Research Article

A Control Method for Balancing the SoC of Distributed Batteries in Islanded Converter-Interfaced Microgrids

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In a low-voltage islanded microgrid powered by renewable energy sources, the energy storage systems (ESSs) are considered necessary, in order to maintain the power balance. Since a microgrid can be composed of several distributed ESSs (DESSs), a coordinated control of their state-of-charge (SoC) should be implemented, ensuring the prolonged lifespan. This paper proposes a new decentralized control method for balancing the SoC of DESSs in islanded microgrids, without physical communication. Each DESS injects a current distortion at 175 Hz, when its SoC changes by 10%. This distortion is recognized by every DESS, through a phase-locked loop (PLL). In order to distinguish the origin of the distortion, each DESS injects a distortion of different time duration. This intermediate frequency has been selected in order to avoid the concurrence with the usual harmonics. The DESSs take advantage of this information and inject a current proportional to the SoC. Implementing this strategy, a comparable number of charging/discharging cycles for each DESS are achieved. Furthermore, an active filter operation, implemented in the dq rotating frame for each individual harmonic, is integrated in the control of the distributed generation units, supplying nonlinear loads with high-quality voltage. The effectiveness of this method is verified by detailed simulation results.

1. Introduction

The tremendous increase in renewable generation penetration level in the electrical grids has favored the development of the microgrid concept, which is defined as a cluster of inter-connected distributed generation units (DGUs), loads, and ESSs [1]. A microgrid is able to operate in an uninterrupted way under grid-connected or islanded mode.

Different approaches concerning the effective energy management of such microgrids have been proposed in the literature. Most of them suggest a communication-based management system with central and local controllers [2, 3]. However, if the communication is lost, the controllers may generate undesirable control commands. Therefore, dependence on communication reduces the reliability of the control strategy. On the other hand, decentralized methods without communication rely on the power sharing among the micro-sources by taking into account only local measurements. A

control method without communication is the droop control method, where the DGUs emulate the operation of parallel synchronous generators [4].

In the technical literature, the critical role of the energy storage in microgrids is focused on the regulation of the voltage and frequency [5] and on preserving the power balance due to the intermittent operation of the renewable energy sources (RESs) [6]. Furthermore, other ancillary functions of the energy storage [7] may include the low-voltage ride-through (LVRT) capability, load leveling, peak shaving, and operating reserve. Integration of ESSs in microgrids allows flexibility but adds further complexity in the energy management and control. A crucial parameter to be considered when designing the energy management control is the SoC of the ESS. The SoC is the ratio of the remaining capacity to its nominal one.

The conventional control methods do not take into account the different capacities of the DESSs, leading to a

significant differentiation in their lifespans. Therefore, the applied power sharing methodology in an islanded microgrid should consider the SoC of each DESS as a crucial parameter. The target is to maintain a comparable number of charging/discharging cycles among all energy storage devices. Most of the technical references on SoC balancing refer to DC microgrids with distributed batteries [8, 9]. In [10] a power sharing control for an autonomous AC microgrid with batteries is presented. Although the sharing is based on the battery SoC, extensive communication is proposed, using central and local controllers.

Another important issue of the islanded microgrid concerns the voltage quality. Since the common loads feature nonlinearity, the control of DGUs should incorporate strategies for the attenuation of the most common harmonics. Assuming only three-phase symmetrical loads, the harmonics of third order are absent. The literature deals with the harmonic problem by placing extra converters parallel to the nonlinear loads [11, 12] or incorporating the active filter operation in the internal control of the DGUs [13, 14]. On the one hand, the placement of extra devices raises the initial investment of the microgrid, while it limits the further addition of nonlinear loads. On the other hand, the active filter control seems more effective. In [15], current harmonic loops are added in the current control, while in [16] the authors propose the distorted current waveform for the harmonics in phase with the voltage at the terminals of the DGU. In [17], an enhanced virtual impedance control on selected harmonics is implemented; however low-bandwidth communication is regarded. Other methodologies propose the use of resistive virtual impedances [18, 19]. Nevertheless, the voltage is severely distorted. In [20], the control strategy employs negative virtual harmonic impedance, in order to compensate the effect of line impedance on harmonic power delivery. The harmonic attenuation methods proposed in the literature are implemented in either abc or $\alpha\beta$ stationary frame. In first case, independent control systems for each phase are required, provoking a more complex control scheme. In case the $\alpha\beta$ stationary frame is used, the resonant frequency of the proportional-resonant (PR) controllers should be updated for every frequency change.

This paper proposes a new decentralized method for controlling the SoC of DESSs in an islanded AC microgrid with linear and nonlinear loads. A primary aim of the control is to balance the number of charging/discharging cycles of the DESSs, by adjusting their power sharing. For this reason, a power sharing strategy according to the SoC of each DESS is implemented. This method is based on the superstition of a distortion at 175 Hz in the injected output current of each DESS, when the SoC changes by 10%. In order to recognize the origin of the distortion, different time durations are used for each DESS. In this way, each DESS adapts the power injection according the SoC in respect to the SoC of the other DESSs. An intermediate frequency at 175 Hz has been selected in order to avoid the concurrence with harmonics of the basic frequency of 50 Hz. Moreover, unlike the high frequency (>3 kHz) power line communication (PLC) methods [21], where the signals might be attenuated by the low-pass filters, a signal at 175 Hz can effectively be propagated in the

microgrid bus. The magnitude of the injected distortion has been selected in compliance with the permissible limits for harmonic distortion in the LV grids. The proposed method is integrated in the control of each DESS, without requiring any additional communication infrastructure leading in reduced installation cost. A second target of the proposed control is to deal with the nonlinear loads. A nonlinear method for attenuating the 5th, 7th, 11th, and 13th harmonic of the voltage is applied. Unlike the presented methodologies in the literature, the proposed method is implemented in the dq rotating frame for each individual harmonic order. Its effectiveness is highlighted in islanded microgrids, due to the operation with variable frequency around the preassigned limits, without needing any further control update.

