BESS LOCATED IN PRIMARY SUBSTATION FOR RES INTEGRATION AND ANCILLARY SERVICES PROVISION

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ABSTRACT

In this paper a model for simulating provision of multiple services via Battery Energy Storage System (BESS) is presented. The results of several sets of simulations are proposed. Applications analysed are renewable energy source support and provision of frequency regulation via BESS. The approach proposed is designed with respect to many directions: the system operator perspective (accuracy and reliability of the service provision are the main goals); the economic viability perspective (highlighting capex, cash flows, return on investment); the technology perspective (i.e. evaluating the impact that different setpoints could have on the BESS state of health), via qualitative and quantitative analysis of the level of exploitation of the system. The final goal is to evaluate the feasibility in the provision of multiple services simultaneously.

INTRODUCTION

Managing the increasing quantity of Distribute Energy Resources (DERs), mainly non-programmable Renewable Energy Sources (RESs), results in a larger effort for power system in guaranteeing instant balance. Battery Energy Storage Systems (BESSs) can help this evolving system thank to their high ramping capability (MW/min) and strong reliability in setpoint tracking [1]. To increase the economics of the battery, the same device can be used to provide multiple services. A possible solution is depicted in this paper. The application proposed calls for a regulatory framework evolution [2], to exploit possibilities of BESS on networks with large presence of DERs [3].
The paper is organized as follows: the rest of *Introduction* describes the Italian regulatory framework as the benchmark for the study, presenting possible issues in performing mentioned applications; the section *Input data & Methodology* describes the data used and proposes a model for BESS operating following three different applications; chapter *Results* presents economic and performance outcomes of the simulation campaign; finally, *Conclusions* summarize the main findings.

RES-E support

A concrete possibility to mitigate the need for new grid services is to reduce the unpredictability of non-programmable renewable plants by combining a BESS capable of correcting injection to grid in real time so to coincide with the energy contracted programme on Day Ahead Market (DAM) + Infra day Market (IM). This can be achieved withdrawing energy in the event of a positive imbalance, or injecting it to the grid in the opposite case. The BESS supporting non-programmable RES can be integrated with the production unit (PU) or aggregated at a distribution network level. Aggregation could be managed by a Balancing Service Provider (BSP) or, in principle, a DSO that is able to monitor and control the flows at HV/MV interface. If the service is provided by the DSO, the balancing of production and load units would take place at the primary substation (PS) level, with actions that are in line with a nodal management of imbalances. Instead, BSP carries out balancing action on a zonal basis, with the TSO managing resources in real time.
In the case of nodal management of imbalances, also charges for Balance Responsible Parties (BRP) should be proposed at a nodal level. As of now, a *dual pricing* (DP) mechanism is in place to valorize imbalance charges in Italy at a zonal level [4]. This means that charges depend on the combination of zonal and PU imbalance.

Frequency regulation

BESS can support the system also by providing frequency regulation as an Ancillary Services Market (ASM) player. Primary Control Regulation (PCR) is the ancillary service aimed to contain frequency deviations caused by network imbalance. In Italy, the provision of this service is mandatory for conventional PUs. It is controlled by means of a symmetric and constant droop curve. Droop value is between 0.4 and 1.0 MW/Hz, depending on technology of the unit [5]. The remuneration of this service is not subject to market, but there are two constant energy-based values (€/MWh) yearly defined as revenue for upward and cost for downward reserve to be added each hour to DAM zonal price [6].
Secondary Control Regulation (SCR) is the service aimed to automatically restore nominal frequency. It is traded on Italian ASM with market sessions in blocks of four hours. Italian ASM is a pay-as-bid, with hourly energy-based prices. SCR is automatically regulated through a signal (*Segnale di Livello*) on a one-minute basis; power requested is a fraction of the symmetric regulating band associated to each PU [5].

INPUT DATA & METHODOLOGY

The methodology proposed consists in simulating BESS operations based on real data of year 2016. Operations of BESS include different combination of PV support and provision of ancillary services for frequency regulation.

A real-time SOC evolution model is used to simulate diverse scenarios. The model receives as input a power setpoint each loop representing grid-side demand; it returns the SOC variation related to power flowing in battery, after accounting for the efficiency of the system [7]. A State of Health (SOH) model developed in Politecnico di Milano [8] is used to compute battery lifetime as a function of average c-rate of operation. Replacement costs at the end of battery lifetime equal half of capex. C_{inv} of BESS is computed as follows.

$$C_{inv}[k€] = k_e * E_n[MWh] + k_p * \left(P_n[MW] - \frac{E_n[MWh]}{1\,h}\right) \quad (1)$$

where k_e is 400 k€/MWh, E_n is nominal energy of battery, k_p is 150 k€/MW, P_n is nominal power of battery. This formula comes from elaboration on report [9] and is used to take into account energy-to-power ratio (EPR = E_n/P_n) different from 1. Economics are computed using NPV and Profitability Index (PI = NPV/C_{inv}).

