Aggregation of residential Energy Storage Systems

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***Abstract*—This paper aims to perform a technical feasibility study of a Virtual Energy Storage System (VESS) composed of 1400 residential users with a PV plant and a Battery Energy Storage System (BESS). A control strategy has been developed and applied to find out the amount of grid services that the VESS is able to provide. The results show that, aggregating hundreds of residential users with a BESS, there is sufficient power and energy margin to provide grid services ensuring the services behind the meter such as the self-consumption functionality. The results of the feasibility study are quite promising: the VESS is able to provide up to 49 MWh of grid services, both upward and downward, over the day.**

Keywords*—*Energy Storage System, Virtual Energy Storage System, Ancillary services

I. Introduction

A large amount of renewable and distributed energy resources (DERs) are being installed in order to achieve the RED II targets [1], reducing the greenhouse gas. This paper takes into account the scenario that is going to spread over the Italian network, in particular considering the Low Voltage Network. The number of PV plants installed is keeping growing [2] because they help to reduce electricity bills for retail electricity customers. Recently the coupling of small-scale BESS and PV is becoming an increasingly popular option in Italy to improve the self-consumption and decrease further the electricity bill [3] [4].

The increase of renewable resources, which are usually not programmable, implies higher requests for ancillary services, provided by dispatchable resources. In this context the Italian Regulatory Authority for Energy, Networks and Environment (ARERA) implemented a new regulation [5] that allowed aggregated DERs to participate in the Ancillary Services Market (ASM). The aggregate can be composed of different types of resources (generators, loads, BESS, Electric Vehicles, etc.); there is not any limit to the rated power of the single resource, but the aggregate must have an overall minimum regulating power of 1 MW. Moreover, ARERA introduced the figure of the Balancing Service Provider (BSP), that has the role of managing the aggregate in order to participate to the ASM as a single unit.

This paper tackles the problems related to a VESS [6-9], composed of several BESSs for residential applications, that provides grid services. The aim of this study is to demonstrate that also a small dispatchable resource in the electrical grid, such as a residential BESSs, can provide a meaningful support to the grid if gathered together other small resources, without affecting the provision of services to the user.

The article is structured in the following sections: Section II describes the system under test considered for the technical feasibility study; in Section III the control strategy implemented to manage the aggregate is proposed and finally Section IV shows the results of the study.

II. System under test

This section describes the aggregate considered in the case study and the ASM in which it operates.

A. VESS characteristics

The system under test is a VESS composed of 1400 residential users, each one with a PV and a controllable BESS. Thus, every user in the VESS can be considered as a dispatchable resource.

The load profiles have been randomly generated starting from the statistical features of a set of residential users monitored in previous research activities [10] [11] during a winter working day. Fig. 1 shows the average and the standard deviation of the simulated consumer load profiles. The average profile has two peaks, one in the morning and one in the evening, and the standard deviation is quite high (typical for residential user). Fig. 2 shows the 1400 load profiles generated and used as input for the following technical feasibility study.

Regarding the generation profile, a typical PV production during a winter sunny day is considered for each user. Fig. 3 shows the PV power profile in per unit; the power profile of the 1400 users have been obtained multiplying the power profile in per unit and the nominal power of the PV plants of each user (Fig. 4). This set of PV profiles have been generated under the assumption that the PV plants are placed in a restricted area in which the irradiance is the same. The difference between the PV production of one user compared to another one is only due to the amplitude of the profile.

