

Coordinated Control of Supercapacitor-Battery Tandem by Smart Converters in Microgrid Scenario



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Abstract Microgrids represent a promising energetic scenario applicable in different contexts, especially in residential clusters. In this paper, authors propose a novel control logic to implement a coordinated management of generators, loads, and hybrid energy storage systems (HESS) in a microgrid by means of a hierarchical smart converter architecture. The innovative algorithm is embedded in a master converter. It allows the online management of energetic fluxes in cooperation with slave converters distributed among the microgrid resources. They carry out a smart coordination of microgrid generation, absorption, and battery-supercapacitor storage systems with the aim to improve the availability of the storage systems for providing ancillary services to the power grid. The effectiveness of the control is tested applying the smart converter master-slave architecture, including the combined management BESS-supercapacitor algorithm, to a grid-connected residential microgrid.

1 Introduction

The threat of climate change demands a rapid global shift to a sustainable energy system. Increasing renewable energy is necessary to progress on decarbonization, as well as the need for more efficient use of the grids, in order to sustain very high penetration of variable renewable electricity. Thus, grid flexibility and operational support for the electricity grids are expected to increase. In such a scenario, battery energy storage systems (BESS) could play a critical role in providing ancillary services. Supporting power grids, enabling microgrid operation, and participating in restoring unintentional islanding are just some examples of the new possibilities for BESS application. Major manufacturers are already developing BESS solutions

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for the support and the safety of the grid [1]. In literature, many works study the integration of BESS in power systems, including technical and market issues [2–4]. In general, most researchers agree that the effective integration and use of BESS depends on efficient control capabilities of the storage systems. Thus, many works concentrate on developing intelligent control systems for providing ancillary services to the grids by means of distributed BESS [5] or to control grid connected hybrid power system including BESS [6] also in microgrid configuration [7]. In this paper, authors propose a novel control logic to implement a coordinated management of generators, loads, and hybrid energy storage systems (HESS) in a microgrid by a hierarchical smart converter architecture aiming to improve the availability of microgrid storage systems to provide ancillary services to the power grid. To this aim, the developed control logic integrates an innovative algorithm to evaluate the capability for the BESS to participate in providing ancillary services to the power grid and manage the charge/discharge of the couple BESS-supercapacitor in coordinated manner in order to ensure BESS ability to keep the needed level of energy. From a conceptual point of view, the work has been developed by means of three steps. First, a master-slave smart converter architecture was configured and developed by using the tool PiCon-RET, implemented in [8]. In particular, PiCon-RET is a software tool assisting the designers in configuring optimal smart converters for different energetic scenarios; it is based on a multi-objective optimization obtained by combining a SPEA-II algorithm and an electro-thermal design procedure. Then, a control algorithm for the coordinated management of microgrid resources and smart control of the couple BESS-supercapacitor was programmed by the software environment. Finally, as proof of concept for the proposed control, MC effectiveness is tested on a case study representative of a grid-tied residential microgrid.

The paper is structured in four sections, as follows. Section 2 introduces the proposed control logic. Section 3 summarizes a case study to highlight effectiveness of the proposed controller, whereas Sect. 4 recaps main conclusions and possible development for further works.

2 The Control Logic

2.1 *Master-Slave Architecture Design*

The proposed master-slave architecture is dedicated to the coordinated control of microgrid systems and devices. The considered energetic context is schematically represented in Fig. 1. All the resources in the microgrid (BESS, supercapacitor, AC and DC loads, and distributed generation units—DER) are controlled by means of a master converter (MC), which manages a cluster of smart converter slaves (SCSs), distributed among the resources. The novel HESS algorithm, programmed by the

