IET Generation, Transmission & Distribution

Research Article

Synergistic operation between battery energy storage and photovoltaic generator systems to assist management of microgrids

ISSN 1751-8687
Received on 19th February 2018
Accepted on 1st April 2018
E-First on 3rd May 2018
doi: 10.1049/iet-gtd.2018.0314
www.ietdl.org

Tiago Davi Curi Busarello[1] ✉, *Helmo K.M. Paredes*[2], *José A. Pomilio*[3], *Marcelo G. Simões*[4]
[1]*Department of Engineering, Federal University of Santa Catarina, Rua Pomerode, 710, 89065-300 Blumenau, SC, Brazil*
[2]*Institute of Science and Technology, São Paulo State University, Av. Três de Março, 511, 18087-180 Sorocaba, SP, Brazil*
[3]*School of Electrical and Computer Engineering, University of Campinas, Av. Albert Einstein, 400, 13083-852 Campinas, SP, Brazil*
[4]*Department of Electrical Engineering and Computer Science, Colorado School of Mines, 1610 Illinois Street, 8400 Golden, CO, USA*
✉ *E-mail: tiago.busarello@ufsc.br*

Abstract: This study presents a synergistic operation between a battery energy storage (BES) and a photovoltaic generator (PVG) system to assist management of microgrids. The BES and the PVG work synergistically in a virtual single agent. The single agent consists of a group containing the BES, the PVG, and the loads in a feeder. The single agent results in a virtual distributed energy resource, capable to obey orders imposed by the supervisory controller (SC). The loads within the single agent seem not existent anymore to the SC, but they kept fed all the time. This is convenient to the microgrid in terms of management because the SC interacts with only one element and not more with all elements within the single agent. The synergistic operation arises when the SC demands orders to the single agent. To make the single agent obey the SC, the BES and PVG need to decide their operation mode, working synergistically for each other. The conservative power theory is applied to quantify active power, reactive energy, and harmonic currents in points of interest along the microgrid. The efficacy of the synergistic operation is verified through experimental results.

1 Introduction

Contributions to the improvements of microgrids have constantly been reported in the literature. Consequently, the worldwide total installed capacity of microgrids increases considerably every year, achieving 12 GW in the end of 2015 [1]. The realisation of a microgrid is possible mainly due to the capacity of interaction among their distributed energy resources (DER) through information and communication technology (ICT). A supervisory controller (SC) is responsible for managing and taking decisions to the DERs in order to guarantee stability, reliability, uninterrupted supply, a cost-effective operation, and other related issues.

Two common DER in microgrids are photovoltaic generator (PVG) and battery energy storage (BES) systems. PVG systems represent a great portion of the energy generation of microgrids [2]. However, PVG systems face unavoidable behaviours like intermittency of the delivered power over different timescales and temporal difference between generation and load consumption. On the other hand, storages are a DER with programmable power dispatch and they are an indispensable technology for microgrids.

Several ways to store energy were developed over the years. Some examples are pumped hydro, compressed air, flywheel, batteries, capacitor, and supercapacitor [3–7]. The choice of storage technology depends on criteria like cost, power and energy density, life-cycle, and environment impact. Batteries are a promising technology for energy storage systems used in low-scale microgrids because several hurdles are being broken. One example is the possibility to recycle 99% of total weight of sodium-sulphur batteries [8].

In microgrids, DERs interact with SC through exchanging information and obeying set-points imposed by the SCs. Moreover, in some cases, the PVG and BES can perform tasks beyond their basic, such as harmonic current compensation, power factor correction, voltage, and stability supporting [9–11]. With DERs performing ancillary services, the SC increases its options in choosing the best way to manage the microgrid.

SCs usually manage a microgrid by applying strategies like energy dispatching [12–19], load sharing, voltage/frequency and power quality regulation, market participating, short- and long-term schedules for DERs, and so on. In [12], the authors exploited coordinated energy dispatching approaches in a microgrid. The SC gets information of PVG power and load demand and sends set-points to the PVG. In [13], it is proposed a distributed economic dispatch strategy for microgrids with multiple BES systems. The SC reads each BES unit and it runs a strategy assuring the dynamic couplings among all decision variables in a centralised dispatching formulation. In [17–19], strategies for frequency regulation and power quality achievement are proposed. In each case, the SC measures voltage, current, and frequency and decide the mode of operation of each DERs.

Synergistic and cooperative strategies appear to simplify the management of a microgrid [20–22]. In [20], it is proposed a cooperative control strategy for coordinating the energy storages to maintain the supply–demand balance and minimise the total power loss associated with charging/discharging processes. In [21], the authors describe an approach to the cooperative operation of a system of distributed harmonic and reactive compensators acting in the same network.

A common point in such strategies is the need for the SC to obtain information from all elements within the microgrid. Later, the SC sends commands to all DERs according to the microgrid objectives. As the number of DERs and loads in a microgrid increases, the volume of information also increases, requiring more complex algorithms and making the management more difficult.

This paper proposes a synergistic operation between a BES and a PVG system. Some elements of the microgrid, including the BES, PVG, and loads, are virtually transformed into a single agent. As a result, an SC manages the microgrid in a simplified manner. The SC passes to interact with the single agent, not more to the elements individually. It is assumed that each feeder of the microgrid is transformed into a single agent.