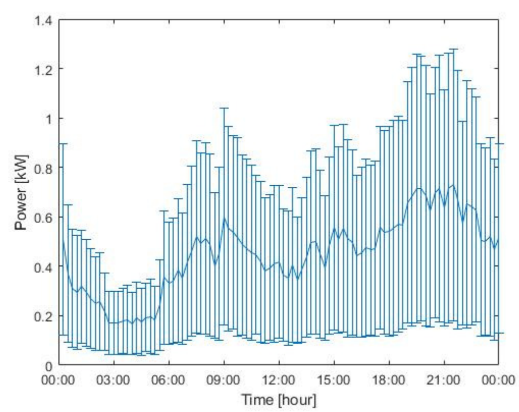

Fig. 1. Average and standard deviation of the simulated consumers load profile

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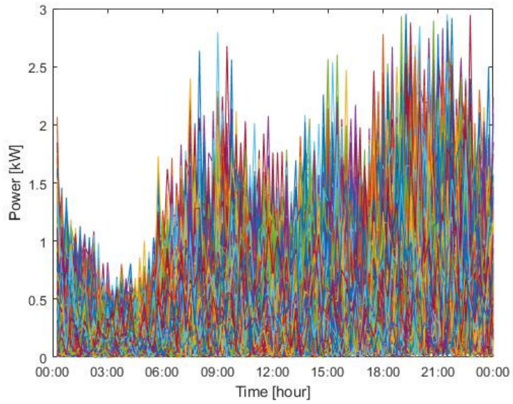

Fig. 2. Load profile of the consumers simulated over the day

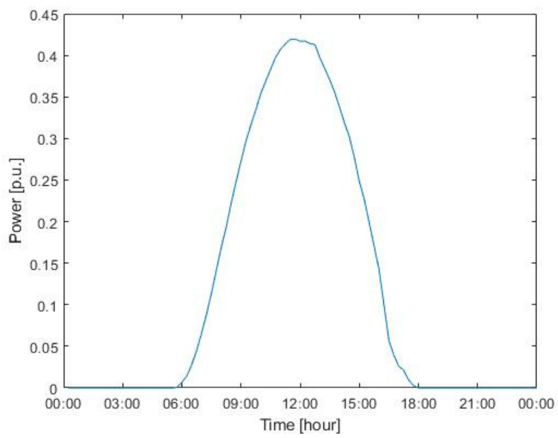

Fig. 3. PV power profile in per unit over the day

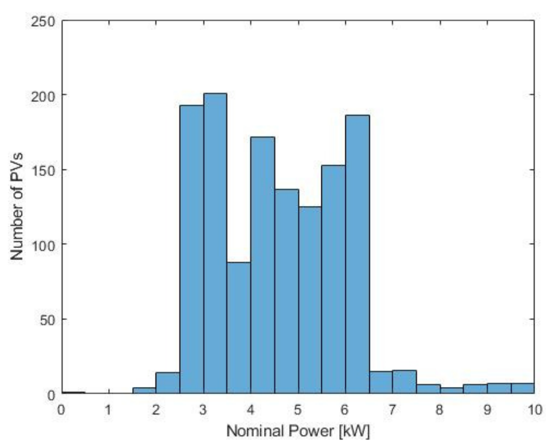

Fig. 4. Nominal power of the PVs considered

The last components of the considered VESS are the BESSs. These storage units are supposed to be installed to provide services behind the meter. In particular the main functionality performed by the BESSs is the self-consumption that allows the users to save money on the electricity bill. The BESS sizes used for the study are shown in Fig. 5. BESSs were sized to optimize the self-consumption of the users. The average capacity of the BESSs is 7.5 kWh with a fixed charge and discharge rate of C/3 for all the BESSs.

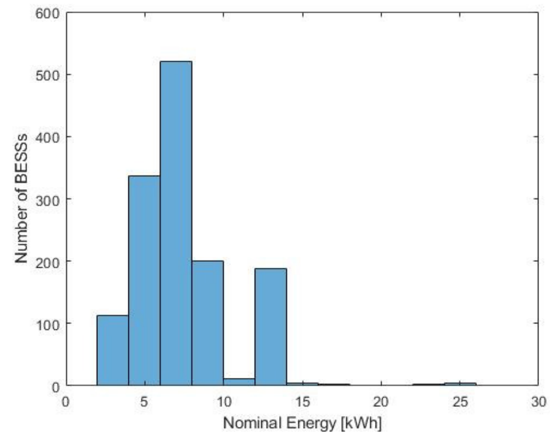

Fig. 5. Nominal Energy of the BESSs considered

In the technical analysis performed, no dissipating phenomena for the BESSs have been considered. This assumption simplifies the study and at the same time does not affect significantly the results since there would not be relevant change in the resulting available power and energy.

