Battery energy storage system for primary control reserve and energy arbitrage

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The transition to high penetration of renewable energy sources brings about problems related to the se-curity and reliability of the electric power system. For this reason, EU countries are considering extend-ing participation in the provision of ancillary services to distributed generators. Grid-connected Battery Energy Storage Systems (BESS) are a promising technology for enabling this transition. Besides the re-search efforts to regulate and integrate BESS into the existing power systems, several studies have intro-duced improvements in BESS control for ancillary services provision. In this paper, attention is focused on primary control reserve (PCR). An introduction to the suitability of using BESS for PCR is followed by a literature review on BESS control strategies and controller models. Then the paper presents a model to investigate methods to increase BESS potential in providing PCR. The model is based on two different operating options: (i) *variable-droop*, meaning the droop-control is allowed to vary in time in order to avoid state of charge saturations and guarantee PCR availability; (ii) *energy arbitrage*, meaning that the battery is charged and discharged when economically favourable. A 1MW/1MWh BESS was simulated in MATLAB R Simulink R by implementing the two operating options via two fuzzy logic controllers that determine the droop and the arbitrage set points. The simulations rely on real metred data inputs (i.e. fre-quency and electricity prices) and demonstrate that both options improve BESS operations. Specifically, a study on the Italian case was applied to evaluate the feasibility of these applications in a real life scenario.

1. The general framework of battery energy storage systems for ancillary services

Power systems currently undergo considerable change in op-erating requirements because of an increasing amount of dis-continuous distributed generation (DG), mainly renewable energy sources for electricity (RES-E). The integration of RES-E into power system grids affects optimum power flow, power quality, volt-age/ frequency control and system economics. RES-E traditionally have priority in load dispatching because their production must be exploited when available. This brings about a reduction of available resources necessary for the safe and reliable operation of an inter-connected power system. Moreover, RES-E plants usually connect to the grid via a static converter. Thus, the inertia level of the whole power system reduces, causing the frequency to drop faster after an outage. For this reason, the Transmission System Operators for Electricity (ENTSO-E), with key legal mandates from the European Agency for the Cooperation of Energy Regulators (ACER), are con-sidering extending participation in ancillary services provision to DGs [1–3].

After the European energy sector unbundling process, ancillary services include both mandatory services and others subjected to market-based competition. They allow the local TSO to control fre-quency and stability of the system, voltage along the transmission network, loading of the power lines and to restart the system in certain circumstances. The primary control reserve (PCR) is one of these services. In Italy, PCR is a mandatory service every tra-ditional power plant (not RES-E), with rated active power greater than 10 MW, has to guarantee [4].

Nevertheless, technical issues arise when considering the suitability of DGs equipment to function effectively as part of the electricity system [5,6]. This topic is part of the theme about the evolution of existing electrical systems towards the smart-grid paradigm [7]. Taking Italy as an example, regulations have been introduced in order to set DGs duties for ensuring the security and stability of the network [8–10].

Actually, RES-E plants have to deal with the unpredictable nature of the primary resources; therefore, stringent regulations

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Nomenclature

Acronyms used in the text

BESS	Battery Energy Storage System
DG	Distributed Generation
EPR	Energy–Power Ratio
FC1	Fuzzy logic Controller number 1
FC2	Fuzzy logic Controller number 2
GoL	Gain or Losses
LoR	Loss of Regulation
MF	Membership Function
MPC	Model Predictive Control
RES-E	Renewable Energy Sources for Electricity
RoPCR	Revenue of PCR
PCR	Primary Control Reserve
PUN	Prezzo Unico Nazionale (i.e. day-ahead national energy price)
ROCOF	Rate Of Change Of Frequency
SOC	State Of Charge
TSO	Transmission System Operator

Symbols

c_p	Cost of penalties
f	Frequency
r_{ARB}	Revenues or losses deriving from energy arbitrage
P_n	BESS nominal power
p_{EE}	Market price of electricity
η_{CH}	Battery charge efficiency
η_{DISCH}	Battery discharge efficiency
p	Profit
P_B	Battery power
P_{PCR}	Power for PCR
P_{SET}	Power set-point from the regulation model
P_{ARB}	Power for energy arbitrage

can strongly affect their operations and profits. For instance, asking RES-E plants to contribute to PCR or to sustain voltage dips means forcing them to limit their active power injection which is an incentive for them (e.g. Green certificates, feed-in premium). Hence, if the service remuneration from the ancillary service market is not enough to cover the losses, the profitability of these systems will decrease.

Battery energy storage systems (BESSs) are the most promising technology to enable RES-E to meet this challenge. BESSs can pro-vide high power capability in relation to energy capacity. They are therefore suited to a variety of grid uses, such as PCR, secondary control reserve, voltage regulation, peak shaving, load shifting and energy trading [11]. Generally, they can operate both as individ-ual units or associated with RES-E plants. In the second option, the presence of BESS can make the ancillary services market more at-tractive for the RES-E owner. Indeed BESSs allow a more flexible use of the RES-E plant without limiting the exploitation of the pri-mary source. Moreover, in a future scenario with a higher share of RES, it may be necessary to increase the ramp rates of units provid-ing PCR. Such fast ramp rates could be provided by many storage technologies including BESSs.

For these reasons, in a few countries BESSs already have the opportunity to offer ancillary services. For instance in Germany, according to the Energy Act four different entities are responsible for PCR [12]. Each of the four TSOs, namely 50 Hz, Amprion, Ten-neT and Transnet BW operates a separate control area in which the system balance needs to be guaranteed by the operation and coordination of different control mechanisms. Therefore, within the German legal framework, PCR is a task undertaken by each TSO for each grid user within its control area as part of its responsibil-ities, with the ensuing cost charged to the users [13].

Moreover, the German regulation on access to power system defines precise requirements for the market-based procurement of balancing services [14]. Control reserves and control energy have to be procured via a common internet platform through an anony-mous tendering process, and successively they have to be deployed according to the merit-order list resulting from this tendering pro-cess [15]. Actually, suppliers are paid a fixed price per MW of ‘‘standby’’ reserve for the whole tendering period. Therefore, since BESSs provide high power capability in relation to energy capac-ity, services generating profits based on power is a real oppor-tunity for the BESS owner. Additionally, capacity constraints are normally not stringent thereby allowing economic operation of BESS (investment costs are proportional to capacity) [16].

However, the provision of ancillary services will be allowed as long as BESSs fulfil technical and commercial requirements set by the TSO. The most challenging requirement for BESS is service continuity. Indeed, even if we assume a zero-mean ancillary service signal is supposed, the battery will constantly decrease in the SOC level due to the internal efficiency that affects charge and discharge processes. In the end, the battery will reach its capacity limits cutting the service provision and incurring penalties that reduce the profits.

In this paper, we investigate methods to improve BESS potential in providing PCR in interconnected power systems. Our aim is to identify control strategies able to maximize the availability and profitability of this use. Specifically, we explore two different operating options (multi-services BESS) and we want to verify their capability in recovering the SOC:

1. *Variable-droop*, meaning that we let the droop-control vary in time to better exploit the fast response capability of a battery system. Indeed, the BESSs interface with the grid normally consists of static inverters, which are characterized by a response time in the range of hundreds of milliseconds. This is much faster than what is required from traditional power plants for PCR provision (e.g. in the current frequency control framework of ENTSO-E, full regulation power is required within 30 s). Hence, in our model, the droop is not fixed but changes in time in order to avoid SOC saturations and to guarantee PCR availability.
2. *Energy arbitrage*, meaning that the BESS owner will gain from market opportunity. In particular, the BESS will be charged and discharged when economically favourable.

The paper is organized in five sections: Section 2 provides a literature review on BESS control strategies and controller mod-els; Section 3 describes the approach used to model the BESS for PCR service, which includes (i) a battery model able to cal-culate and update the battery state of charge (SOC), (ii) a BESS droop-control model with variable-droop and energy arbitrage modes of operations, (iii) two fuzzy logic controllers that set the droop and the arbitrage set points; Section 4 introduces the MATLAB ® Simulink ® BESS model that implements the proposed approach; finally, Section 5 presents the main findings of our simulations (i) the detailed analyses of BESS operations using variable-droop and energy arbitrage options under real metred inputs of frequency and electric market prices (ii) a sensitivity analysis on BESS round-trip efficiency to verify the complete BESS discharge (iii) a comparison of different control strategies using variable-droop option (iv) a final analysis of BESS operations in multi-services long-term configuration in order to prove the effec-tiveness and convenience of this application.