When managing the microgrid, the SC considerers the single agent as a new DER capable of obeying requirements like cancelling the input current completely, cancelling input distortive and reactive current, and also supplying active power through sinusoidal input current. The loads within the single agent keep constantly fed. The synergistic operation arises when the SC demands orders to the single agent. To make the single agent obey

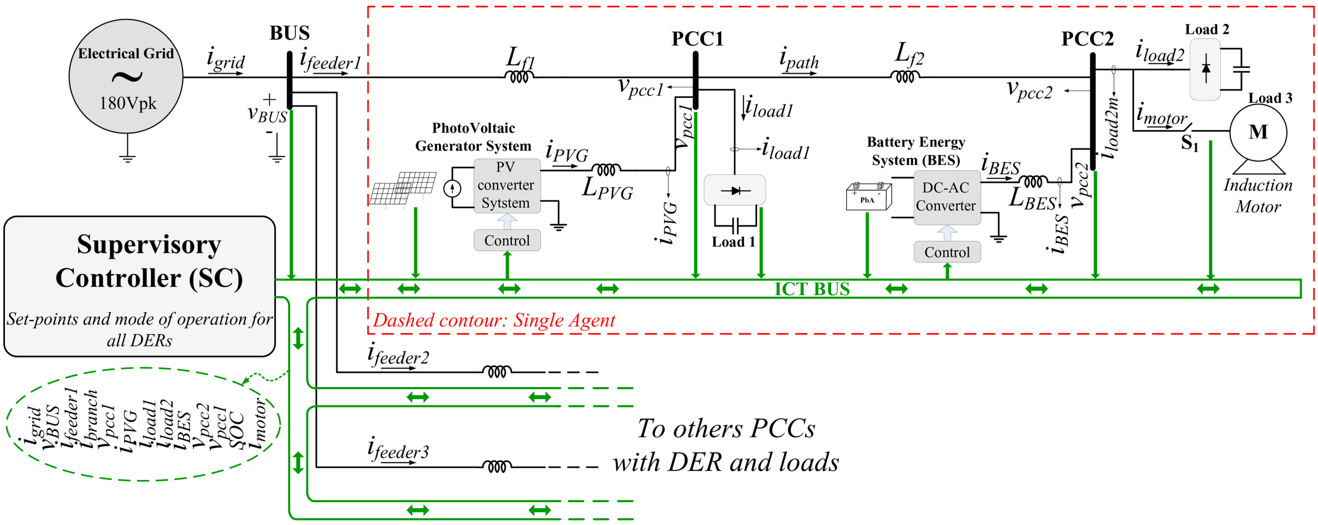

Fig. 1 *Simplified diagram of a microgrid*

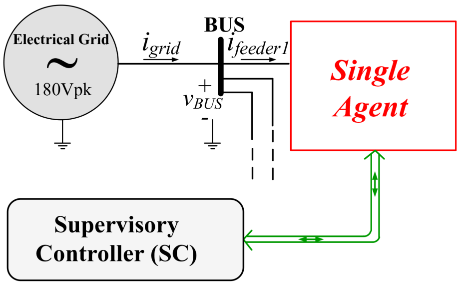

Fig. 2 *Diagram of the microgrid, but now with the single agent*

the SC, the BES and PVG need to decide their operation mode, working synergistically for each other. The single agent keeps obeying the SC even under the following events: over-temperature in the batteries, where a reduction on its delivered power is required, abrupt connection of highly inductive load, and power intermittency of the PVG system.

Another proposal of this paper is the use of the conservative power theory (CPT) to quantify active power, reactive energy, and harmonic currents along the microgrid to establish the synergist operation correctly. The current decomposition feature of the CPT is an attractive tool to decompose any current into three parts. For single-phase systems, these parts are named as active current, reactive current, and void current [23]. Decomposing the current into three parts contributes to the selectivity capability of the synergistic operation to decide the best current reference for the DERs grouped within the single agent.

Summarising, the contributions of this paper are listed as follows:

- Propose a synergistic operation between the BES and PVG to facilitate an SC to manage the microgrid.
- Propose an appropriate definition of current references for the BES and PVG through a load power sharing strategy and further guarantee the synergistic operation between them.
- Use the CPT to compute active power, reactive energy, and harmonic currents.
- Show the capability of the proposal synergistic operation to keep working even under some condition like over-temperature in the batteries, where a reduction on its delivered power is required, abrupt connection of highly inductive load, and power intermittency of the PVG system

The advantages of using the proposed synergistic operation over a conventional battery–PV systems are the fact that the SC interacts with a reduced number of elements. In this case, due to the experimental prototype, the feeder has only two DERs. However, in a feeder with several DERs, an extension of the proposed synergistic operation would reduce the effort developed by the SC from several DERs to only one. This is the reason that this proposal is more attractive than those presented in [20–22].

The synergistic operation is somewhat a synonym of cooperative operation, but with some differences. One of them is that the synergistic operation aims the operation of the DERs involved as one virtual DER. On the other hand, cooperative operation among DERs considers each DER as a controllable unit. The existence of the single agent plus the synergistic operation is similar to a decentralise strategy, where decisions are taken locally instead of centrally, but with the concept of a virtual agent.

2 System perspective

Fig. 1 presents a simplified diagram of a microgrid. The dashed board represents the part of the microgrid which is going to be virtually transformed into a single agent. The microgrid is single phase and it has the main generation, feeders, point of common coupling (PCC), an SC, and an ICT bus. Only feeder 1 is detailed for the sake of simplicity. Feeder 1 has a path after PCC1. It is assumed that the PVG and BES can work as active power filters simultaneously to their basic functions. Moreover, the synergistic operation is guaranteed when the charge of the batteries are within its nominal range in the state-of-charge (SOC) curve. The BES and the PVG have their own current controller. The reference for these controllers are sent from the SC. These controllers have enough bandwidth to follow their reference with negligible steady-state error. Details of these controllers can be found in [22, 24].

Fig. 2 presents the same diagram but now with the single agent created. Using the synergistic operation between PVG and BES, the SC interacts now with a single agent. The goal within the single agent is to handle the energy in the most appropriate manner while addressing the orders imposed by the SC. In this case, it is assumed that the SC knows the PVG and BES power rate. The single agent is formed in feeder 1 and envelops all elements of this feeder. The BES serves as a local controller to manage the elements within the single agent. The BES uses information from the ICT bus to compute the CPT currents and to send information to the PVG.