Considering the above components, the VESS considered has a maximum theoretical nominal power (equal to the sum of the BESSs power) of 3.3 MW and a maximum storable energy (equal to the sum of the BESSs energy) of 10 MWh.

B. VESS baseline

Since the individual BESSs have been installed to provide services behind the meter as main functionalities, a baseline power and energy profile of each BESS has been calculated. The grid services provided by the VESS must not prevent any kind of service behind the meter, such as the self-consumption.

In the techno-economic feasibility study the following basic control of each BESS is assumed.

$$P_{BESS_i} = P_{PV_i} - P_{load_i} \qquad 0 < E_{BESS_i} < E_{BESS_{MAX_i}} \tag{1}$$

$$P_{BESS_i} = 0 \qquad E_{BESS_i} = 0 \vee E_{BESS_i} = E_{BESS_{MAX_i}} \tag{2}$$

$$E_{BESS_i} = \int P_{BESS_i} dt \tag{3}$$

This is the simplest control strategy for a BESS that improves self-consumption. When the power provided by the PV is higher than the power consumed by the load, the surplus charges the BESS. On the contrary, when the PV power is lower than the load, the BESS provides all the remaining power in order to keep the power coming from the grid close to zero. Additionally, the BESS power is also constrained by the state of charge limits.

Fig. 6 shows the BESSs energy profiles in *per unit* (each one refer to its nominal energy) assuming that the BESSs do not provide grid services, hence ensuring the self-consumption. It can be noted that some BESSs reach their boundary, forcing the system to stop working, while others not. In the first case the BESSs capacity is fully exploited; in the second case the BESSs are probably oversized.

Considering the whole aggregate, the overall VESS power and energy profile is plotted in Fig. 7 and Fig. 8. As additional constraint, the power profile makes the initial and final states of charge coincide, in order to preserve the daily periodicity and remove any border effect.