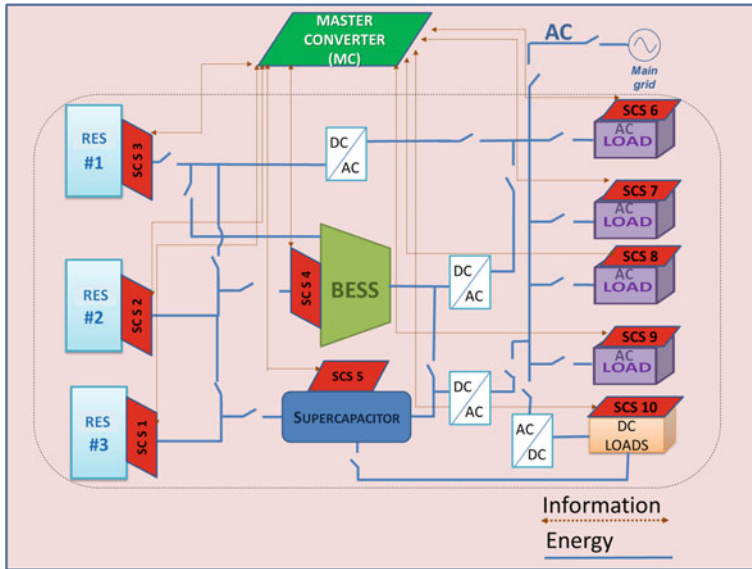


Fig. 1 Microgrid master-slave functional scheme

software environment, is integrated in the more general MC control flow and allows BESS and supercapacitor to operate in a coordinated manner.

More in detail, MC continuously receives RES data from SCS1, SCS2, and SCS3 (Fig. 1) and loads data from SCS6, SCS7, SCS8, SCS9, and SCS10 (Fig. 1). In addition, it verifies the BESS SOC instantaneous value (SCS4) and the supercapacitor status (SCS5). Starting from this information, MC is able to carry out a continuous “online match” (communication time = 5 μ s) among energetic fluxes and to apply the proposed control logic. In order to maximize the use of RES, reduce electricity withdrawn from the grid, and apply the BESS-supercapacitor coordinated control for improving the capacity to provide ancillary services, MC implements the conceptual steps synthesized below (Table 1).

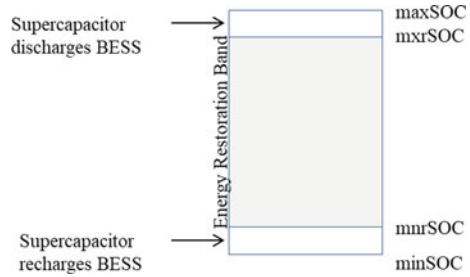
2.2 BESS-Supercapacitor Coordinated Management

In the current energetic scenario, storage systems are going to be more and more applied for supporting reliable operation of power networks. Since the last 10 years, BMS has included algorithms to verify the SOC’s instantaneous value falls within an admissible interval (interval between the minimum value of discharge (minSOC) and the maximum value of charge (maxSOC)) to guarantee the battery safeguard. Many works in literature have also proposed BESS control algorithms to improve BESS participation in ancillary services [5–7]. In [9], authors propose a control logic to ensure the BESS SOC falls within an interval (energy restoration band)

Table 1 MC conceptual actions

Resources	MC actions
AC loads	<p>When RES total amount in the microgrid is not enough to fulfill the demand from AC loads, MC verifies the BESS SOC. Therefore, MC evaluates BESS mxrSOC and then verifies the BESS availability to supply AC Loads</p> <p>If BESS is not available, the loads are supplied by the power grid</p> <p>If BESS is just partially available, MC assigns the loads to BESS supply according to a specific merit order list (the priority level is assigned to each load in function of the possibility to interrupt it without causing criticalities in the microgrid operation)</p>
DC loads	<p>When RES in the microgrid are not enough to fulfill the demand from DC loads, MC verifies the supercapacitor SOC</p> <p>If it is greater than admissible minimum state of charge, the DC loads are supplied by the supercapacitor; otherwise, the loads are fulfilled by the BESS, if it is available, or conversely from the power grid if also BESS is not available</p> <p>If BESS is just partially available, MC assigns the loads to BESS supply according to a specific merit order list (the priority level is assigned to each load in function of the possibility to interrupt it without causing criticalities in the microgrid operation). Distinguishing the use of supercapacitor for DC loads from the use of BESS for AC loads allows improving the performance of the overall system so reducing the need of DC/AC conversions</p>
BESS	<p>When BESS SOC does not fall within energy restoration band, the supercapacitor charges/discharges BESS up to BESS SOC coming back within the restoration band</p>
RES	<p>MC controls RES SCSs in order to improve generator performance. More in detail, maximum power point tracking (MPPT) algorithms have been embedded in the SCS control logic to maximize power extraction under all conditions with wind turbines and photovoltaic solar systems</p>