3 Conservative power theory

The CPT is a time-domain theory that can be applied to single or multiphase system with or without a neutral conductor. It is based on the orthogonal decomposition of electrical variables, resulting in electrical quantities with physical meanings [23]. The CPT does not need any variable transformation like occur in PQ theory and other reference transformation techniques [24, 25].

After the measurements of electrical variables (voltages and currents) in the microgrid, the BES computes active power, reactive energy, and harmonic currents through the CPT.

The objective of quantifying the active power, reactive energy, and harmonic current is to enlarge the options of the SC to manage the grid. In this context, the SC can create the single agent according to the current values of the active power, reactive energy, and harmonic current along the grid. This is also attractive to best define the current references for the BES and PVG. The SC defines the elements within the single agent based on these quantities.

Therefore, for scalar quantities, the following operators are defined.

The average value of a variable x is given by the below equation

$$\bar{x} = \frac{1}{T}\int_0^T x(t)\mathrm{d}t \tag{1}$$

The time-integral of a variable x is given by the below equation

$$x_f(t) = \int_0^T x(\tau)\mathrm{d}\tau \tag{2}$$

The unbiased integral of a variable x is given by the below equation

$$\hat{x}(t) = x_f(t) - \bar{x}_f(t) \tag{3}$$

where the second term of (3) is the average value of (2). The unbiased term means average value.

The time-derivative of a variable x is given by the below equation

$$\breve{x}(t) = \frac{\mathrm{d}x(t)}{\mathrm{d}t} \tag{4}$$

The unbiased integral and the time-derivative present the following properties:

$$\begin{aligned} &\hat{\breve{x}} = \breve{\hat{x}} = x \\ &\langle x, \breve{x}\rangle = \langle x, \hat{x}\rangle = 0 \\ &\langle x, \breve{y}\rangle = -\langle \breve{x}, y\rangle \\ &\langle x, \hat{y}\rangle = -\langle \hat{x}, y\rangle \\ &\langle \breve{x}, \hat{y}\rangle = \langle \hat{x}, \breve{y}\rangle = -\langle x, y\rangle \end{aligned} \tag{5}$$

where $\langle\cdot,\cdot\rangle$ is the internal product.

The RMS value of a variable x is represented by the below equation

$$X_{\mathrm{rms}} = \| x \| \tag{6}$$

Thus, in any single-phase system, for a given voltage $v(t)$ and a current $i(t)$, the active current, responsible for carrying active power, is given by the below equation

$$i_{\mathrm{a}}(t) = \frac{\langle v(t), i(t)\rangle}{\| v \|^2}v(t) \tag{7}$$

In a similar way, the reactive current, responsible for carrying reactive energy, is given by the below equation

$$i_{\mathrm{r}}(t) = \frac{\langle \hat{v}(t), i(t)\rangle}{\| \hat{v} \|^2}\hat{v}(t) \tag{8}$$

The residual distortive current is given by the below equation

$$i_v(t) = i(t) - i_{\mathrm{a}}(t) - i_{\mathrm{r}}(t) \tag{9}$$

The residual current contains all quantities that do carry neither active power nor reactive energy [23].

Unlike i_{a}, all the other portions of current (i_{r} and i_v) characterise a non-ideal aspect of load performance. Detailed discussion of such currents and power components can be found in [22, 23].

The active power delivered by the PVG is given by the below equation

$$P_{\mathrm{PVG}}(t) = \frac{1}{T}\int_t^{t+T} v_{\mathrm{PCC1}}(t)i_{\mathrm{a\_PVG}}(t)\mathrm{d}t = \langle v_{\mathrm{PCC1}}, i_{\mathrm{a\_PVG}}\rangle \tag{10}$$

Similarly, the active power delivered by the BES is given by the below equation

$$P_{\mathrm{BES}}(t) = \frac{1}{T}\int_t^{t+T} v_{\mathrm{PCC2}}(t)i_{\mathrm{a\_BES}}(t)\mathrm{d}t = \langle v_{\mathrm{PCC1}}, i_{\mathrm{a\_BES}}\rangle \tag{11}$$

where $i_{\mathrm{a\_PVG}}$ and $i_{\mathrm{a\_BES}}$ are the active currents of the PVG and BES, respectively.

4 Principle of the synergistic operation

The synergistic operation between the PVG and BES is established after the SC requires an activity to the single agent. An activity can be the cancellation of the input current, the cancellation of distortive and reactive currents at the input port, and the injection of active power into the main grid with sinusoidal current. These requirements are independent of each other and the loads are fed all the time. Since the single agent is created, the BES and the PVG work synergistically to obey the aforementioned activities. This is necessary because the SC ‘sees’ all elements within the single agent as a unique DER. Therefore, the power processing within the single agent is dependent on the synergistic operation. Specific references are calculated to the BES and PVG for such achievement. This is the sense in how the synergistic operation is defined. In other words, the BES and PVG help each other in processing the energy to accomplish the activities. It is important to highlight again that all the loads are kept fed.

Regarding the three requirements analysed here, the first, the cancellation of the input current of the single agent, means eliminate completely the input current of the single agent. This emulates a scenario where the SC is computing the optimise set-points for the DERs along the microgrid to achieve a goal, like power loss reduction. Instead of using all primary source powers from the DERs as input data in the optimisation algorithm, the SC uses lower data, since the single agent is a virtual DER and the BES and PVG are working synergistically. The other two requirements have also its purpose, as will be explained later.

To the single agent obey these requirements, the synergistic operation is an attractive alternative. The BES and the PVG exchange information about the available power on their primary source and the local controller defines their current references.

Events like over-temperature in the batteries, abrupt connection of highly inductive load, and power intermittency of the PVG system are inserted in order to show that the synergistic operation keeps obeying the SC even under these behaviours.