Business model adopted

The study case deals with a BESS located in a PS and owned by DSO, coping with the imbalance of PV systems underlying that PS and providing ancillary services (see **Figure 1**).

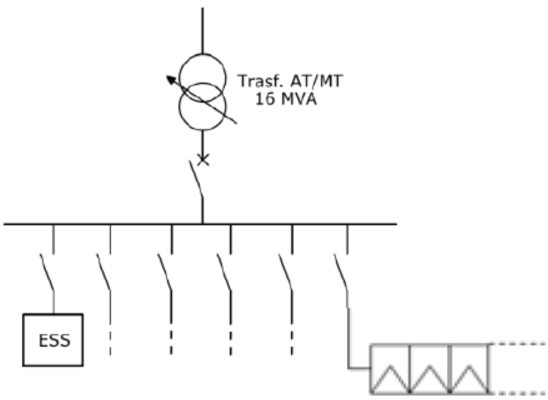

Figure 1. Principle scheme of the case study: PS underlying DERs equipped with a BESS

APPLICATION	PV support	Frequency regulation provision
1	✔	✘
2	✘	✔
1+2	✔	✔

Table 1. Applications summary

Netting of PV imbalance at PS is assumed to be in place. BESS is the unit receiving directly dispatching orders and participating to ASM. Revenues and charges are computed based on net metering of the services provided and on superposition of power setpoints. As of now, this configuration is not admitted by Italian regulatory framework, since no imbalance netting at PS is in place and DSO cannot work as BSP.

PV data

PV system analyzed is a bunch of PV units under the same PS in Sicily. Global nominal power is 2.8 MW. Data used include hourly energy injected (E_{real} in MWh) and imbalance with respect to injection forecast (E_{imb}). DP mechanism uses indicative zonal price (P_z, 60 €/MWh) and ASM marginal price for upward (P_{ASMupw}, 200 €/MWh) and downward (P_{ASMdwn}, 25€/MWh) reserve. Energy exchanges for SOC restoration occur on IM: prices are 50 €/MWh for purchasing and 40 €/MWh for selling.

Frequency and market-related data

Network frequency log at 1 Hz of sampling rate for year 2016 comes from 50Hertz website [10]. The regulating signal for SCR in Italy (*Segnale di livello*) on a one-minute basis comes from Italian TSO website [11]. Market prices for 2016 are used to characterize the market model included. Data of 2015 are used as a basis for bidding strategy [12]. Energy-based penalties are implemented for failure in respecting dispatching orders. Charges for failure are 50 €/MWh for PCR and 100 €/MWh for SCR.

Application 1: PV support

The tool proposed collects the input data and builds an hourly schedule for one year of operation. Data required are the injected energy, the imbalance (greater than 0 if real production is higher than forecast, and viceversa), the cost of imbalance (applying DP). For sizing the BESS, several simulations will test different (P_n, E_n) pairs. Since real data are used for PV, there are no degrees of freedom for sizing BESS capacity: BESS size will be consistent with PV one. A SOC evolution model simulates BESS operation. Each hour *i*, a constant power setpoint ($P_{req,PV,i}$ in MWh) is requested for providing PV support. The aim of the controlling strategy is minimizing the imbalance after BESS operation ($E_{imb,post}$) by respecting BESS limits. Therefore, $P_{req,PV,i}$ is defined as follows.

$$\begin{cases} P_{req,PV,i}[MW] = \min(-E_{imb}[MW], P_n) \;\; if\; E_{imb} < 0 \\ P_{req,PV,i}[MW] = -\min(E_{imb}[MW], P_n) \;\; if\; E_{imb} > 0 \end{cases} \quad (2)$$

SOC is updated every hour *i* according to $P_{req,PV,i}$. In detail, SOC evolution from hour *i* to *i+1* is described as follows.