2. Literature review

Several studies and real applications in the past have demon-strated the effectiveness of BESS when used for balancing services in island power systems. In [17] the authors describe a pioneer-ing project for a battery that provides load–frequency control in the isolated city grid of West-Berlin. They found it technically and economically favourable to build a base-load plant for electric-ity production coupled to a large BESS for instantaneous reserve capacity, rather than building a load-following power plant. In [18] the authors quantify the effect of a 30 MW/25 MWh BESS on the frequency regulation in the Israeli isolated power system. They simulate the BESS by mean of a first-order function model assum-ing a maximum load of disturbances of 30 MW and a ROCOF of 10 MW/s. They show a clear reduction in the frequency deviations until the battery was fully discharged.

Moving from isolated networks to wider and regulated power systems, several opportunities of PCR are well discussed in literature. Nevertheless, no real life tests are today available in order to validate the effectiveness of the approach. For instance, PCR from an electric vehicle is one of the most promising [19,20], but there are no real life tests/figures to validate the effectiveness of the approach (e.g. one possible critical aspect is ageing effects driven by PCR service on e.car batteries and, consequently, the effect on e.mobility economics).

A hypothetical BESS for PCR would firstly have to respect all the technical constraints required by TSOs and then compete econom-ically with traditional power plants in ancillary services markets. Therefore, focusing on PCR, appropriate SOC control strategies are needed in order to assure service continuity and competitiveness. In the literature we can find [21–29]:

- *Scheduled strategies*: which define a pre-defined number of charging periods (e.g. [17]).
- *Dead-band strategies*: which propose to charge or discharge the battery by changing the BESS set point only when the grid frequency is within the dead-band. In [23] the authors use fixed SOC limits in order to (i) prevent overcharge condition and the consequent use of dissipation resistors, (ii) anticipate the charge phase. Additionally, they allow selling relatively small amount of energy on the electric market to stay within SOC limits. In [24] an adjustable SOC limit is proposed by following the expected frequency profile based on load forecasting and power production planning.
- *Dynamic strategies*: these strategies force the frequency in-put signal to be zero-mean by introducing set-point adjust-ments. The assumption is that TSOs generally allow power plants to make some changes in their schedule. It is then pro-posed to enable storage systems to add a time-dependent off-set to the frequency control signal in order to promote charging and discharging processes that keep the SOC within acceptable levels. The adjustment of the working point has to be consider-ably slower than the associated service. BESS would help com-pensate fast components of supply–demand mismatch, while passing slow components to slower units. In [25] the authors propose adjustments when the BESS reaches specific SOC levels. The offset variation is slow enough for slower plants to follow and it has to stay flat for a certain period between two ramps of different signs. In [26] they propose a similar approach but the power set-point is based on a moving average of the previous period. They can control the ramp rate of the offset by increasing or decreasing the averaging period. The calculation takes into account also losses during charging and discharging processes;
- *Model Predictive Control (MPC) based strategies*: used since the 1980s, in recent years they have entered the power system balancing models [27]. By relying on dynamic models of the processes, they allow the current time-step to be optimized, while considering future time-step. Differently from PID con-trollers, MPC has the ability to anticipate future events and can take control actions accordingly. In [28] the authors present a real-time optimal control scheme used to control batteries from plug-in hybrid electric vehicle in the provision of PCR. An MPC algorithm is able to manage and allocate control reserve power efficiently, taking into account BESS constraints such as SOC limits, ramp capabilities, power/ capacity limits. In [29] a linear dynamic model is proposed to approximate the operation of a BESS for PCR application. The proposed model consists of a con-trol system model, MPC-based controller, and a frequency pre-dictor. The authors achieve an optimal operation to prolong the lifetime of batteries and optimize the cost of BESS.

Some of these strategies have already been analysed in real case studies. In [30] the authors present 1 MW/0.58 MWh BESS applica-tion able to work in 3 different configurations: MV direct coupling, LV coupling with load support, and island mode operation. They claim to use a dynamic recharge strategy that uses frequency mea-surements and droop-control directly implemented in the power conversion system. The presented BESS passed all prequalification requirements posed by the TSO for the provision of PCR (included minimum ramp rate and reaction time requirement). In [31] the simulation results of different BESSs for PCR are presented. The authors simulate BESS operation using dead-band strategies with unlimited capacity, limited capacity and with or without SOC con-trol. Then they carry out a cost–benefit analysis comparing the economic returns in the Italian context. They conclude that remu-neration based on control power instead of energy is necessary to make the business profitable.

Controller models are a further field of study under develop-ment. BESSs operating behaviour differs significantly from that of a traditional power source, so different control models are needed. In the past, a number of controller's solutions were proposed to achieve PCR [32]. The most widely employed is the conventional proportional integral controller (PI). Fuzzy logics and artificial neu-ral networks have been successfully applied to the PCR problem with promising results [33,34]. In particular fuzzy logic has drawn attention given the huge number of possible uses in electric power systems [35]. Fuzzy logic is a rule-based approach to decision mak-ing, which has a number of advantages: (i) it is not so sensitive to the variation of system structure, parameters and operation points,(ii) it is easy to design and implement, (iii) it allows expressing knowledge with subjective concept. However, to achieve a satis-factory tuning of the method's parameters, the designer's experi-ence is necessary. In [36] the authors present the design of a fuzzy logic PCR controller for a two-area interconnected power system. In particular, they propose a new algorithm for the membership functions (MFs) definition in order to avoid a trial and error ap-proach to proceed. In [37] the authors propose a new design of a Sugeno-based fuzzy logic controller in RES-E (PV) + BESS power plants. Their aim is to stabilize the frequency of a multi-area inter-connected power system. They use frequency deviations and solar irradiation as controller input signals to command the BESS output power. Finally, in [38] the authors propose a fuzzy logic controller to balance SOC levels of distributed BESSs in AC micro-grids. They try to obtain a faster recharging of those BESSs with the lowest SOC. By summarizing status information through fuzzy logics and ad-justing the droop coefficient accordingly, they obtain good storage performances with equalized SOC levels.

3. Proposed BESS model for ancillary services

Adopting the Italian power systems as the targeted market, this paper evaluates a BESS model capable of providing multi-services regulation, evaluating also the economic impact of the application.

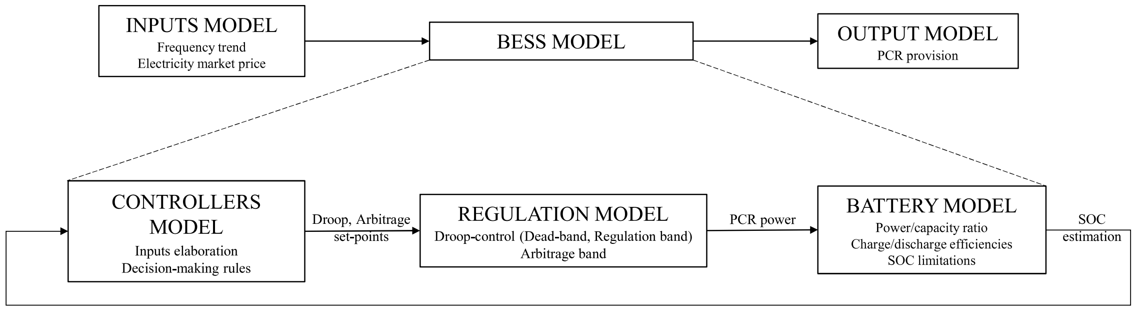


Fig. 1. BESS model and parameters.

Table 1
BESS model structure.

Sub-model	Name	Description
1	*Battery model*	Computes and updates the SOC
2	*Regulation model*	Defines the power set point according to PCR requirements
3	*Controllers' model*	Decides the working strategies according to external inputs

We neglect I/O models and their mutual effects (i.e. the effect of the BESS power injections on the system frequency), but we take real metred profiles of grid frequency and electricity prices. These inputs are imposed on the BESS model and different control logics are tested by varying the battery parameters. The BESS model is divided into three sub-models (Table 1 and Fig. 1).