4.1 Requirement 1: cancellation of the input current

As previously explained, the BES and PVG operate synergistically to make the single agent has its input current eliminated. This emulates that the SC wants power loss reduction and decided that the input current of the single agent is necessary for that. Several ways could be establish as current reference for the BES and the PVG for such an achievement.

From Figs. 1 and 2, when the single agent is demanded by the SC to cancel its input current, the synergist operation is expressed mathematically as presented in the below equation

$$i_{\mathrm{in}}(t) \to 0 \quad \text{as} \quad i_{\mathrm{feeder1}}(t) \to 0 \tag{12}$$

In order to cancel the current of the feeder, the PVG and BES current references are given by the below equation

$$i_{\mathrm{PVG}}(t) = i_{\mathrm{load1}}(t) \quad \text{and} \quad i_{\mathrm{BES}}(t) = i_{\mathrm{load2}}(t) \tag{13}$$

Table 1 Prototype parameters

Parameter	Value
grid peak voltage	$V_p = 180$ V
grid frequency	$f_g = 60$ Hz
feeder 1 inductance	$L_{f1} = 0.3$ mH
PVG power	$P_{PVG} = 1$ kW
PVG inductance	$L_{PVG} = 4.25$ mH
BES maximum power	$P_{BESmax} = 500$ W
BES rated capacity	$C_{aBES} = 7$ Ah
load 1: inductance of the rectifier DC-side filter	$L_{rect1} = 35$ mH
load 1: capacitance of the rectifier DC-side filter	$C_{rect1} = 470$ μF
load 1: rectifier filter load	$R_{rect1} = 95$ Ω
load 2: inductance of the rectifier DC-side filter	$L_{rect2} = 35$ mH
load 2: capacitance of the rectifier DC-side filter	$C_{rect2} = 470$ μF
load 2: rectifier filter load	$R_{rect2} = 200$ Ω
load 3: induction motor apparent power	$S_m = 100$ VA
sampling frequency	$F_s = 30$ kHz

By setting (13) to the PVG and BES, they work synergistically. It is assumed that both the BES and PVG have enough power on their primary source. As a result, the requirement imposed by the SC is obeyed.

4.2 Requirement 2: cancellation of distortive and reactive currents at the input port

The circulation of harmonic currents may cause several undesirable effects in a microgrid. Some examples are voltage distortion, overstress in transformers, increase in the power losses, electromagnetic radiation, malfunction of protection device, and others. Reactive energy may cause over- or under-voltage along the microgrid. In this context, it is emulated that the SC is interesting in having high power quality indices along the microgrid. Since the micrgrid has non-linear loads, the SC would establish to DERs to operate as active filter if single agent was not existent. However, the SC only demands that the input current of it cannot contain reactive and harmonic content. Therefore, the BES and the PVG must again work synergistically to make the single agent obey such a demand.

When the SC demands to the single agent to cancel the circulation of non-active current at its input port, the input current of the single agent must have same waveform proportional and in-phase to the input voltage. A convenient manner to accomplish this requirement, even though there are several ways to do that, is to set the PVG and BES to operate exclusively as active power filter. The PVG must supply the non-active current for the non-linear load connected at PCC1, while the BES to the non-linear load connected at PCC2. In general, the waveform (ifeeder1) can be defined using the instantaneous voltage at the PCC or its fundamental components, representing resistive current or sinusoidal current injection, respectively. Therefore, the currents into the microgrid for requirement 2 can be expressed mathematically as in the below equation

$$\begin{gathered} i_{\text{feeder1}}(t) \to i_{\text{a\_load1}}(t) + i_{\text{a\_load2}}(t) \\ \text{as}\, i_{\text{PVG}}(t) \to i_{\text{r\_load1}}(t) + i_{v\text{\_load1}}(t) \\ \text{and}\, i_{\text{BES}}(t) \to i_{\text{r\_load2}}(t) + i_{v\text{\_load2}}(t) \end{gathered} \tag{14}$$

4.3 Requirement 3: injection of active power into the main grid with sinusoidal current

This requirement is one of the most interesting advantageous of grouping elements in a single agent. The SC can demand the injection of active power from the single agent input terminals. In this context, it is emulated that the SC needs active power from the single agent in order to avoid load curtailment in the loads located upstream from feeder 1 or for power losses reduction along the microgrid. Then, the BES and PVG again operate synergistically to make the single agent to achieve such a requirement. Considering this requirement and the previous one, the single agent works similar to a prosumer – a consumer and a producer. This is due to the fact in this requirement the single agent inject active power into the grid while in the previous one, the single agent consumes active power from the grid. This capability of the single agent to work similar to a prosumer enlarges the options of the SC to manage the microgrid.

In case that the PVG has no available power to inject and in the case of a demand for injecting active power into BUS with sinusoidal current, the synergistic operation establishes that the input current (ifeeder1) of the single agent must be sinusoidal and in counter-phase related to the input voltage (vBUS). The counter-phase is required because there is no requirement to inject or consume reactive energy.

Requirement 3 can be mathematically expressed as

$$i_{\text{feeder1}}(t) \to \frac{P_{\text{ref}}}{\| v_{\text{BUS}} \|} \sin\left(\theta t + \frac{\pi}{2}\right) = i_{\text{power}}(t) \tag{15}$$

where P_{ref} is the amount of power the SC desires and θ the angle of the PCC1 voltage, obtained from a phase-locked loop.

In order to the single agent to fulfil this requirement, it is necessary to feed all loads, which means to supply the active power and to compensate distortive and reactive currents. The PVG is set to operate exclusively as active power filter for load 1 and the BES is set to inject active power and to operate as active power filter, simultaneously.