$$\begin{cases} SOC_{i+1} = SOC_i \quad if\; P_{req,PV,i} = 0 \\ SOC_{i+1} = SOC_i - \frac{P_{req,PV,i}}{\eta_{dis} * EPR} \quad if\; P_{req,PV,i} > 0 \\ SOC_{i+1} = SOC_i + \frac{P_{req,PV,i} * \eta_{ch}}{EPR} \quad if\; P_{req,PV,i} < 0 \end{cases} \quad (3)$$

where η_{dis} and η_{ch} are fixed efficiencies (90%) of the BESS for charging and discharging phase and EPR is the energy-to-power ratio of the BESS. If SOC_{i+1} overpasses saturation limits, it is set exactly to saturation limits (0 or 100). Then, power actually provided ($P_{BESS4PV,i}$ in MWh) from BESS is computed. If no SOC saturation limits were hit, it is equal to $P_{req,PV,i}$. Otherwise, it is defined as follows.

$$\begin{cases} P_{BESS4PV,i} = (SOC_i - 0) * EPR * \eta_{dis} & if\ P_{req,PV,i} > 0 \\ P_{BESS4PV,i} = -(100 - SOC_i) * \frac{EPR}{\eta_{ch}} & if\ P_{req,PV,i} < 0 \end{cases} \quad (4)$$

$E_{imb,post}$ is equal to 0 only in the case no limits (on either SOC and power) are hit. Otherwise, it is computed as the difference between E_{imb} and energy provided ($P_{BESS4PV,i}$ in MWh).

SOC restoration is performed during night, when no imbalance is present since generation is always null. Transactions happen on IM, at prices mentioned before.

The tool returns revenue (DP charges avoided) and cost (IM transaction) streams, energy flows and estimated BESS lifetime. The DP mechanism used to compute imbalance fees is shown in **Table 2**.

	UNIT +	UNIT –
ZONE +	MIN (P_z, P_{ASMdwn})	P_z
ZONE -	P_z	MAX (P_z, P_{ASMupw})
What unit must do	***SELL***	***PURCHASE***

Table 2. Dual pricing mechanism

The entity of the fee is established based on the matching of zonal imbalance and unit imbalance. The penalization is in place if the zonal imbalance has same sign of unit imbalance (i.e. surplus of generation for both the zone and the unit, or lack of generation for both).

Application 2: provision of frequency regulation

Dynamics of frequency regulation impose to develop a tool with smaller timestep (i.e. 1 s) and higher level of detail. The model receives as inputs the network parameters mentioned at 1 Hz of sampling-rate. The model represents a BESS built up by a Li-ion battery and an inverter, both with variable efficiency depending on c-rate of operation. Details are provided in [8]. In each simulation, at each time step, the model receives the power setpoint grid side and defines SOC evolution based on the efficiency of the system as a function of the c-rate requested. The setpoints are tracked similarly to what already shown with (2), (3) and (4).

- Each loop, the power requested to BESS ($P_{req,FR}$) is the minimum between P_n and the power needed for provision of frequency regulation (P_{FR}).
- SOC_{i+1} is an update of SOC_i that takes in account the variable efficiency of the system (η_{BESS}), computed as in (5).

$$\eta_{BESS}(P_{FR}) = \eta_{inv}(P_{FR}) * \eta_{batt}(P_{FR}) \quad (5)$$

  where η_{inv} and η_{batt} are the inverter and battery efficiencies, both function of $P_{req,FR}$.
- If SOC gets to saturation, then power effectively flowing is rescaled to avoid limits overpass.

Even in this case, the amount of energy non-provided to grid generates penalties. Loss of Regulation (LOR, in MWh) is the amount of energy non-provided for services (due to SOC saturation or overpassing of P_n threshold). A penalty (€/MWh) is paid per unit of LOR.

Ancillary services layout

P_{FR} is expressed as follows.

$$P_{FR} = P_{PCR} + P_{SCRupw} + P_{SCRdwn} \quad (6)$$

Services modeled are PCR and SCR, both upward and downward mode. A controller translates inputs in power setpoints. The provision algorithm follows Italian regulatory framework illustrated above. Nevertheless, some variations are present to adapt ASM to BESS as a player. These modifications have been considered reasonable since they are among the likely evolutions of ASM, based on recent pilot projects [13].

PCR produces a setpoint per second translating frequency deviation into power using droop curve. With respect to Italian regulatory framework, droop value is 21.3 times P_n MW/Hz. This choice aims at using a large amount of power to regulate, limiting risks to overpass P_n with global P_{FR}. Quantitative analysis is proposed in *Results*, showing distribution function of P_{FR}. Prices are fixed at 80 €/MWh for upward reserve and 20 €/MWh for downward.