Fig. 2 BESS SOC virtual bands



where the BESS has a sufficient amount of energy reserves to participate, at each time, in ancillary services during the microgrid operation. To this aim, whenever the BESS has not a sufficient level of energy reserves, the control algorithm requires the needed energy from the power grid. In this paper, an additional control is integrated to the previous one, at a higher hierarchical level, to extend the logic described in [9] to a HESS. More in detail, an innovative control algorithm is proposed to coordinate BESS and supercapacitor operation, allowing faster BESS energy reserve restoration from supercapacitor (Fig. 2), getting more efficient the process for providing ancillary services to the grid. The algorithm allows keeping the BESS SOC within the “energy restoration band” (gray band with interval limits: $mnrsSOC$ and $mxrSOC$ in Fig. 2), which is the SOC interval where the BESS is certainly able to participate to the frequency restoration process. The latter allows ensuring the needed amount of energy restoration reserves during the microgrid operation for next frequency deviation events.

3 The Proof of Concept

In this section, the microgrid, managed by the MC developed in this work, has been tested on a case study described as follows. It is worth noting that the main aim of the test consists in showing the effectiveness of the MC control applied to the proposed smart converter master-slave architecture, including the combined management BESS-supercapacitor. The improved capability of the BESS to participate in grid balancing, after the introduction of the control algorithm, was already demonstrated in [9]; therefore, this point is not the main focus of this proof of concept.

The simulation of the control logic developed and embedded in the microgrid master-slave converter architecture has been carried out applying it to a grid-tied residential microgrid covering one building composed of eight apartments. A photovoltaic generation system, a battery storage system, and a supercapacitor operate to fulfill energetic requirements of AC and DC residential loads.

The BESS included in the microgrid is a multi-stack Li-ion battery, designed to store 25% of the energy produced by the photovoltaic system during July at Napoli City (latitude coordinate, 40.853294° ; longitude coordinate, 14.305573° —optimal tilt). Each stack is conceived to cover the AC absorption for one apartment. The

Table 2 Simulation parameters

Resource	
Connection to the external grid	YES
Photovoltaic	25 kWpSc = 157 m ² η = 0.15
BESS	Capacity: 13 kWhLi-ion—multi-stack
Supercapacitor	XLR supercapacitors

BESS, connected to the electric grid by a bidirectional DC/AC converter, covers AC loads but it cannot cover the DC loads, since they are connected both to the supercapacitor and the power grid. More in detail, the supercapacitor, connected to the electric grid by a bidirectional DC/AC, fulfills DC loads but also acts on BESS charging/discharging to bring the BESS SOC in the energy restoration band, as shown in Sect. 3.2.

The MC manages the SCs cluster, distributed among the resources of the microgrid, including BESS, supercapacitor, AC and DC loads, and PV system, according to the functional schema reported in Fig. 1 and logical steps described in Table 1.

Main features and significant microgrid parameters are reported in Table 2.

The load profile of each apartment has been constructed considering the average trends in load demands based on a customer consumption behavior of an Italian typical four-person family [10–12], also including average power consumption for AC home appliances such as one oven, one washing machine, four air-conditioners, and one dishwasher and DC home appliances such as four smartphones, one tablet, and one laptop.