The PVG current is given by

$$i_{\text{PVG}}(t) = i_{\text{r\_load1}}(t) + i_{v\text{\_load1}}(t) \tag{16}$$

The BES current is given by

$$i_{\text{BES}}(t) = i_{\text{a\_load1}}(t) + i_{\text{load2}}(t) + i_{\text{power}}(t) \tag{17}$$

Since the PVG and BES follow their current reference, they work synergistically to achieve this requirement.

4.3.1 Active power sharing between the PVG and BES: In the previous requirement, the synergistic operation makes the PVG to operate exclusively as active power filter. However, the PVG can also set to inject active power. The PVG supplies active power according to the solar radiation. Then, the BES supplies power according to the difference between the reference and the instantaneous PVG output power. The active power reference for the BES is given by

$$P^{*}_{\text{BES}}(t) = P_{\text{ref}}(t) - P_{\text{PVG}}(t) \tag{18}$$

Therefore, the power reference for the BES is translated into a sinusoidal current reference according to the below equation

$$i_{\text{ref\_BUS}} = \frac{P_{\text{ref}}}{\| v_{\text{BUS}} \|} \sin\left(\theta t - \frac{\pi}{2}\right) \tag{19}$$

5 Experimental results

The synergistic operation was experimentally verified in the system presented in Fig. 1. The parameters used in the prototype are presented in Table 1. The PVG system is emulated by a DC/AC converter, a DC source, and an inductive output filter and with a characteristic deliver power profile. The BES was built in a multilevel inverter with lead–acid batteries. Details of them are beyond the scope of this paper, but can be found in [26, 27].

The following scenarios were experimentally verified under the following assumptions:

- The synergist operation is performed when the SOC of the batteries is within the interval between 40 and 90%.

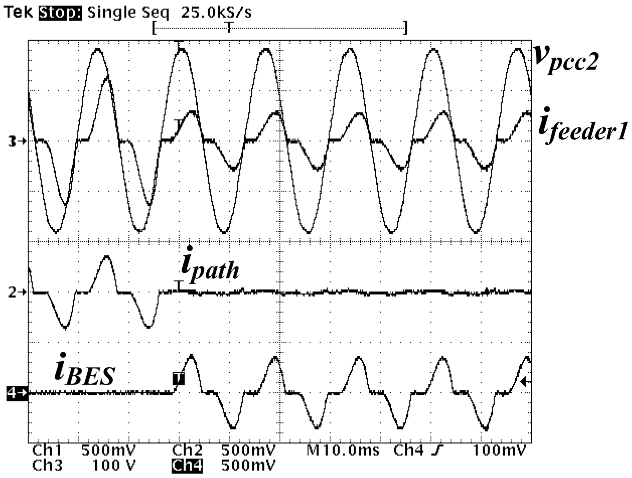

Fig. 3 *Initial results for the synergistic operation in requirement 1 (Ch1, Ch2, Ch4: 0.1 V/A)*

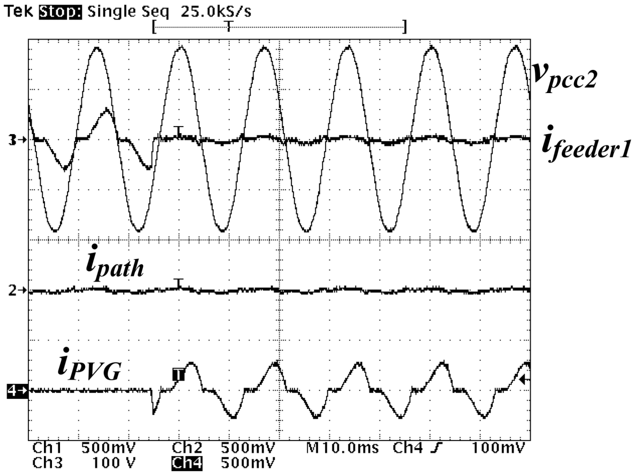

Fig. 4 *Final results for the synergistic operation in requirement 1 (Ch1, Ch2, Ch4: 0.1 V/A)*

- The synergist operation is guaranteed never requesting to the BES to supply active power more than its maximum power.
- The primary source of the PVG may vary its value along the time, but it is considered free of energy shortages.

5.1 Requirement 1: cancellation of the input current

Fig. 3 presents initial results for the synergistic operation in requirement 1. Initially, both PVG and BES are turned off. The BES turns on at the scope trigger position. Before that, feeder 1, which is the input current of the single agent, and the path have high distorted currents. As soon as BES begins to operate, the path has its current cancelled. The BES current is the current of load 2 (not showed). Feeder 1 has its current decreased, but it is still highly distorted due to the PVG still be turned off.

Fig. 4 presents final results for the synergistic operation in requirement 1. The PVG current is the load 2 current. Both feeder 1 and path have null current. Requirement 1 is fulfilled. The input current of the single agent is cancelled while the loads keep fed. The cancellation of the currents was cancelled sequentially for better visualisation, but they could be done simultaneously.

5.1.1 Event: abrupt connection of a squirrel-cage inductive motor: The BES has a special mode dealing with the starting process of a squirrel-cage induction motor when the single agent is addressing requirement 1. For this, the motor is connected to PCC2 through the S_1 switch shown in Fig. 1. The non-linear load at PCC2 was removed for better visualisation of the path current. Fig. 5 presents results when S_1 switch is turned on. The path and the single agent currents are kept null. In this case, the current drained by the motor is completely supplied by the BES.