SCR produces a setpoint per second based on *Segnale di Livello* and on market outcome. SCR differs from Italian framework since provisions of upward and downward reserves are independent. This allows to manage SCR regulating band offered for performing passive SOC restoration. Regulating bands offered in market session for upward and downward reserves are computed as follows.

$$\begin{cases} P_{SCRupw} \propto \frac{P_n * EPR}{t_{mkt}} * \frac{(SOC(t_{in}) - 0) - \Delta SOC_{PCRupw,est}}{100} \\ P_{SCRdwn} \propto -\frac{P_n * EPR}{t_{mkt}} * \frac{(100 - SOC(t_{in})) - \Delta SOC_{PCRdwn,est}}{100} \end{cases} \quad (7)$$

where t_{mkt} is 4 hours of traded period; $SOC(t_{in})$ is SOC value when market session happens; $\Delta SOC_{PCR,est}$ is an estimation of the SOC variation in the traded period in both upward and downward directions, obtained via a statistical study. Indeed, only a passive SOC restoration strategy is in place in this application. Because of this, when SOC is close to 100% and a market session approaches, a larger upward regulating band is offered on the market; on the other side, small or no downward regulating band is offered. In the SCR market model, price offered is based on market outcomes of 2015, added by a price signal (greater or lower than 0) increasing the probability of being selected in the convenient direction.

Application 1+2: Multiservice

PV support is acting only in daytime. To increase the economics of BESS, the simultaneous PV support and ancillary services provision is proposed.
Even in this case the power setpoint requested from grid (P_{multi}) is sent at a 1-second sampling rate. It is the result of superposition of PCR, SCR and PV support, rescaled on a 1-second basis.

$$P_{multi} = P_{PCR} + P_{SCRupw} + P_{SCRdwn} + P_{PV} \tag{8}$$

where P_{PV} is equal to E_{imb} in MW. Offered band of SCR depends, each 4 hours, on expected SOC variation for PCR and PV support. A statistical study on PV imbalances permits to define the expected SOC variation per hour.

RESULTS

Results of simulations for each applicative case are reported in **Table 4** in terms of LOR and economics.
Three different battery designs are proposed for each application. Each design is defined as a pair (P_n, E_n), see **Table 3**.

Design	E_n	P_n
A	2	1
B	4	2
C	6	3
D	1	1
E	2	2
F	6	2

Table 3. Designs summary

As per **Table 4**, design B (2 MW, 4 MWh) is constantly proposed for each application. The other designs have been selected according to the peculiar characteristics of each application. A larger EPR (2-3 h) is more suitable for application 1 (PV support) since it is an energy-intensive application. A smaller EPR (1-2 h) allows to reduce capex for Application 2 (frequency regulation provision), a power-intensive application. In general, application 2 assures higher net cash flows than application 1. Yearly cash flow for application 2 (71.70 k€) almost doubles the one guaranteed by application 1 (46.45 k€) (design B). This is because of a better exploitation of the limited energy reservoir of BESS. PV support often requires consecutive withdrawn or injection of energy for many hours, leading to SOC saturation. This obliges BESS to stay unavailable for long periods.
ASM participation often requests power in both directions in a short period. This prevents SOC from saturating and increases energy flows.
Moreover, as already described, application 1 requires active SOC restoration, introducing a further cost stream. In application 2 and 1+2, the independent provision of upward and downward reserve for SCR works as a passive SOC restoration. This allows the BESS to restore SOC at more convenient costs. Average simulated prices on SCR market are 105 €/MWh for upward reserve and 13€/MWh for downward (design B, application 1+2).
Energy flows are maximized in application 1+2. Since the largest part of investment is capex, the possibility of trading more energy increases the economics. The only positive NPVs of the study are reached for this application.
LOR increases with smaller size. This is explained by the larger weight of PV support on total energy requested within application 1+2, leading to early saturation and unavailability of BESS for frequency regulation. In fact, PV system size is fixed *a priori*: there is no advantage in performing application 1+2 in case of BESS downsized with respect to PV due to high LOR. Since in this study LOR has been assumed feasible if below 5%, smaller design parameters have not been considered.
In application 2, performances only depend on EPR. Design D and design E of ASM application show that both PI and LOR do not change if providing same services with (1 MW, 1 MWh) and (2 MW, 2 MWh) settings. Lower EPR (1 – 2 hours) guarantees higher economics in both application 2 and 1+2.
Maximum power requested to battery is only 5.8% of time greater than P_n (design A, application 1+2, see **Figure 2**). In those cases, power requested is reduced exactly to P_n, usually curtailing PV support, less penalized.