The specific hypotheses adopted in the BESS model are:

- *Field of application*: the model is applied to BESS in individual configuration, but it can be extended in the case of BESS supporting RES-E power production.
- *Technical assumption*: when BESS for the PCR is compared with traditional power sources, there are three important differences that need dealing with:
  1. Since BESSs connect to the grid through interface convert-ers the resulting benefits of their fast response time can be exploited. We considered modifications to the traditional droop-control law, specifically in the droop that can vary ac-cording to specific logics (i.e. variable-droop).
  2. Differently from traditional power plants, the regulation-band is not fixed to a percentage of the rated power, but it could be defined in relation to the specific application the BESS is installed for. For instance, if in an individual BESS con-figuration, we can use all the rated power for the PCR; if in BESS + RES-E configuration we can use only a fraction for the PCR and the remaining part as energy buffer.
  3. BESS charging and discharging processes are not ideal. In our model, we deal also with internal efficiency by using proper parameters.
- *Economic assumption*: in Italy remuneration of PCR has been defined by the Italian Energy Authority (AEEGSI) in a specific resolution [39]. This resolution is not devoted to create a PCR market mechanism, vice versa the goal is to identify adequate reimbursement mechanism for PCR regulation from traditional power plants (in particular, an advanced metre is required in order to measure properly the contribution of each generation unit to the PCR service [40]). Consequently, we chose to adopt different hypothesis (i.e. not

to refer to the current Italian scenario), but at the same time we chose to keep the paper at a general level (i.e. not to limit it to a specific market mechanism already in place: in the authors' opinion such market structures are going to quickly change driven to relevant electric grid evolution caused by renewables growth). Actually, an economic gain for the PCR service has been introduced as ''Revenue of PCR'' (RoPCR), supposing it to be proportional to the PCR regulation band provided by the BESS. This model is similar to the ancillary market structure in place in Germany (today's discussions in Italy adopt the German ancillary services market as a term of reference). Moreover, in the authors' opinion, a market structure based on the regulation-band provided by the player is considered to be a simple, effective and transparent option for the PCR service.

In our simulations, we compare different control strategies assuming that the PCR regulation-band (power) provided by the BESS remains fixed (in variable-droop scenarios the minimum regulation-band, i.e. the maximum droop allowed, has been adopted to define the RoPCR). Consequently, the RoPCR remain constant. Nevertheless, we added also Gain of Losses (GoL) deriving from the difference between:

- *Extra-revenues or losses* from energy arbitrage. We valorized the energy bought at the current electricity prices.
- *Penalties* for not having provided the PCR. In this case, we valorized the energy not regulated at the current electricity prices. This regards two cases:
  - The battery is fully discharged when it has to inject power. In fact, theoretically but not practically speaking, one could buy energy from the grid to be used for the PCR.
  - The battery is fully charged when it has to withdraw power. In this case, the energy required to perform the PCR must be bought and dissipated on emergency resistors [23].

The energy stored in the BESS at the end of each simulation was calculated. With respect to the hypothesis adopted in the pa-per, this energy could lead to an economic gain if used for arbi-trage. Nevertheless, the quantification of this economic value is not deterministic according to the energy price values. Similarly, LoR (Loss of Regulation, i.e. failure to provide the PCR service, typically due to BESS saturation) could lead to economic penalties accord-ing to the ancillary service market in place. In the paper, in order to keep the discussion at a general level, LoR has been quantified as percentage of the expected PCR energy.

As depicted in Table 1 the proposed model is classified with re-spect to three sub-models. In the following, a detailed description of each one of them is reported.

3.1. The battery model

For the purposes of our analyses, an ideal battery model has been employed in order to be independent of any particular tech-nology. The model considers a steady-state operation of the battery since it computes the amount of energy that flows through the bat-tery and updates the change in the battery state of charge over a given time step [41–43]. Aspects such as lifetime degradation, in-fluence of temperature variations on performances, variability of BESS capacity according to operating current, and specific electri-cal circuitry are not considered [44–46].

Specifically, the battery model receives the power set point ΔP_{SET} (in per unit of the nominal power) from the regulation model and gives the updated battery SOC as output. The model computes the real power ΔP_B required from or injected to the battery (generators convention) as follows:

$$\Delta \dot{P}_B = \begin{cases} \eta_{CH} \Delta \dot{P}_{SET}, & \Delta \dot{P}_{SET} < 0 \\ \Delta \dot{P}_{SET} / \eta_{DISCH}, & \Delta \dot{P}_{SET} \geqslant 0 \end{cases} \quad (1)$$

where η_{CH} and η_{DISCH} are respectively the BESS charge and dis-charge efficiencies. Note that the BESS output is computed in terms of delta. This, as stated in Section 3, means that a fraction of the BESS available capacity is allocated for the regulation while the re-maining part could be used for other purposes (energy buffer, etc.).

Then, the SOC variation at each time-step is computed as follows:

$$\Delta SOC = \frac{\int_t^{t+1} \Delta \dot{P}_B dt}{EPR} \quad (2)$$

where EPR is the BESS energy–power ratio. Note that each calcu-lation is in per unit of the generator nominal power. Therefore, the model is scalable to the specific market conditions (current or prospective) or application context.

3.2. The regulation model

The purpose of the PCR is to maintain the power balance on the electric network, ensuring that the sum of the electric power injected by all the power generators is equal to the electric power asked by the loads. Power generators must follow their specific droop-control law. Traditionally, the droop-control differentiates among droop, regulation-band and dead-band:

- *The droop*: this is the slope of the curve. It describes the capacity of the power generator to act slowly rather than faster to a change of frequency. The definition is given by:

$$\sigma = -\frac{\frac{\Delta f}{50}}{\frac{\Delta P}{P_n}} \times 100 \quad (3)$$

  where the frequency variation Δf, in per unit of the nominal value of 50 Hz, is divided by the variation of the electrical power ΔP, measured in stable working condition and in per unit of the nominal power of the generator P_n. In Italy, a traditional power generator must theoretically provide the capability to operate with any degree of droop between 2% and 8%. In practice, the PCR service is shared among all the power plants according to their predefined droop values. The power generator with the smallest droop will react with the biggest power regulation margin while the power generator with the biggest droop with the smallest power regulation margin. The requested performances are coded by Terna S.p.A. in the Section A-15 of the Italian Grid-Code [4].

- *The regulation-band*: this is the maximum upward or downward power that the generator must make available when the frequency deviation exceeds a defined threshold. In Italy, the regulation-band is about ±1.5% of the nominal power.
- *The dead-band*: this is a small band around the nominal frequency (in Italy at ±20 mHz), in which no power needs to be provided in order to preserve the power plant apparatus.

In our regulation model, a non-conventional droop-control law with variable-droop mode of operation has been adopted. Indeed, we move from a fixed-droop approach to a variable-droop ap-proach in order to bring benefits to both the electric power system and BESS owner. Specifically, the proposed variable-droop mode exploits at maximum the fast response capability of the BESS when SOC is in good state (thus helping effectively the electric power sys-tems), while works at minimum when SOC moves towards satura-tion (thus protecting the owner's interests).

Moreover, the power set point for PCR (from the droop-control) is summed to the one for energy arbitrage:

$$\Delta \dot{P}_{SET} = \Delta \dot{P}_{PCR} + \Delta \dot{P}_{ARB}. \quad (4)$$

The chosen droop range takes inspiration from the Italian Grid-Code which states that DGs droop must be set to a fixed value between 2% and 5% [8]. We decided to respect the same limits also in case of PCR provision form BESS. Therefore, assuming a *regulation-band* of 0.25 in per unit of the BESS nominal power and keeping the frequency saturation limits constant, the droop-range [0.12%–0.3%] has been computed from Eq. (3).

The general idea is to let the BESS exploit all the possible droops with respect to a specific control strategy set up by the controllers. According to our purposes, if the battery is about to reach the minimum allowable SOC and the grid frequency is under 50 Hz, we would like to provide as little power as possible (saving SOC) by keeping the droop to the maximum value. In the same way, if the grid frequency is above 50 Hz, it is advisable to change the droop to the minimum in order to charge the battery as much as possible, while providing PCR. In practice, once the controller has chosen the most suitable droop value given the inputs, the ΔP_{PCR} is computed following Eq. (3).

Additionally, energy arbitrage is adopted to prevent low battery SOC by charging during low electricity price periods and discharging when the prices are high. For example, if the SOC is at the minimum allowable value and the price of electricity is low, it is advisable that the controllers urge to charge the battery to the maximum possible. In fact, we have introduced an *arbitrage-band* that works like a vertical translation of the whole droop-control curve. The controller will exploit this band to set the most suitable value of ΔP_{ARB}.

Fig. 2 shows the regulation curve made by the combination of a regulation-band (linked to the PCR service) and an arbitrage-band (linked to the energy arbitrage operation). By the composition of the two bands, an *overall active-band* can be defined among which the controllers can range to exploit the BESS characteristics. In the figure, the overall active-band is 0.35 per unit of the nominal BESS power (0.25 for PCR and 0.1 for energy arbitrage).