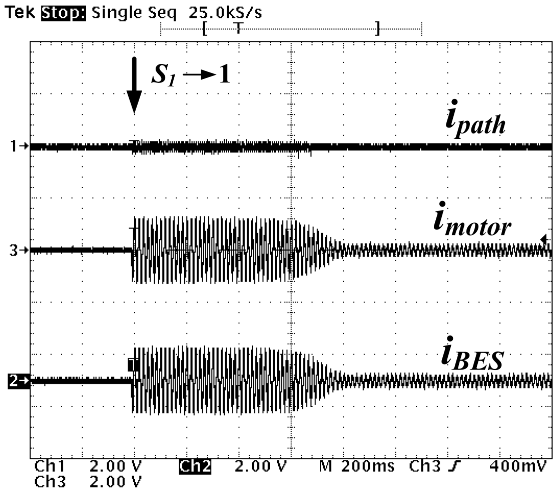

Fig. 5 *Results when S_1 switch is turned on (Ch1, Ch2, Ch3: 0.1 V/A)*

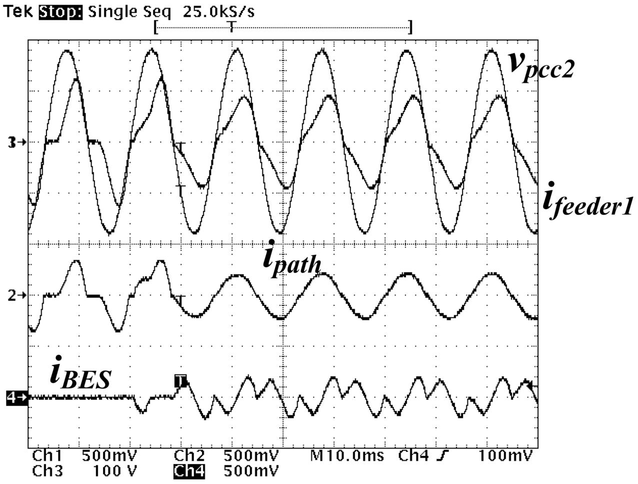

Fig. 6 *Initial results for the synergistic operation in requirement 2 (Ch1, Ch2, Ch4: 0.1 V/A)*

5.2 Requirement 2: cancellation of distortive and reactive currents at the input port

Fig. 6 presents initial results for the synergistic operation in requirement 2. Initially, when the BES turns on at the trigger position, the path current becomes sinusoidal and the feeder 1 current has its distortion reduced.

Fig. 7 presents final results for synergistic operation in requirement 2. The feeder 1 current reaches a sinusoidal waveform by the moment the PVG turns on. In the end, both the feeder 1 and path currents are sinusoidal and in-phase related to the PCC1 and PCC2 (not shown) voltages, respectively. Requirement 2 is fulfilled.

5.3 Requirement 3: injection of active power into the main grid with sinusoidal current

Fig. 8 presents the PCC1 voltage and the feeder 1 and path currents in a large time scale during synergistic operation in requirement 3. All waveforms are sinusoidal, as will be presented later. The amplitude of the waveforms must be observed in the following analysis: initially, the waveforms of the feeder 1 and path currents are those presented in Fig. 7. The path reaches first the zero current, indicating that the BES is injecting active power in a certain rate. As the time goes on, the amount of injected power is enough to feed the load at PCC2 and also to invert the flux on the path. Feeder 1 is still draining power from the grid due to the load connected at PCC1. The BES continues injecting power. At the

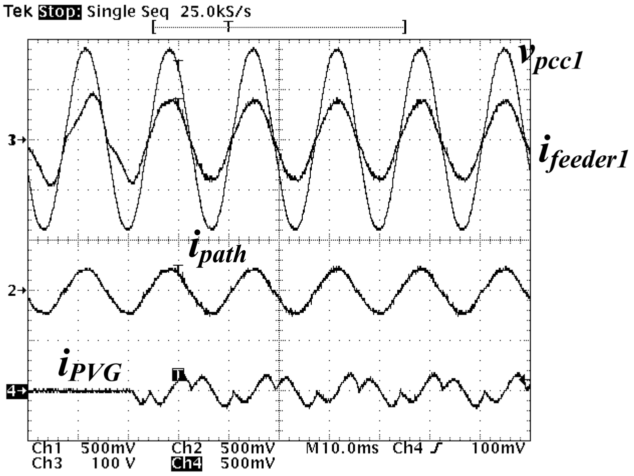

Fig. 7 *Final results for the synergistic operation in 2 (Ch1, Ch2, Ch4: 0.1 V/A)*

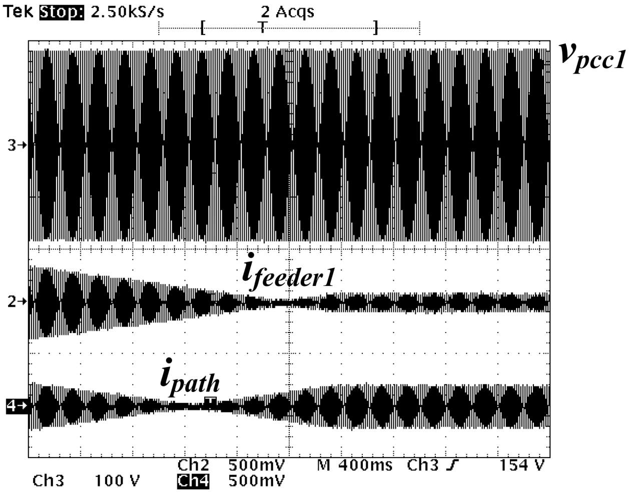

Fig. 8 *PCC1 voltage and the feeder 1 and 2 currents in a long time scale during synergistic operation in requirement 3 (Ch1, Ch2, Ch4: 0.1 V/A)*

end, load 2 is fully supplied and the grid receives power with sinusoidal current. Requirement 3 is fulfilled.

Fig. 9 presents the steady-state results after the fulfilment of requirement 3. Both feeder 1 and path currents are sinusoidal and in counter-phase related to the PCC1 voltage. Therefore, the grid receives active power and requirement 3 is confirmed.