To verify the effectiveness of the proposed model, a validation process based on two simulations has been conducted. The first simulation evaluates the μg operation during the normal operating conditions; the second one simulates, at a certain time, the simultaneous disconnection of six apartments (a significant load) to verify the BESS ability to participate in the restoration process when an imbalance occurs and, then, the BESS capability to come back at the energy restoration band. The energy restoration band is set between 40% (mnrSOC) and 60% (mxrSOC), whereas the BESS security SOC limits are 20% (minSOC) and 90% (maxSOC).

3.1 First Simulation

The study lasts 24 h and starts at midnight with the SOC BESS at 50% (Fig. 3). The nighttime demand is contained and it is fulfilled by the BESS. During the time period between 6:00 a.m. and the 7:00 p.m., the supercapacitor starts assuring the DC loads charge, so fulfilling citizens' requirements. Then the BESS satisfies the AC energetic needs. During the day, the PV generation firstly charges the battery until the maximum SOC is reached and then it charges the supercapacitor. This

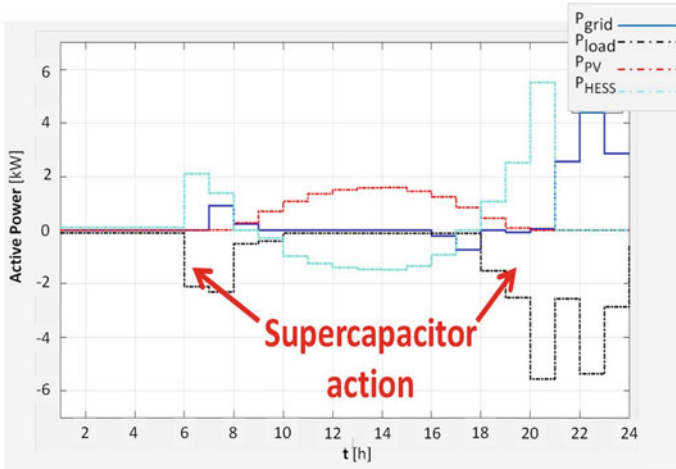


Fig. 3 Adopted control applied to the proposed case study

operation contributes to reduce the μg losses since a further AC/DC conversion is avoided. Once the family returns home at 6:00 p.m., energetic demand increases reaching peak consumption at 8:00 p.m. and 10:00 p.m. In general, citizens who returned home require mobile and portable devices to be recharged. As shown in Fig. 3, from 7:00 p.m. to 8:00 p.m., the MC demands the supercapacitor action. Then the BESS fulfills the energetic absorption until 9:00 p.m. and the grid intervention is necessary until midnight.

In Fig. 4 details about the BESS SOC graphs are reported. The adopted control strategy assures satisfaction of BESS SOC limits during normal operating conditions (step 1).

3.2 Second Simulation

The second simulation supposes an imbalance occurs in the μg at 12.57 a.m. (Fig. 4). To simulate the imbalance, a sudden load decrease is applied (load curtailment: -75%). After the grid balance-restoring process, when the BESS SOC is equal to 61%, this simulation evaluates the capability of the proposed control strategy to bring the BESS SOC in energy restoration band in order to ensure its potential participation in other grid-balancing processes.

In detail, to verify the benefit in applying both the proposed controller and the supercapacitor for the fast BESS recharging, three simulations have been conducted (Fig. 5). In the first case, the controller is not active (controller OFF) and the supercapacitor just works to fulfill DC loads (supercapacitor is disconnected from BESS); in the second case, the controller is active (controller ON) and