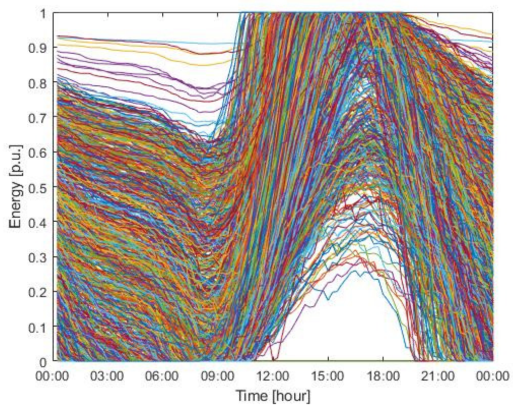

Fig. 6. BESSs stored energy profile in per unit over the day

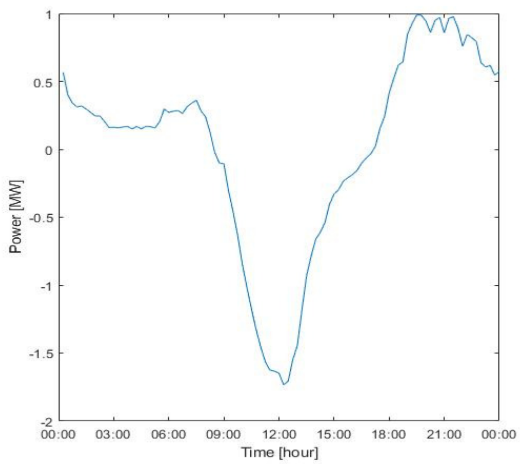

Fig. 7. Power profile baseline of the VESS

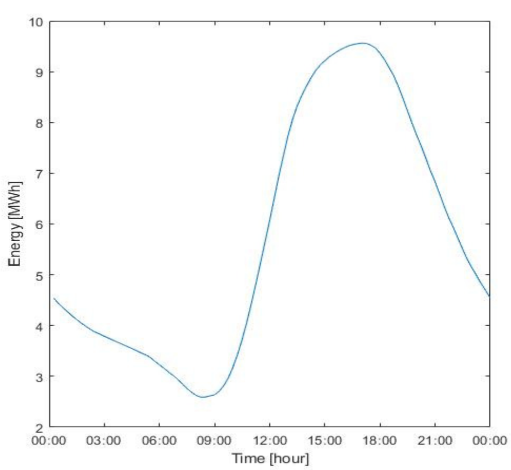

Fig. 8. Energy profile baseline of the VESS

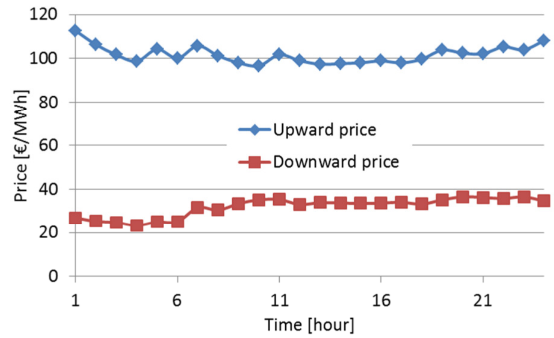

Fig. 9. Accepted prices of the ASM-Balancing Market over the day

C. ASM requirements

The directive of the Italian Transmission System Operator [12], in whose context the considered VESS would operate, implies several constraints to the bid. In particular, since the considered aggregate is composed of resources with a limited capacity, the only service that can be provided by the VESS is the balancing service.

Every bid done by the aggregate must be higher than 1 MW and last for at least two hours. The ASM follows the “pay as bid” criteria. Fig. 9 shows the average price over one year of the accepted upward and downward bids. In order to simplify the study, it has been assumed that all the bids are done at the prices in Fig. 9.

III. Control Strategy

Several challenges about the VESS management have to be faced [13]. Indeed, the BESSs have a limited capacity compared to other resources, such as the classical generators, that can provide service for an indefinite time. This requires the BSP to modify the control strategy used so far.

In particular, since the BESSs have a limited capacity, the scheduling of the BESS at time k must take into account the status of the BESS at time $k\text{-}1$.

The control strategy adopted for this study is based on a deterministic approach and does not require an optimization tool. It is a sequential algorithm that finds a suitable management of the VESS ensuring the self-consumption functionality for the next hours. The inputs of the algorithm are the VESS power and energy baseline, calculated as described in section II part B, the power offered, the average price of the bids and the technical and economic constraints. The output of the algorithm is the sequence of upward and downward bids. Based on the technical input of the VESS, the control strategy performs the following steps:

1. Evaluate the upward and downward margins (both in terms of power - Fig. 10 - and energy - Fig. 11) of the VESS over the day.

$$P_{flex_{up}} = \sum_{i=1}^{N} P_{MAX_i} - P_{BESS_i} \tag{4}$$

$$P_{flex_{down}} = -\sum_{i=1}^{N} P_{MAX_i} + P_{BESS_i} \tag{5}$$

$$E_{flex_{up}} = \sum_{i=1}^{N} E_{BESS_i} \quad (6)$$

$$E_{flex_{down}} = \sum_{i=1}^{N} E_{BESS_{MAX_i}} - P_{BESS_i} \quad (7)$$

2. The control strategy verifies if the upward power margin is greater than the threshold of power offered. If not, the control strategy goes to the point 3, otherwise evaluates the behaviour of the VESS energy in the next *T_ver* hours assuming it will provide the grid service.

2.1. If at the end of the two hours this value is negative (it means that the self-consumption of the user will not be ensured) the control strategy goes to the point 3, otherwise it verifies if the VESS has sufficient energy and power to provide the service in the next two hours. If yes, then the VESS will provide the upward service and the control strategy moves two hours afterward and goes back to the point 2. If not, the control strategy goes to the point 3.