5.3.1 Event: power intermittency of the PVG: In connection with the scope of requirement 3, Fig. 10 presents results for PVG floating power compensation in a large time scale (at the bottom) and a detail (at the top). At the narrow position, the amplitude of the BES output current begins to be modified according to the PVG current. The amplitude of the input current of the single agent is kept constant, indicating constant injected power. The PVG and BES current are sinusoidal and in-phase related to the BUS voltage. The grid current is also sinusoidal, but in counter-phase related to the BUS voltage. Therefore, even under an intermittent behaviour of the power delivered by the PVG, the single agent keeps obeying the requirement imposed by the SC.

5.3.2 Event: over-temperature in the batteries: Still addressing requirement 3, an event about over-temperature occurs, making the BES to reduce its delivered power until the situation is normalised. The following steps occur in this event.

- The SC establishes that the single agent must inject 340 W into BUS with sinusoidal current.

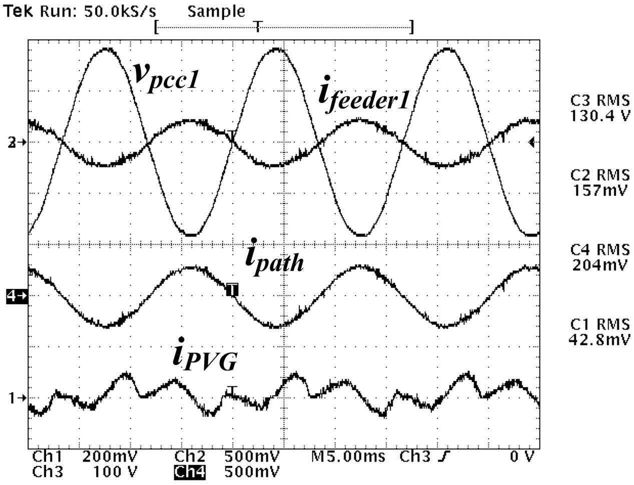

Fig. 9 *Steady-state results after the fulfilment of requirement 3 (Ch1, Ch2, Ch4: 0.1 V/A)*

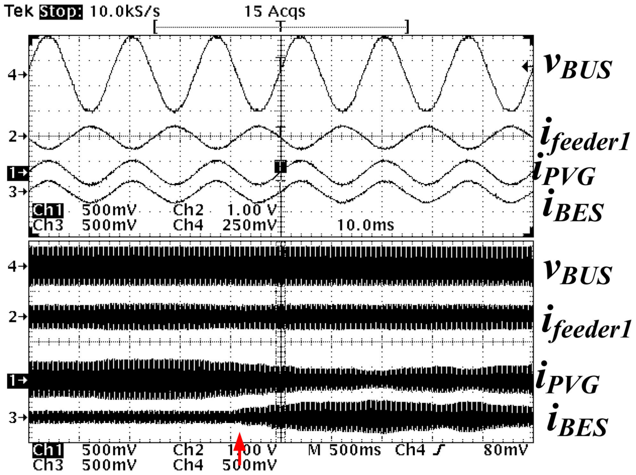

Fig. 10 *Results for floating power compensation in a large time scale (at the bottom) and a detail of the centre of the screen (at the top) (Ch4: 0.5 V/V; Ch1, Ch2, Ch3: 0.1 V/A)*

- The local controller decides based on the PVG primary source and the SOC curve the amount of power delivered for both PVG and BES.
- The BES detects over-temperature on its battery bank.
- The BES reduces by half its delivered power.
- The PVG doubles its delivered power.

It is assumed that the BES has a proper thermal measurement and the measured information is sent to the local controller.

Fig. 11 presents the results for the moment when the BES reduces by half its injected power while the PVG current is doubled. The input current of the single agent is kept unchanged, showing that the requirement imposed by the SC is obeyed. Similar results were obtained during the moment where the situation was normalised. This result also shows a similar case of active power sharing, since both the BES and PVG output currents are in-phase related to the bus voltage.

6 Discussion

6.1 About the ICT bus

The ICT bus is mainly intended to guarantee interoperability among the DERs and the SC in a microgrid. Such interoperability must address the following features [28]: (i) exchange of meaningful, actionable information among DERs and SC across organisation boundaries; (ii) a shared understanding of the exchanged information; (iii) an agreed expectation for the response to the information exchange; and (iv) a minimum quality of service like reliability, fidelity, and security.

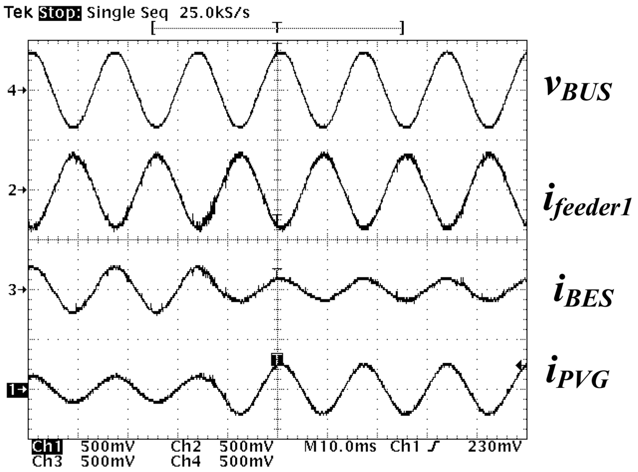

Fig. 11 *Results for the moment when the BES reduces by half its injected power while the PVG current is doubled (Ch4: 0.5 V/V; Ch1, Ch2, Ch3: 0.1 V/A)*