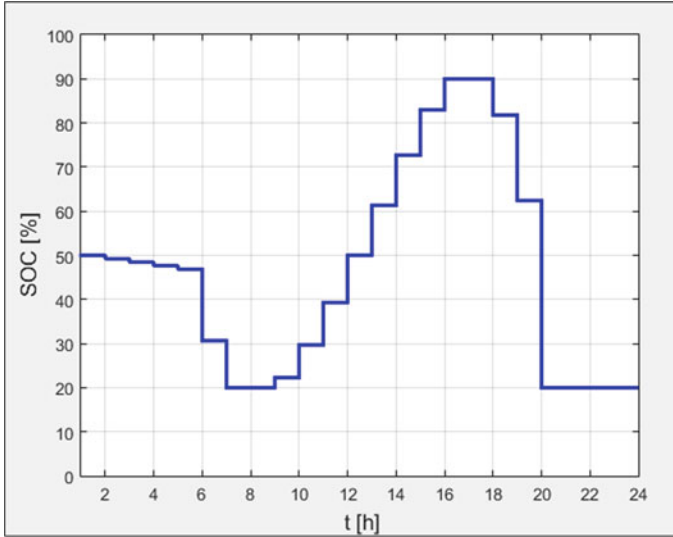


Fig. 4 BESS SOC graph during normal operating conditions

the supercapacitor just works to fulfill DC loads (supercapacitor is disconnected from BESS); in the last case, the controller is active (controller ON) and the supercapacitor is connected with BESS. As shown in Fig. 5, in the first case, the BESS, after participating in balance restoring, moves away from $mxrSOC$ (the loads are disconnected and the controller is OFF). In the second case, MC acts to bring BESS SOC back into the energy restoration band; the BESS provides the surplus of energy to the grid and the BESS SOC comes back to the energy restoration band in about 2–5 min. In the last case, MC again acts to bring BESS SOC back into the energy restoration band, but the BESS surplus of energy is taken by the supercapacitor; thus the process is much faster than in the second case; the BESS SOC comes back to the energy restoration band in less than a minute. Finally, it is clear that the combined use of the proposed control algorithms embedded in the MC and HESS is really useful to ensure BESS capability to provide ancillary services to the grid.

4 Conclusions

In this paper an innovative control logic is introduced to operate the smart management of generators, loads, and hybrid storage devices in a microgrid by means of distributed smart converters in a hierarchical master-slave architecture. The proposed algorithm, operating at the higher control level, evaluates the more suitable match between the hybrid storage system and all resources (generation/demand)

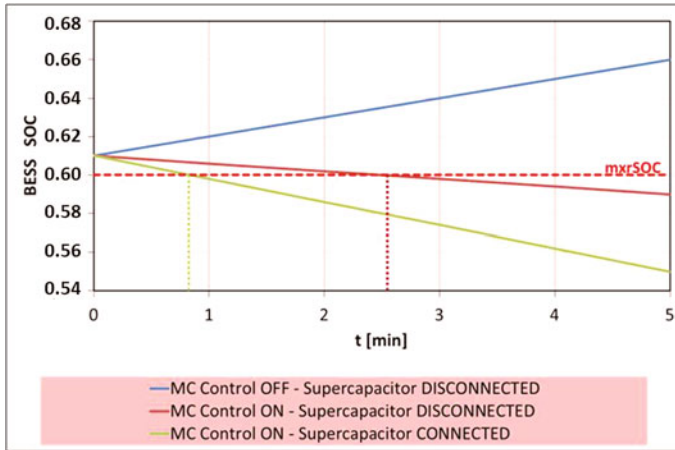


Fig. 5 BESS SOC graph after balance-restoring process

to obtain both the user energetic satisfaction and the availability of a sufficient energetic level to guarantee the BESS participation in grid balance-restoring processes. In order to show the effectiveness of the proposed approach, the control logic is applied to a grid-connected residential microgrid. Results show that, after a frequency instability event, in absence of the proposed algorithm, the BESS energy reserves are not restored during the simulation period (5 min), whereas they are restored in a few minutes when the algorithm works. Furthermore, the simulations show that the restoration time is about 2–5 min when the controller operates only on BESS, and it is reduced to less than 1 min when the algorithm is applied to the couple BESS-supercapacitor. Finally, these results show that the combined use of the proposed control algorithms embedded in the MC and HESS is really useful to improve microgrid storage system capability to provide both user services and ancillary services to the grid.