3.3. The controllers' model

The controllers' model is based on fuzzy logic since it allows expressing knowledge using higher level of abstraction originating from our knowledge and experience. Two fuzzy logic controllers were built:

- *Fuzzy logic controller* 1 (FC1) defines the droop according to the current SOC and the grid frequency deviation from the nominal value of 50 Hz.
- *Fuzzy logic controller* 2 (FC2) defines the arbitrage set point according to current SOC and electricity market price deviation from the yearly average price. Note that the set-point change is made only if the price deviation is ±20% of reference price. This is done to avoid purchasing or selling electricity when it is not economically convenient.

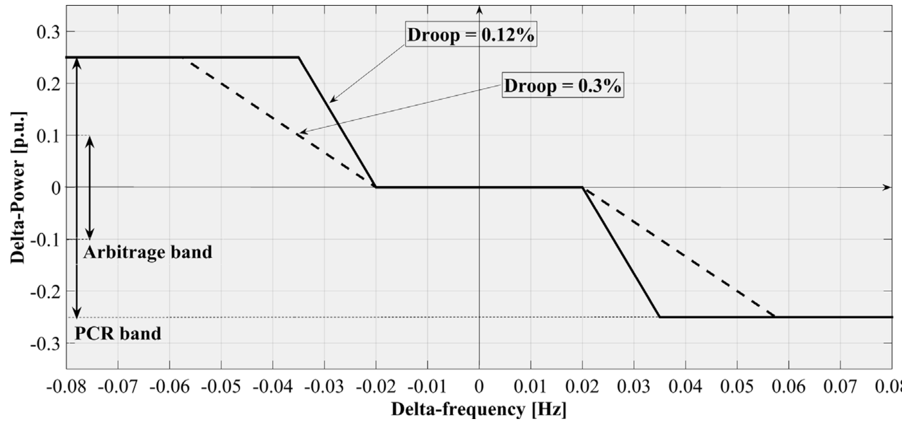


Fig. 2. Regulation curve.

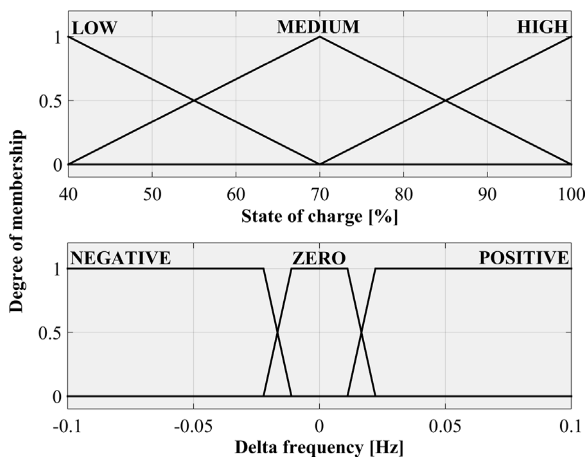


Fig. 3. FC1: Fuzzy sets of the inputs.

Note that the two controllers act on different time intervals. The first logic controller follows the simulation time-step while the second one changes its output on an hourly basis, following electricity market price variation. In other words, FC2 sets the hourly basis working condition of the BESS, above which the FC1 overlaps the output for PCR.

3.3.1. Fuzzy logic controller 1

FC1 is linked to the variable-droop operation mode. Fig. 3 shows how the two inputs (i.e. the battery SOC and the deviation from the grid-frequency) have been transformed into two fuzzy sets:

- *SOC*: three triangular MFs were used to cover the whole universe of discourse. The range of values can vary within the SOC limits and they are assigned to low, medium and high level of SOC-MFs.
- *Delta frequency*: in this case, it was decided to use three trapezoidal MFs able to identify the positive or negative deviation from the nominal value (50 Hz). The zero MF corresponds to the dead-band of the droop-control. Since the PCR must be provided as soon as the grid frequency goes out from the dead-band (it is then up to the droop-control to decide the power magnitude), the degrees of membership of the negative and positive MFs are constant.

Regarding the output, three singleton MFs are used. In this way, the droop actually ranges between 0.12% and 0.30% even though we chose the centroid one as the defuzzyfication method.

The fuzzy inference rules (Table 2) show how the variable-droop works. The idea is that to a decrease of SOC the droop should:

Table 2
FC1: fuzzy inference rules for droop definition.

Δf (Hz)	SOC (%)		
	Low	Medium	High
Negative	High	Medium	Low
Zero	Medium	Medium	Medium
Positive	Low	Medium	High

- gradually decrease when the delta-frequency is positive (thus absorbing more and more energy from the network) in order to restore the SOC;
- progressively increase when the delta-frequency is negative (thus delivering less and less power to the network) in order to save the SOC.

3.3.2. Fuzzy logic controller 2

The second fuzzy logic controller is linked to the energy arbitrage operation mode. It gives as output the arbitrage-weight $[-1;\ 1]$ that is multiplied per the arbitrage-band to define the arbitrage power ΔP_{ARB} of Eq. (4). In this case, the two inputs are the battery SOC and the deviation of the electricity price from the average yearly price (Fig. 4). Specifically:

- *SOC*: is modelled in the same way as for FC1.
- *Delta electricity price*: similarly to delta frequency in FC1, three trapezoidal MFs are used to identify the positive or negative de-viation from the reference price. Their degrees of membership rise as they move out from the zero MF (±20% region). This to exploit the arbitrage benefits increasingly as soon as they be-come cost-effective. The inference rules (Table 3) show that selling energy (thus

discharging BESS) is allowed only if the SOC is at medium–high level. In particular, to a decreasing of SOC, the arbitrage-weight should:

- gradually decrease from positive values to zero if the delta price of electricity is positive (thus selling is convenient) in order to preserve the SOC;
- further decrease to negative values if the delta price of electric-ity is negative (thus buying is convenient).

4. The implemented model

The BESS model was implemented in MATLAB ® Simulink ® by following the structure proposed in the previous sections (Fig. 5). The model under analysis is in ''open-loop'', meaning that the battery power output does not affect the input frequency to the controllers (i.e. we do not consider an I/O model). This is because

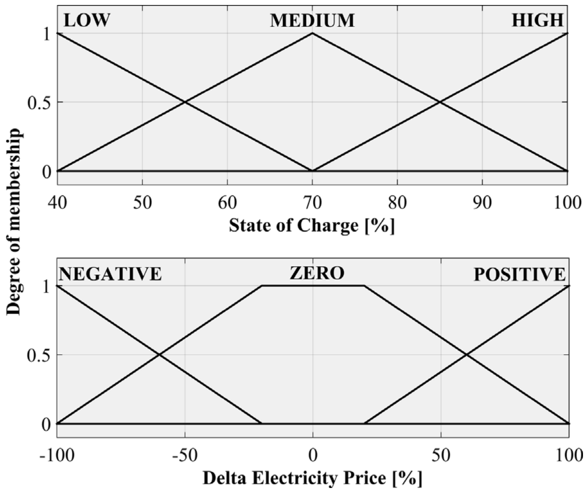


Fig. 4. FC2: Fuzzy sets of the inputs.

Table 3
FC2: fuzzy inference rules for arbitrage-weight definition.

ΔP_EE (%)	SOC (%)		
	Low	Medium	High
Negative	Negative	Negative	Zero
Zero	Zero	Zero	Zero
Positive	Zero	Zero	Positive

Table 4
BESS parameters adopted in the simulations.

Description	Parameter name	Value
Nominal power	Pn	1 MW
Energy–power ratio	EPR	1 h
Initial state of charge	SOC_start	70%
Maximum SOC	SOC_max	100%
Minimum SOC	SOC_min	40%
Dead-band	–	±0.02 Hz
Regulation-band	–	25%
Arbitrage-band	–	10%
Droop (FIX strategy)	–	0.30%
Variable-droop mode	–	ON/OFF
Arbitrage mode	–	ON/OFF

the goal of the work proposed is to investigate the effect of the regulation on the BESS itself.

1 MW/1 MWh BESS is simulated, which is supposed to be a re-alistic size of a BESS connected to the distribution grid. The results are then generalized. The response time of a battery inverter was also modelled by introducing a transfer function that imposes the signal from the regulation model on the battery model, with a set-tling time of 200 ms (time constant of 40 ms).

Table 4 shows the parameters adopted in the simulations (some of the assumptions will be investigated in depth in the next sections). They are compliant with the current regulation rules and plausible if related to the discussed application. The overall active-band is 0.35 p.u. and the dead-band is 20 mHz (in agreement with the Section A-15 of the Italian Grid-Code [2]). As default, con-servative values for the battery efficiencies were used and it was supposed the battery starts the simulation with half of its useable capacity respecting standard SOC limits.