3. The control strategy verifies if the downward power margin is greater (in module) than the threshold of power offered. If not, the control strategy goes to the point 4, otherwise evaluates the behaviour of the VESS energy in the next two hours assuming it will provide the grid service.

3.1. If at the end of the two hours this value is higher than the maximum VESS capacity (it means that the self-consumption of the user will not be ensured) the control strategy goes to the point 4, otherwise it verifies if the VESS has sufficient energy and power to provide the service in the next two hours. If yes, then the VESS will provide the downward service and the control strategy moves two hours afterward and goes back to the point 2. If not, the control strategy goes to the point 4.

4. The control strategy moves to the next quarter and comes back to the point 2.

IV. RESULTS

The control strategy has been implemented in MATLAB® and tested on the system under test described in Section II, assuming to offer 2 MW upwards or downwards. This section shows the results of the technical feasibility study.

In order to perform the analysis, the control strategy has been applied to calculate the VESS power profile and the amount of energy offered. The upward flexibility margin is generally higher in the afternoon, when the PV systems are injecting energy into the batteries, while the downward flexibility margin is higher in the early morning, when batteries are typically at a low state of charge. Fig. 10 and Fig. 11 show the theoretically available flexibility for a prototypical 24-hour period, which can also be understood as the volume of flexibility services available for bidding into the ASM from the VESS. The flexibility along the day is available only in the case the VESS has not yet provided any grid service. Indeed, if the VESS provides grid service, from that moment on the available VESS flexibility will change accordingly to the surplus of power. It is noted that even in the cloudy day, where the PV production is very low (even less than one equivalent operating hour) and the BESS does not work (after it is discharged), the flexibility margin of the VESS allows to provide grid services.

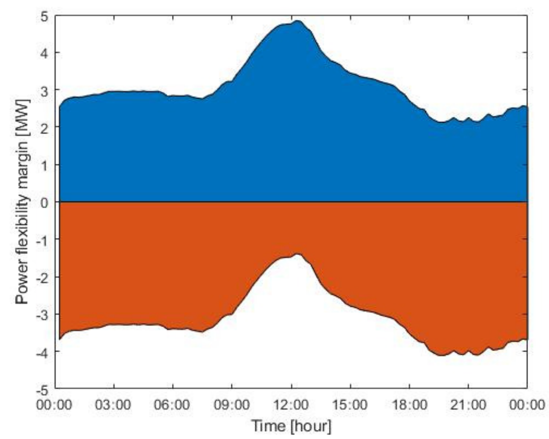

Fig. 10. Available power-based flexibility margin of the simulated VESS

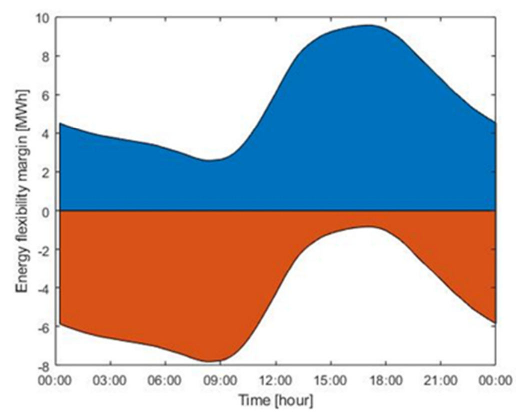

Fig. 11. Available energy-based flexibility margin of the simulated VESS

Fig. 12 shows the power profile of the VESS due to the services behind the meter (*Baseline P*) and bidding (*Offer P*). The yellow and purple lines are the upward and downward margins of the VESS in the case it provides grid services. Fig. 13 shows the comparison of the VESS energy profile with and without the grid services supply. Since the VESS energy flexibility is always positive, the self-consumption is guaranteed.