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References

1. ABB Energy Storage Solutions Brochure, *EssPro™ energy storage Power Conversion System (PCS) - the power to control energy*. Available at: https://library.e.abb.com/public/a9b8ede76a664383b8ecffaad161730b/EssPro-PCS_Brochure.pdf

2. A.B. Attya, J.L. Domínguez-García, F.D. Bianchi, O. Anaya-Lara, Enhancing frequency stability by integrating non-conventional power sources through multi-terminal HVDC grid. *Int. J. Elect. Power Energy Syst.* **95**, 128–136 (2018). <https://doi.org/10.1016/j.ijepes.2017.08.032>. ISSN 0142-0615
3. M. Brenna, F. Foiadelli, M. Longo, D. Zaninelli, Ancillary services provided by BESS in a scenario characterized by an increasing penetration of unpredictable renewables, in *2017 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe), Torino, 2017*, (IEEE, Piscataway, NJ, 2017), pp. 1–6. <https://doi.org/10.1109/ISGTEurope.2017.8260215>.
4. C. Brivio, S. Mandelli, M. Merlo, Battery energy storage system for primary control reserve and energy arbitrage. *Sustain. Energy Grids Netw.* **6**, 152–165 (2016). <https://doi.org/10.1016/j.segan.2016.03.004>. ISSN 2352-4677
5. G. Foggia, A. Neto, A. Michiorri, A. Bocquet, Coordinated control of dispersed battery energy storage systems for services to network operators, in *23rd International Conference on Electricity Distribution - CIRED 2015, 2015, Lyon, France*, (CIRED, Liège, 2015)
6. N. Chettibi, A. Mellit, Intelligent control strategy for a grid connected PV/SOFC/BESS energy generation system. *Energy* **147**, 239–262 (2018). <https://doi.org/10.1016/j.energy.2018.01.030>. ISSN 0360-5442
7. C.-H. Yoo, I.-Y. Chung, H.-J. Lee, S.-S. Hong, Intelligent control of battery energy storage for multi-agent based microgrid energy management. *Energies* **6**, 4956–4979 (2013). <https://doi.org/10.3390/en6104956>
8. G. Graditi, G. Adinolfi, R. Ciavarella, V. Palladino, Design support tool for multi-DER residential microgrids, in *ICRERA 2018 - 7th International Conference on Renewable Energy Research and Applications*, (IEEE, Piscataway, NJ, 2018), pp. 667–672. <https://doi.org/10.1109/ICRERA.2018.8566729>
9. G. Graditi, R. Ciavarella, M. Valenti, An innovative BESS management for dynamic frequency restoration, in *17th IEEE International Conference on Environment and Electrical Engineering and 2017 1st IEEE Industrial and Commercial Power Systems Europe, EEEIC/I and CPS Europe 2017*, (IEEE, Piscataway, NJ, 2017). <https://doi.org/10.1109/EEEIC.2017.7977864>. Article number 7977864
10. Istat, *Data Warehouse, Censimento Popolazione Abitazioni*. Available at: <http://dati-censimentopopolazione.istat.it/index.aspx>
11. C. Ricerche, *Determinazione dei fabbisogni e dei consumi energetici dei sistemi edificio-impianto. Caratterizzazione del parco immobiliare ad uso residenziale - Ricerca Di Sistema Elettrico, Report RdS/2012/109* (ENEA, Rome, 2012)
12. S. Maggiore, *Studi e valutazioni sull'uso razionale dell'Energia Elettrica - Impatto su comportamenti e consumi delle famiglie di un sistema di prezzi biorari dell'energia elettrica: RSE reference number 11000398* (RSE, Milan, 2011)