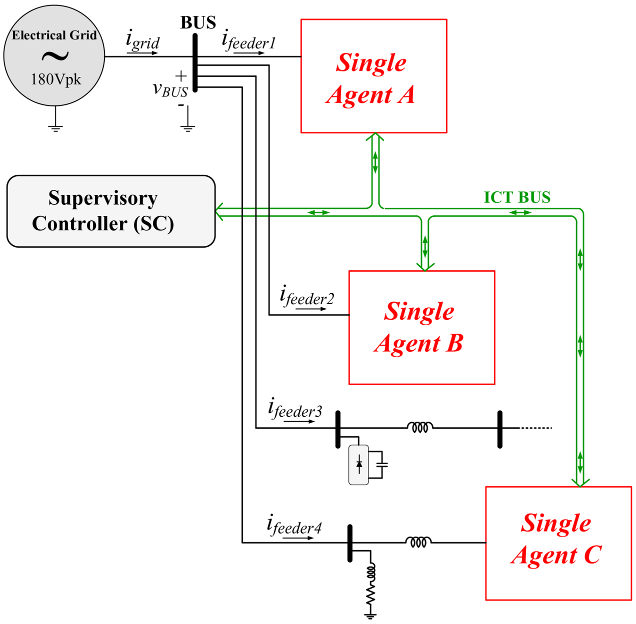

Fig. 12 *Idealised microgrid with several single agents*

Many technologies can be used to realise the ICT bus like open wireless mesh, power line communication, and 3G/4G service provider. Recently, the long-range wireless (LoRa) was introduced as a low-bandwidth wireless technology. Some of the advantage of LoRa is the low cost for communication, it can reach up to 10 km radius from the base station, it can operate on 433, 868, or 915 MHz bands, depending on the region in which it is installed and thousands of devices can be connected to a single gateway [28–30]. Additionally, phasor measurement units (PMU) is preferable chosen over the supervisory control and data acquisition (SCADA) [31] to measure voltage and current phasor along the microgid. PMU samples voltage and current typically at 30, 50, and 60 samples/s while SCADA has timescale of 4 s. Therefore, microgrids with LoRa or similar technology and PMU tend to present fast and reliable information exchange. In this paper, since the main goal is to propose the synergistic operation between PVG and BES system, the ICT bus in the prototype was done with serial peripheral interface (SPI) [32].

6.2 Superiority of existing a single agent

For the SC's point of view, the single agent is a single-input element in the microgrid. Grouping several PCCs, DERs, and loads is a great contribution to the SC in a variety of aspects. Moreover, this concept differs from a common microgid with SC because: (i) occurrences and decisions within the single agent are not affected by outside agents; (ii) the SC reduces its computational efforts when running optimisation algorithms. Since the single agent envelops some PCCs, an optimisation algorithm of the SC has lower input data; (iii) the SC can count on the single agent to support in management of the microgrid like in a voltage profile regulation; and (iv) the DERs within the single agent act as a decentralised controller, but limited to the boundaries of the single agent.

Given the features mentioned above, the existence of several single agents brings much more contributions to the microgrid, especially to the SC. The decisions become more decentralised and lower data travel through the microgrid. The SC manages the microgrid considering several single-input elements instead of several individual elements. Moreover, the SC does not lose its authority to decide how the single agents must operate.

One of the main capabilities of a single agent is to cancel its input current completely and keep all loads inside it constantly fed. In a microgrid with several single agents, the SC can configure the structure without making physical connection and disconnection. Additionally, a single agent can communicate to another singe agent in order to negotiate an energy transaction, when applicable. As a result, the SC is not perturbed and its order is kept obeyed. Fig. 12 presents an idealised microgrid with several single agents. In this case, it was created three single agents. Notice that not necessary all elements in a feeder are enveloped in a single agent. Feeder 4 has a single agent which does not envelop the PCC and the RL load located at the beginning of such feeder. Feeder 3 is not contemplated by a single agent because it does not fit the constraints to create one. Similar to the single agent in this paper, one DER within each single agent must operate as a local controller. The ICT bus links all agents and the SC. Therefore, the more single agents exist in a microgrid, the more simplified is to the SC to manage the microgrid.

6.3 Constraints on the single agent formation

In this paper, part of a microgrid was virtually transformed into a single agent. Then, a synergistic operation was established between two DERs to accomplish tasks imposed by the SC to the single agent. However, creating single agents and applying the synergistic operation is conditioned to some constraints in the microgrid. Firstly, it must be known what tasks the SC desires to demand to the single agent. If one of these tasks involves active power handling, then it arises a condition of the presence of a stationary energy storage system. This is because a storage does not have intermittent behaviour like generators based on renewable sources. This ensures a prompt supply of active power when demanded, in case the storage element is charged. Therefore, a single agent can be created with a storage and some DERs and loads around it. DERs in microgrids are supposed to have their controller and to have the capability to perform ancillary services. This helps out the formation of the single agent. Thus, a single agent can be created by including a local controller and arranging the communication network among DERs and the SC. The local uses information from the ICT bus; it establishes the synergistic operation and distribute the set-points for all DERs within the single agent. The SC has its orders obeyed without getting knowledge how the power is being processed within the agent. This simplifies considerably the management of the microgrid. The SC may reduce the interaction with some DERs to only one unit, the single agent.

7 Conclusions

This paper presented a contribution to the design of microgrids. A synergistic operation between a PVG and BES systems was proposed. Since part of the microgrid was transformed into a single agent, the SC passes to demand tasks to it. Then, the BES and the PVG work synergistically to make the single agent to obey the SC and to keep the load fed. Three requirements were order by the SC to the single agent. They were: cancellation of the input current, cancellation of non-active currents at the input port, and injection of active power into the main grid with sinusoidal current. The synergistic operation was tested experimentally, demonstrating its effectiveness in a scenario of practical interest. Such operation was guaranteed even under the events of over-temperature in the batteries, power fluctuation of PVG system, and abrupt connection of high inductive load. Therefore, the proposed synergistic operation is an attractive contribution for designing microgrids.

8 Acknowledgments

The authors are grateful to the São Paulo Research Foundation (FAPESP) (grants #2012/23914-5, #2016/08645-9 and #2017/22629-9) and National Council for Scientific and Technological Development – CNPq (grants #421281/2016-2 and #302257/2015-2) for supporting this research.

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