Design	Application	CAPEX [k€]	Yearly cash flow [k€]	NPV (20 years) [k€]	PI (20 years) [k€]	LOR [%]	Average c-rate [C]
A	1	650	30.41	-413	-0.64	-	0.16
B	1	1300	46.45	-1019	-0.78	-	0.10
C	1	1650	55.22	-1344	-0.81	-	0.07
D	2	400	29.35	-122	-0.31	3.50	0.21
E	2	800	58.70	-244	-0.31	3.50	0.21
B	2	1300	71.70	-679	-0.52	2.95	0.14
A	1+2	650	77.06	215	0.33	3.87	0.16
B	1+2	1300	122.59	6	0.00	2.79	0.13
F	1+2	1800	136.88	-435	-0.24	2.09	0.10

Table 4. Simulations summary

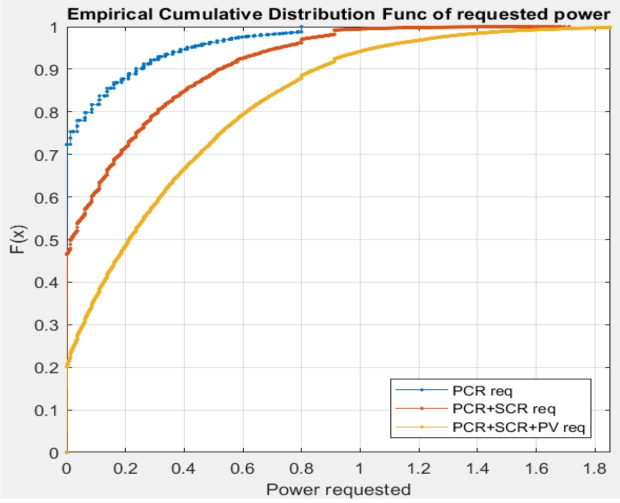

Figure 2. CDF of requested power (absolute value)

The superposition advantage

Superposition of multiple setpoints related to different services proves helpful in improving economics and providing SOC restoration with a passive mechanism. This is because the control strategy aims at having power setpoints requested by PCR, SCR and PV support with opposite sign. In **Figure 3** an example of advantageous superposition of power setpoints is shown. In the morning of May 10, 2016, the following situation took place: PV systems underlying to PS had global negative imbalance (injection lower than forecasted); *Segnale di Livello*, regulating SCR provision in Italy, was for some time asking to generators downward reserve.
This allowed the BESS (design B) to provide simultaneously positive power (discharge) for PV support and negative power (charge) for SCR provision (BESS was selected in the market). This reflected in a c-rate oscillating for some hours between positive and negative values. preventing SOC from saturation for 5 hours.
Generally, 36% of the time in which SCR is acting, its power demand has opposite sign with respect to PV support (only in 20% of time the setpoint signs are equal).

CONCLUSIONS

BESS are one of the most promising resources for an effective management of electric grids in scenarios characterized by a strong penetration of renewables. This paper investigates the possibility to deploy a storage facility in the Primary Substation and to control it in order to fix imbalances of distributed PV resources.
Moreover, in order to improve BESS economic viability, a multi-service control has been investigated. In particular, since BESS has limited energy reservoir, power intensive services are supposed to be more profitable than energy intensive, consequently frequency control has been coupled with PV support.
Numerical simulations on real life data showed technical and economical profitability of the approach proposed; the regulatory framework evolution has to be analyzed.

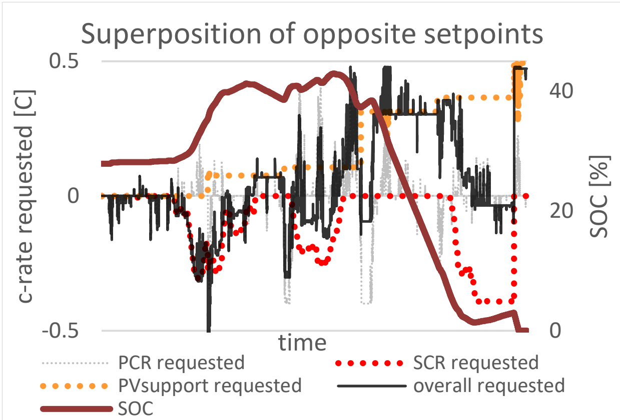

Figure 3. Log of c-rates on 2016-05-10 (5AM-10AM)

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