In the paper, real samples were used in order to test the proposed approach performances in ‘‘standard’’ conditions of the Italian electric power system (Fig. 6). The frequency data refers to three working days in April 2014 and are based on the monitoring and control of the electric energy needs of the TecnoCity (industrial area sited in Legnano, North-West of Milan) in the framework of the AlpStore project [47]. The market price data comes from the database of the Gestore Servizi Elettrici and are related to the day ahead national energy price, in Italy the Prezzo Unico Nazionale (PUN), registered during the same days [48]. It was then assumed the average PUN registered in 2014 as reference price.

Since the performances of the variable-droop and energy arbitrage are directly related to the frequency and energy price samples, we tested a second set-pattern of day ahead energy price (obtained by reverting the previous one). The idea is to better quantify the performance of the approach proposed by using two completely different scenarios. Specifically, the first scenario results particularly critical due to prevalence of high energy prices in samples with over-frequency (in such situations the regulation margins are quite low). On the contrary, the second scenario depicts more convenient price profile, and the combination of FC1 and FC2 is able to perform better (as shown in the next sections).

Finally note that, in case of a ‘‘critical’’ electric grid scenario, on which the frequency results over–under the standard 50 Hz set point for several hours continuously, the approach proposed would result ineffective, responding as a classical fixed droop frequency control (i.e. in the worst situation the performance would be equal to the standard fixed droop control).

5. Simulation, results and discussion

Below, the results obtained by simulating the BESS model are presented. Firstly, it is shown how the model operates regard-ing the two implemented options: variable-droop and energy ar-bitrage. Secondly, the attention is focused on the variable-droop and a sensitivity analysis, which relates BESS performances ac-cording to different values of BESS efficiencies, is carried out. Ac-cordingly, a limit of the BESS roundtrip efficiency necessary to prevent reaching the minimum SOC is suggested. Thirdly, attention is directed to variable-droop operations. Different control strate-gies are tested aiming at improving BESS availability and prof-itability. Finally, a 30 days simulation of BESS in multi-service configuration is also presented to prove the effectiveness and con-venience of this application.

The reader is reminded that in our simulations we compared different control strategies assuming that the power capacity remains fixed. Since we assume a remuneration related to the regulation-band provided to the power system, the revenues from PCR remain constant to a fixed value (i.e. RoPCR). Consequently, the analyses are based on the variations in the BESS SOC and the final goal of the approach is the loss of regulation (LoR) minimization and the expected extra economic benefits (i.e. GoL) maximization.

As shown in the below equations, the LoR computes the PCR not provided due to exceeded SOC limits as a percentage of the expected PCR energy. Whereas GoL computes the gain or losses deriving from the difference between extra-revenues or losses from energy arbitrage (r_{WA}) and penalties for not having provided the PCR (c_p). Finally, the economic benefits (profit) are taken into account both RoPCR and GoL.

$$\mathrm{LoR}\,[\%] = \frac{\left(\int_{t=start}^{t=end} \Delta\dot{P}_{PCR} P_n dt\right)|_{SOC<\mathrm{SOC_{min}} \vee SOC>\mathrm{SOC_{max}}}}{\left(\int_{t=start}^{t=end} \Delta\dot{P}_{PCR} P_n dt\right)|_{PCR\ duties}} \tag{5}$$

$$GoL = r_{ARB} - c_p \tag{6}$$

$$c_p = \int_{t=start}^{t=end} \left|\Delta\dot{P}_{PCR}\right| P_n p_{EE}\, dt, \quad SOC < SOC\_min \vee SOC > SOC\_max \tag{7}$$

$$r_{ARB} = \int_{t=start}^{t=end} \Delta\dot{P}_{ARB} P_n p_{EE} dt, \quad SOC\_min < SOC < SOC\_max \tag{8}$$

$$p = RoPCR + GoL. \tag{9}$$

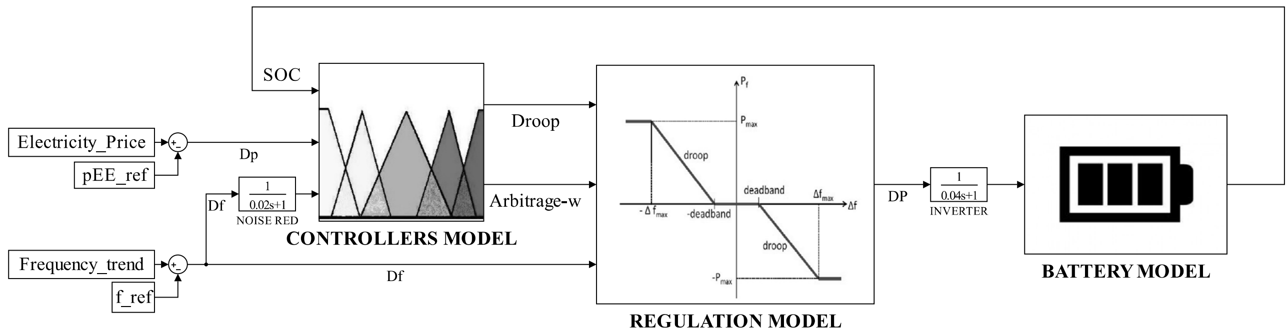


Fig. 5. The MATLAB® Simulink® model.

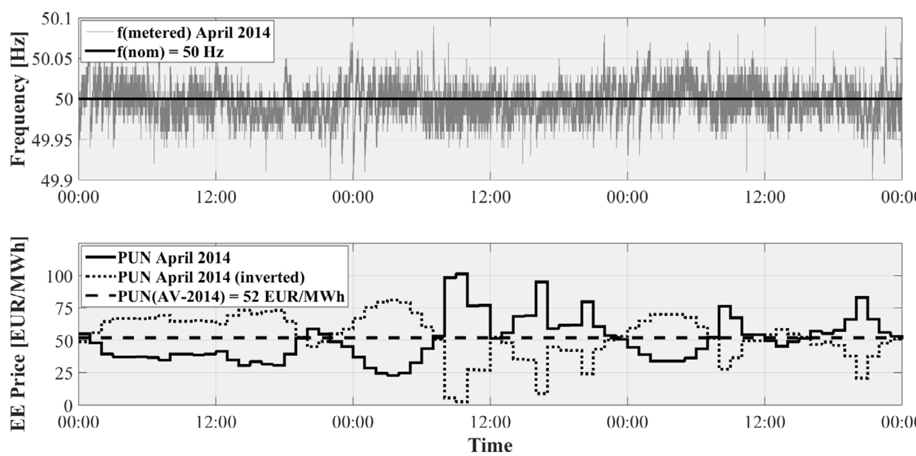


Fig. 6. Frequency trend and electricity price profiles adopted in the simulations.

Moreover, as already introduced in Section 3, the energy stored in the BESS at the end of each simulation (E-BESS) and the Loss of Regulation (LoR) could drive further earnings/penalties.

5.1. Set-up of the procedure

First of all, we dealt with a sensitivity analysis to motivate the chosen value for the *regulation-band*. Table 5 presents several simulations with different magnitudes of the regulation-band and BESS efficiencies. We consider whether, throughout the simulation, the SOC lower bound was reached (SOC_{min} = 40%), and accordingly the LoR has been calculated. We noticed that the regulation-band of 0.25 p.u. is a good trade-off between the necessity to minimize the LoR and the necessity to limit the stress to the BESS, or equivalently to guarantee the independence from a particular BESS technology. Indeed, by using 250 kW out of 1 MW of available capacity (i.e. 0.25 p.u.) it has pursued the viability of all the possible electro-chemistries, with respect to the control laws investigated.

A comparison with a fixed-droop strategy (0.3%) is anticipated. Indeed, a droop fixed at the upper range limit represents the reference choice because it minimizes the PCR contribution and saves the SOC. Table 5 shows that a variable-droop approach is able to reduce the LoR also with lower value of the regulation-band.

As regards the *arbitrage-band*, readers are reminded that the focus of this work is on PCR. Energy arbitrage has to be evaluated as a useful supplementary. A suitable band of 0.1 p.u. lower by more than half of the regulation-band (0.25 p.u.) was chosen, ending with an *overall active-band* of 0.35 p.u. It should be pointed out that our work is developed in per unit of the nominal BESS power. Therefore, the results and analyses that follow are scalable to the specific market conditions (current or prospective) or application context.

Going into detail, the results of a generic simulation are pre-sented in order to show the model operation. This simulation refers to input data of Table 4. Figs. 7 and 8 show the simulations outputs about the two operation modes considered in the implemented model. We found that:

- The variable-droop helps to improve SOC control. Indeed, in both high and low SOC conditions (period 1 and period 2 in Fig. 7), FC1 works close to the extreme values of the droop range in order to avoid SOC limits. For instance, in period 2, the droop is set to work at 0.3% when the frequency is below 50 Hz (thus injecting the least possible), at 0.12% when above 50 Hz (thus absorbing as much as possible). However, for the controller to be effective, even the frequency trend needs to be favourable at the same time. Indeed, if low-frequencies are much more frequent than high-frequencies (as in period 2), the variable-droop operation can only help to retard reaching the minimum allowable SOC. Additionally, BESS round-trip efficiency plays against the SOC recovery, raising the effective energy required in discharge condition and decreasing the one in charge condition.

