2*; nevertheless, in both cases, the error is lower than 0.03%.

Table II
COMPARISON BETWEEN CASES 1 AND CASE 2.

Parameter	**Case 1**	**Case 2**
Max power reduction	40 kW	57 kW
Tracking average error	26.6 W	71.5 W
Standard deviation	0.78 kW	0.10 kW

V. CONCLUSIONS AND FUTURE WORK

This paper has presented a framework for coordinating aggregators of different types of loads that may provide balancing services to the grid. A structure with different balancing services, consistent with the European guidelines on electricity balancing, and a hierarchical coordination of the aggregators, has been considered. Some examples have been shown in which the aggregation of thermoelectric refrigerators is able to respond in a faster way with respect to water booster pressure systems and electric vehicles, thus providing frequency containment reserve in an efficient way, followed by the response of the other types of loads. The combined and coordinated action of the different aggregators enables an efficient response of the overall system across the timings of the balancing processes. Future works will deal with the details of the determination of the set-points of the individual loads considering the uncertainty on the load behavior inside the aggregation. This uncertainty will be included in the analysis of a local system with fluctuating generation from units supplied by renewable energy sources.

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