Several simulations were performed to evaluate the support to the grid by bidding the available flexibility of the VESS into the Italian ASM. The simulations differ in the number of guaranteed hours (*T_ver*) of self-consumption preserved, PV production, offered power and also in the probability that the bids are accepted. Fig. 14 shows the upward and downward daily energy provided by the VESS for grid services as function of the guaranteed hours of self-consumption for two values of offered power and assuming that all the bids are accepted. The VESS can provide up to 25 MWh for upward and 25 MWh for downward grid services per day. This amount decreases when the guaranteed hours of self-consumption increases (down to 10 MWh).

Moreover, there may be a chance that some offers will not be accepted; hence the benefits could be lower. Therefore, the energy provided for grid services shown in Fig. 14 are the maximum values of energy that the VESS can provide according to the control strategy proposed.

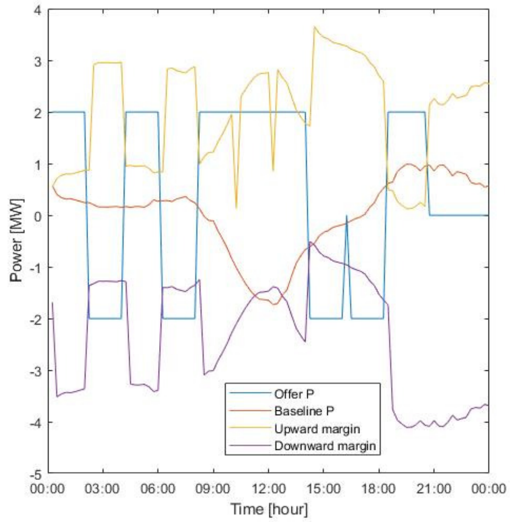

Fig. 12. Power profile of the VESS offering a grid service

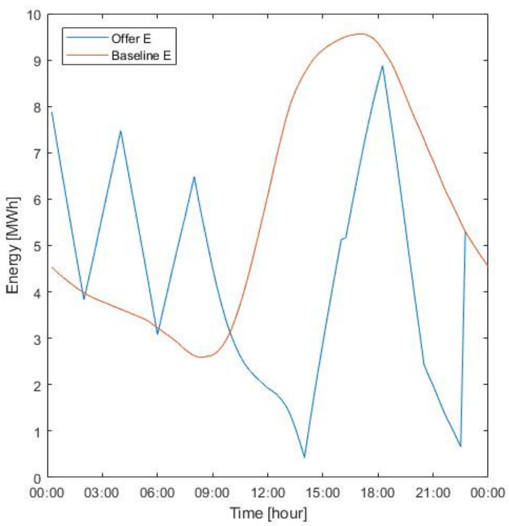

Fig. 13. Energy profile of the VESS offering a grid service

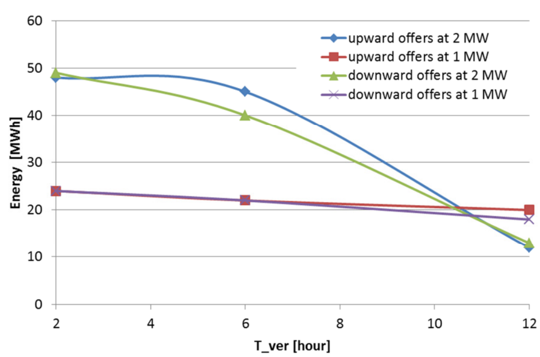

Fig. 14. Estimate of upward and downward daily energy provided by the VESS for grid services versus number of guaranteed hours of self-consumption for two values of offered power.

V. Conclusion

This paper aims to perform a technical feasibility study on a VESS composed of residential users with a PV and a BESS that can be controlled by an aggregator. A simple control strategy has been implemented and tested in simulation on a set of residential users in different scenario.

For each scenario the upward and downward flexibility margins, in terms of power and energy, have been calculated to evaluate if it is sufficient in order to provide grid services. Then a control strategy has been proposed and applied to the VESS in order to find out a suitable power profile that ensure the self-consumption functionality of each BESS. In the end the amount of energy provided and absorbed for grid services has been quantified.

The same analysis can be performed for each day of the year (with different load and PV production profiles) in order to have enough information to develop a complete business case.

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