- Energy arbitrage also helps to improve SOC control, but in this case at periods of low SOC a period of low electricity prices must coincide. Period 1 and period 2 of Fig. 8 show FC2 operations in two opposite situations: in period 1 FC2 restores the SOC thanks to a favourable electricity price; in period 2 FC2 sets the arbitrage level to zero because the price of electricity is too high and it is not economical to buy electricity. Moreover, both in period 2 and period 3, the electricity price would have been favourable to sell electricity. However, it is not advisable to discharge the BESS further due to low/medium level of SOC. Accordingly, the arbitrage level results to be zero to avoid reaching the minimum allowable SOC and incurring penalties.

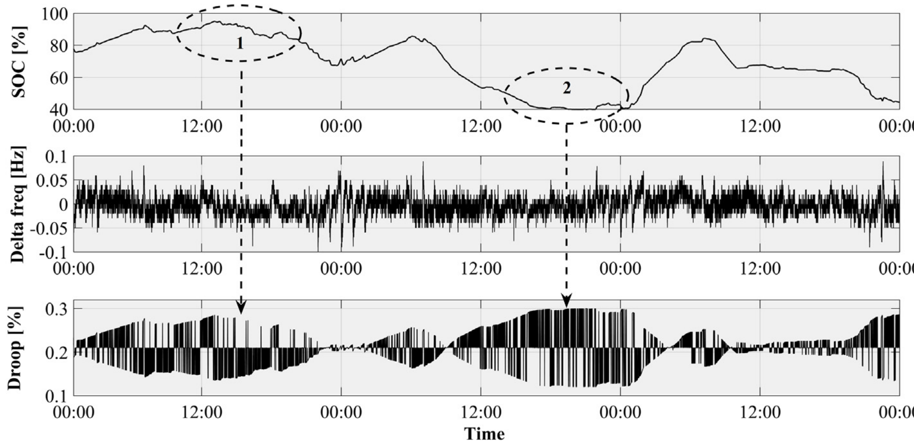


Fig. 7. Simulation output: variable-droop operation.

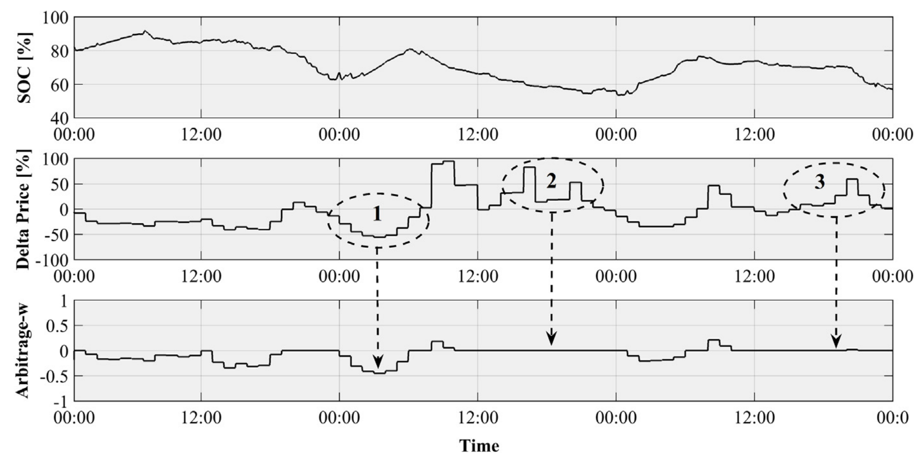


Fig. 8. Simulation output: energy arbitrage operation.

Given these outputs of preliminary simulations, in the following sections different strategies have been investigated to define the level of SOC aiming at better retaining its level around a desired value. This, together with energy arbitrage, can improve the BESS availability for PCR provision.

5.2. Variable-droop: sensitivity analysis on BESS efficiencies

In order to evaluate the effect of charge/discharge efficiencies on BESS performances 49 different round-trip efficiencies were simulated. In this set of simulations the model used only variable-droop addressing the PCR duties for the given frequency profile (Fig. 7). The regulated energy was computed in 1.8 $P_n h$ for all the simulations. Table 6 reports the results of the sensitivity analysis according to different levels of charge and discharge efficiencies. The LoR and the minimum SOC over the simulation are the two parameters used to discriminate the region in which the battery fulfils PCR duties (above the underlined border) and the region in which some PCR is not provided (below). From the simulations, it results that with a BESS roundtrip efficiency of at least 90% it is possible to avoid penalties and to guarantee the continuity of the Multi-services BESS: regulation set-up

In the perspective of a BESS for multi-services provision, also energy arbitrage has been considered in the BESS operation modes and compared with the other possible operation options. Conservatively, low values for BESS efficiencies (η_{CH} = 90%, η_{DISCH} = 85% which result in 3.4% of LoR) have been used in order to verify whether arbitrage helps to avoid any penalties even with low efficiencies.

Specifically, three operational options are compared:

- S0 (variable-droop mode OFF—energy arbitrage mode OFF) in which BESS is simulated as a traditional power plant with a fixed droop of 0.3%. The chosen value represents the reference choice in a fixed-droop approach because it minimizes the PCR contribution and saves the SOC.
- S1-1 (variable-droop mode ON—energy arbitrage mode OFF) in which only FC1 is activated, so the droop is free to adapt to the best value according to the SOC evolution. We stress again that we chose a variable-droop approach over a fixed-droop to verify the possibility of bringing benefits both to the electric power system and to the BESS owner.
- S1-2 (variable-droop mode ON—energy arbitrage mode ON) in which also FC2 is activated and the BESS is able to sell and purchase energy the grid. This is the multi-service configuration.
- S1-2* (variable-droop mode ON—energy arbitrage mode ON) in which we used the inverted-PUN profile of Fig. 6.

In Fig. 9, the SOC trends in the four cases are presented. Following our BESS operating criterion that is to exploit at maximum the BESS's fast response capability when possible (when SOC at medium–high level), S1-1 (black, solid line) decreases faster than S0 (black, dotted line), thus providing more regulation for the ben-efit of the electric power system. However, as the SOC decreases, S1-1 strategy starts minimizing its contribution (higher droop) in under-frequency conditions, while maximizing (lower droop) in the case of over-frequency conditions. For this reason, the BESS is

Table 5
Results of sensitivity analysis for different BESS regulation-band.

LoR [%] / SOC_{MIN} [%]		Regulation-band [p.u.] 0.1	Regulation-band [p.u.] 0.25	Regulation-band [p.u.] 0.5	FIX(0.3%) 0.25
Charge/Discharge efficiencies	97.5 / 97.5	0.00 / 41.49	0.00 / 41.29	0.00 / 42.72	0.76 / 40.00
	95 / 95	0.15 / 40.00	0.22 / 40.00	0.00 / 41.18	2.46 / 40.00
	92.5 / 92.5	1.47 / 40.00	1.16 / 40.00	0.21 / 40.00	4.15 / 40.00

Table 6
Results of sensitivity analysis for BESS efficiencies.

LoR [%] / SOC_{MIN} [%]		Charge efficiency 100	97.5	95	92.5	90	87.5	85
Discharge efficiency	100	0.00 / 42.93	0.00 / 42.35	0.00 / 41.76	0.00 / 41.16	0.00 / 40.55	0.06 / 40.00	0.39 / 40.00
	97.5	0.00 / 41.88	0.00 / 41.29	0.00 / 40.67	0.00 / 40.09	0.28 / 40.00	0.61 / 40.00	1.00 / 40.00
	95	0.00 / 40.78	0.00 / 40.19	0.22 / 40.00	0.50 / 40.00	0.89 / 40.00	1.22 / 40.00	1.61 / 40.00
	92.5	0.22 / 40.00	0.50 / 40.00	0.83 / 40.00	1.16 / 40.00	1.50 / 40.00	1.83 / 40.00	2.16 / 40.00
	90	0.78 / 40.00	1.16 / 40.00	1.44 / 40.00	1.77 / 40.00	2.10 / 40.00	2.44 / 40.00	2.82 / 40.00
	87.5	1.44 / 40.00	1.72 / 40.00	2.16 / 40.00	2.38 / 40.00	2.71 / 40.00	3.05 / 40.00	3.38 / 40.00
	85	2.05 / 40.00	2.38 / 40.00	2.66 / 40.00	2.99 / 40.00	3.38 / 40.00	3.65 / 40.00	3.99 / 40.00

charged more rapidly and the fix-strategy (S0) comes first to satu-ration. Even if S1-1 is not able to prevent a complete discharge of the battery (because of a prevalent under-frequency trend) it helps in avoiding 65% of the LoR, thus protecting the owner's interests.

On the contrary, S1-2 (black, dashed line) and S1-2* (grey, dashed line) differ markedly from the others since they use also the arbitrage-band. In both cases, the use of energy arbitrage helps in bringing the LoR to zero demonstrating the real opportunity of a multi-service BESS configuration. Moreover, in the S1-2* we were also able to restore the SOC to the starting value (70%) thanks to a favourable electricity price profile.

Fig. 10 shows the BESS power output for S1-2 strategy. The PCR contribution oscillates within the regulation-band, while the arbitrage-band is mostly used in charging configuration. Indeed, the particular price profile used in S1-2 leads to a condition where at high energy prices (when selling is convenient) there are never medium–high levels of SOC.

Finally, Table 7 presents the comparisons between the three strategies. On the one hand, it is evident that moving towards S1-2 we obtain better results in term of LoR; on the other hand, GoL says that energy arbitrage helps in restoring SOC but at significant costs. One can observe that the profit with arbitrage is lower than the one without; however, since some BESS energy may still available at the end of simulation, we should give a valorization (at least 63e/MWh according to FC2 settings) also to this component (E-BESS in the table). Moreover, since the remaining energy can be effectively exploited only when energy arbitrage is activated, the final theoretical profit will be in advantage of those solution in multi-services configuration (S1-2 and S1-2*, not in S0 and S1-1), especially if the market price profile is convenient (S1-2*).

5.3. Multi-services BESS: results of the simulated strategies

In order to prevent negative GoL also in case of only variable-droop we investigated the possibilities of better controlling the BESS SOC. We focused on the controllers by changing the SOC-MFs configuration (Fig. 3). Previously, even distributions of the MFs were preferred to obtain a strong smoothness in the output; in this case, we chose more uneven distributions in order to guide SOC around desired values. Consequently, the working conditions of controllers FC1 and FC2 are affected. In this way, a further three strategies, namely S2, S3, S4 were outlined, which we simulated in cases of only variable-droop mode (sub-strategies S2-1, S3-1, S4-1).

As shown in Table 8, the idea has been increasingly to restrict the area of SOC control around the medium level region (SOC = 70%). Additionally, the low and high MFs increase faster in their degree of membership to change the droop more rapidly. Results in Table 8 state that S2-1 and S3-1 operate progressively better when compared to the S1-1 strategy, economic losses are not zero. Only in strategy S4-1, by translating the medium level of SOC towards higher values (80% instead of 70%), losses were avoided too. The same results are highlighted also in Fig. 11 where the SOC trends for the different strategies is presented.

5.4. Multi-services BESS: results on 1-month simulation

Finally, with the aim of verifying the benefit of using variable-droop joint with energy arbitrage, the BESS operation over a longer period (30 days) was simulated. The same input profiles were taken (but stochastically perturbing the trend) and the original FC1 and FC2 configurations of Section 3.3. As expected, the BESS power out-put oscillates within the regulation-band with some vertical trans-lation according to arbitrage logics (Fig. 12). Fig. 13 shows how the combined operations of the two controllers are able to control the SOC evolution over the month and avoid reaching the minimum al-lowable value. The variable-droop gives its contribution especially when the SOC becomes too low, while energy arbitrage is used to restore some percentage of SOC whenever convenient. Looking at the arbitrage-weight trend, it can be noticed that the charging peri-ods are longer than the discharging period. However, since we buy when the price is low and sell when price is high, at the end of the

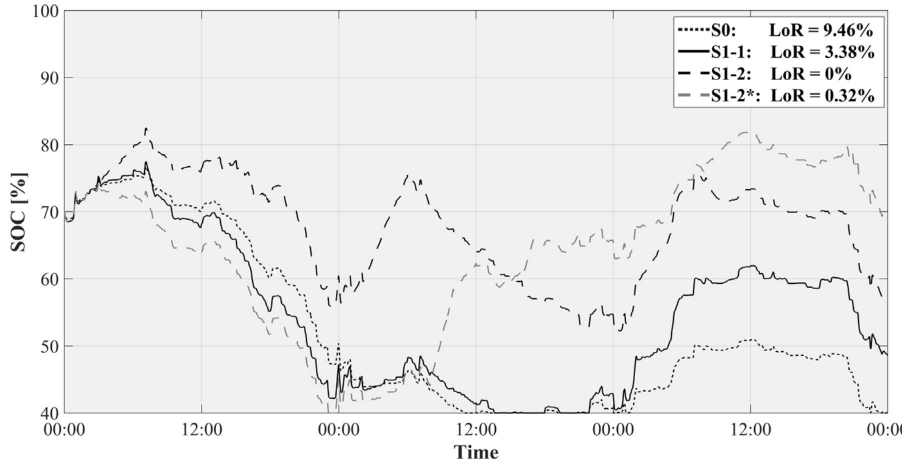


Fig. 9. BESS SOC trend in strategies S0, S1-1, S1-2 and S1-2*.

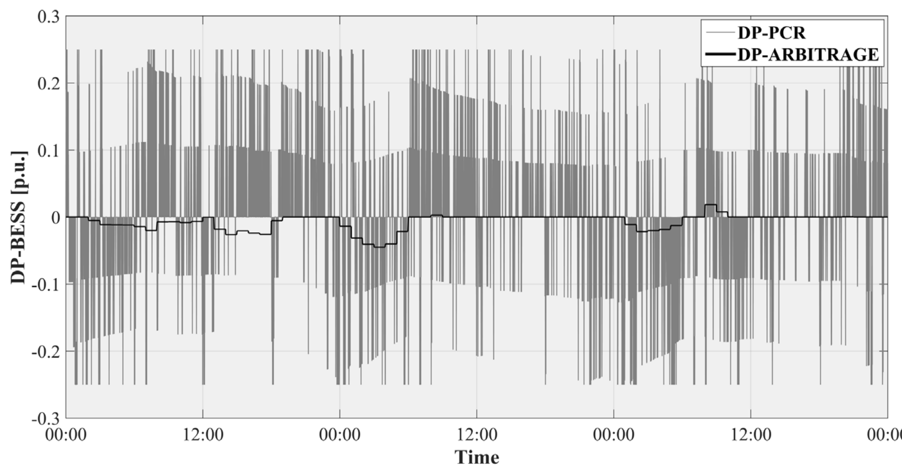


Fig. 10. BESS output in strategies S1-2.

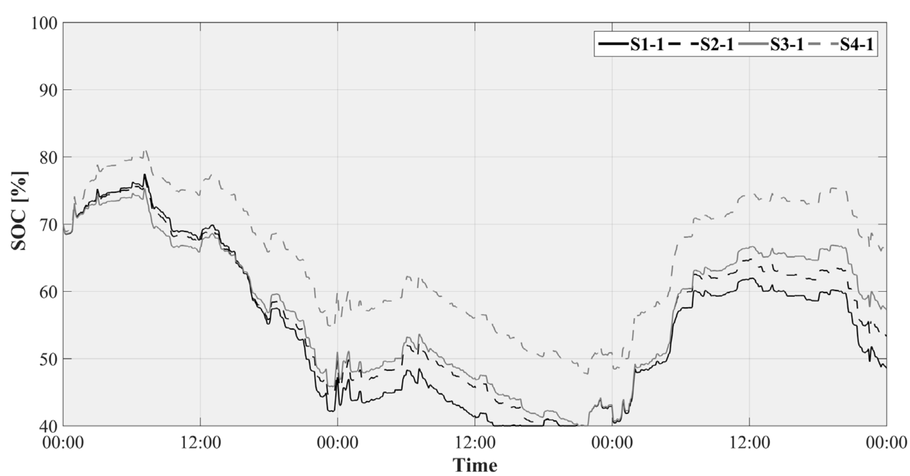
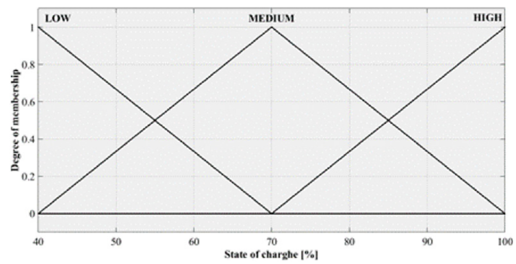
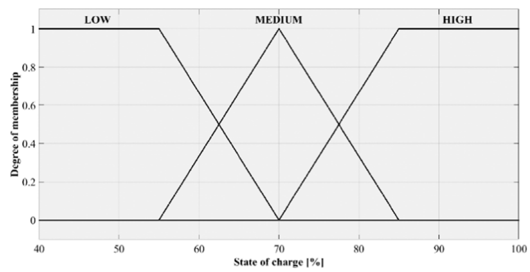
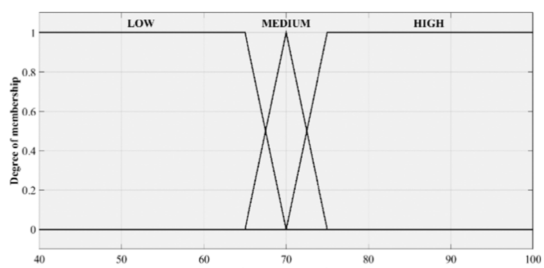
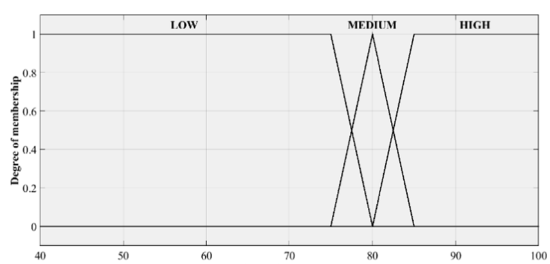


Fig. 11. BESS SOC trend in strategies S1-1, S2-1, S3-1 and S4-1.

Table 7
Simulation results in strategies S0, S1-1, S1-2 and S1-2*.

Strategy	Var-droop mode	Arbitrage mode	SOC (end)	SOC (min)	LoR	GoL	Profit	E-BESS
S0	OFF	OFF	40%	40%	9.46%	−8.1€	RoPCR −8.1€	–
S1-1	ON	OFF	48.7%	40%	3.38%	−4.3€	RoPCR −4.3€	–
S1-2	ON	ON	56.9%	52.1%	0%	−13.6€	RoPCR −13.6€	>10.6€
S1-2*	ON	ON	68.9%	40%	0.32%	−6.4€	RoPCR −6.4€	>18.2€

Table 8
Simulation results of strategies S1-1, S2-1, S3-1 and S4-1.

Strategy	SOC-MFs shape	Simulation results
S1-1		SOC (min) = 40% SOC (end) = 48.7% GoL = −4.3€ Profit = RoPCR −4.3€ LoR = 3.38%
S2-1		SOC (min) = 40% SOC (end) = 53.4% GoL = −1.4€ Profit = RoPCR −1.4€ LoR = 1.21%
S3-1		SOC (min) = 40% SOC (end) = 57.3% GoL = −0.7€ Profit = RoPCR −0.7€ LoR = 0.61%
S4-1		SOC (min) = 47.73% SOC (end) = 65.9% GoL = 0€ Profit = RoPCR LoR = 0%

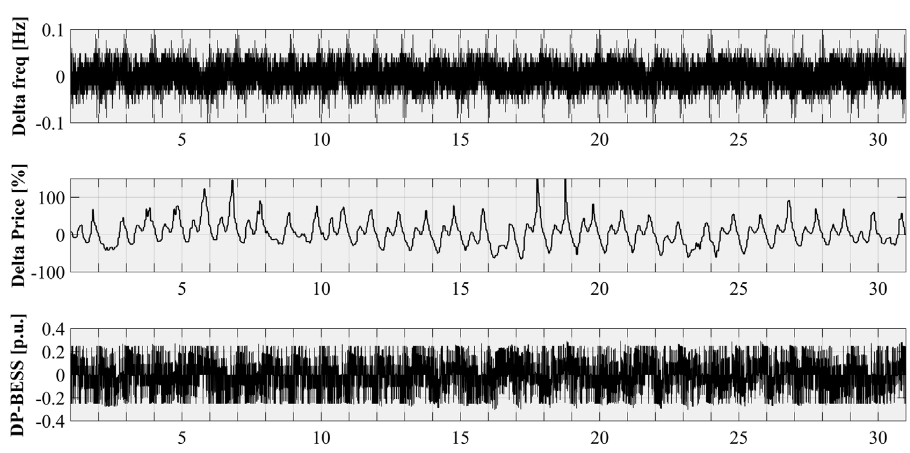


Fig. 12. 30-day simulation: input profiles and BESS output.

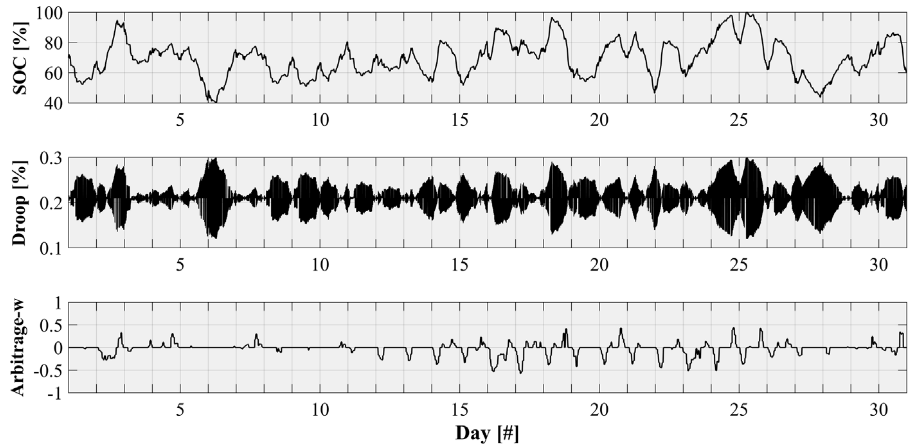


Fig. 13. 30-day simulation: SOC, variable-droop and energy arbitrage.

month the GoL is positive (around e15), increasing the final profit for the BESS owner.

Following these results, it can be concluded that energy arbi-trage could be used as a good option to support PCR service con-tinuity. If a narrow arbitrage-band is used (as in this case), energy arbitrage can act at least against the SOC degradation caused by the BESS internal efficiency. However, if a wider arbitrage-band is adopted this option can provide also significant extra-revenue.

6. Conclusions

Grid-connected Battery Energy Storage Systems are a promising technology for enabling transition towards the high penetration of renewable energy sources into the electric power system. They are well suited for a variety of grid uses like ancillary services, rep-resenting an ideal candidate to help in solving those security and reliability problems that are slowing down this transition. In this paper, we have investigated the response of different strategies for managing BESSs when used for primary control reserve (PCR) and energy arbitrage.

After the introduction about the suitability of using BESS to pro-vide the PCR and the literature review on BESS control strategies and controller models, we have presented our approach to model a BESS for this service. The model includes: (i) a battery model able to calculate and update the battery state of charge (SOC),(ii) a BESS droop-control model with variable-droop and energy arbitrage modes of operations, (iii) two fuzzy logic controllers that set the droop and the arbitrage set points. Then we have shown the related MATLAB^R Simulink ^{R} BESS model that implement the proposed approach. Finally, in the last section we have presented the main findings of the simulation results: (i) a detailed analysis of BESS operations using variable-droop and energy arbitrage options under real metred inputs of frequency and electric market prices;(ii) a suggested value for the BESS round-trip efficiency in order to avoid complete BESS discharge; (iii) a comparison of different con-trolling strategies using variable-droop option; (iv) a final analysis of a 30-day BESS operation in multi-services configuration.

The proposed model is part of the simulation models for the optimum control of BESS performances. When compared with the related literature, our model aims at understanding how BESS features could be used to the advantage of the BESS owner. Thus, attention is focused not only on the SOC control but also on the expected economic benefits for the BESS owner.

It can be concluded that the variable-droop mode of opera-tion improves the BESS performance avoiding part of the penal-ties related to full charge or discharge conditions. The arbitrage mode is greatly determined by electricity prices but our simula-tions demonstrate that if a narrow arbitrage-band is used, it can at least act against the SOC degradation caused by the BESS internal efficiency. If a wider arbitrage-band is adopted this option can also provide significant extra revenues increasing the final profitability of the BESS application.

Moreover, it should be stressed that our model has been conceived to be independent of any specific chosen technology. For this reason, we preferred an ideal battery model that considers a steady-state operations of the battery updating the change in the battery SOC over a given time step. Therefore, we are aware that further research is required to obtain more precise results bound to a specific technology; e.g. to consider lifetime degradation, the influence of temperature variations on performances, the variability of BESS capacity according to operating current, and specific electrical circuitry.

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