The rest of the paper is structured as follows. In Section 2, the microgrid decentralized control strategy for power sharing and harmonic attenuation is presented in detail. In Section 3, the proposed control strategy is described, while in Section 4 analytical simulation tests validate the methodology in an islanded microgrid with linear and nonlinear loads, being fed by PVs and batteries.

2. Microgrid Decentralized Control Strategy

2.1. Droop Control Method. The microgrid can be consisted of different type of DGUs, which are interfaced to the microgrid via DC/AC or AC/DC/AC converters. In order to avoid extra communication infrastructure, a decentralized strategy, based on the droop control method, is applied for the power sharing among the DGUs. Each DGU determines the frequency and the voltage magnitude of the common AC bus according to the injected active and reactive power, respectively. In this way, the DGUs emulate the parallel operation of synchronous generators. Considering inductive line impedances, the microgrid frequency f is determined by the active power P , while the node voltage V_n is determined by the reactive power Q , as it is described by the following equations:

$$\begin{aligned} f &= f^* - m \cdot P - m_d \frac{dP}{dt}, \\ V_n &= V^* - n \cdot Q - n_d \frac{dQ}{dt}, \end{aligned} \quad (1)$$

where f^* and V^* are the output voltage frequency and magnitude at no load, m and n the droop coefficients, P and Q the average active and reactive power, and m_d and n_d the derivative droop coefficients, respectively. The active and reactive output power of the inverter can be adjusted by means of the droop coefficients, while the derivative terms absorb the abrupt variations, preserving the power sharing dynamic stability [22].

When the microgrid consists of RESs, the droop coefficients are adjusted in accordance with the available power

P_{pot} . Thus, the droop coefficients are calculated by the following equations:

$$\begin{aligned} m &= \frac{\Delta f_{\text{max}}}{P_{\text{pot}}}, \\ n &= \frac{\Delta V_{\text{max}}}{P_{\text{pot}}}, \end{aligned} \quad (2)$$

where Δf_{max} and ΔV_{max} are the maximum deviation of the frequency of the magnitude of the voltage as it is defined by the Standard EN 50160.

However, in low-voltage microgrids the line impedance rarely is purely inductive. In most cases it consists of both resistive and inductive part [23]. With complex impedances, an accurate power sharing cannot be achieved, due to the coupled active and reactive power characteristic of the system. As a result, reactive currents are circulating among the DERs. To overcome this problem, the droop control method is modified with the virtual impedance control, as it is well stated in the literature [24]. The control scheme of each DGU is presented in Figure 1.

2.2. Harmonic Attenuation Control. The microgrid should be able to supply the loads with high-quality voltage, even under the presence of nonlinear loads. Therefore, an additional control is incorporated, in order to keep the voltage harmonic content within the permissible limits. In this paper, the microgrid consists of three-phase loads; for this reason the three-order harmonics are absent. Therefore, the proposed control deals with the attenuation of the most common harmonics, that is, the 5th, 7th, 11th, and 13th.

The structure of this control is based on the calculation of harmonic reactive power H and its sharing among the sources. The reactive power sharing takes place according to [25]. This technique uses a G - H droop to share the reactive harmonic power among the DGUs. The harmonic reactive power is calculated from the active and reactive power, as they are analyzed in average and alternating component:

$$\begin{aligned} P &= \bar{p} + \tilde{p}, \\ Q &= \bar{q} + \tilde{q}, \\ H &= \sqrt{\bar{p}^2 + \bar{q}^2}, \end{aligned} \quad (3)$$

where p and q are power measurements by means of Park Transformation, $\bar{p}$ and $\bar{q}$ are the mean values, and $\tilde{p}$ and $\tilde{q}$ are the alternating values. The sharing among the DGUs is carried out according to its apparent power, through the G - H droop control as it is described in

$$G = G_0 - bH, \quad (4)$$

where G is the conductance of the DGU at harmonic frequencies, G_0 the conductance at no harmonic reactive power, and b the droop coefficient. The maximum harmonic reactive power is rated at 0.65 times the apparent power, protecting the converter from large output currents. The last parameter b is defined so as

$$b_1 H_1 = b_2 H_2 = \dots = b_n H_n. \quad (5)$$

The harmonic control current is shown in Figure 2. According to this scheme, the measured voltage at the terminals of each DGU is transformed to the respective dq rotating frame, implementing the Park Transformation for each harmonic. Therefore, the order and the sequence (positive or negative) of each harmonic are taken into consideration for the control angle. A similar control is also implemented for the current transformation. The philosophy of the harmonic attenuation control is to eliminate the distorted voltage at the selected harmonics. Thus, a voltage and current controller, similar to the conventional droop control of the basic frequency, is adopted. The voltage reference for each harmonic order is equal to zero, while the reference of the current is the output of the voltage controller.

2.3. DESS Control. The DESS control is embedded in the DC/AC converter of the energy storage. Aim of the control is to measure the frequency and the magnitude of the common AC-bus voltage and determine the active and reactive power that should be absorbed or released, in order to ensure a high-quality voltage. At least one DESS should be placed on the point of common connection with the utility grid, in order to synchronize the microgrid during the transition from the island to the grid-connected mode, avoiding the considerable transient effects [4]. This operation is not presented in this paper, since it is focused on the islanded operation of the microgrid.

The control of the DESS, using a battery as energy storage device, is described in Figure 3(a). The voltage magnitude and frequency are measured through a dq phase-locked loop (PLL) [26], shown in Figure 3(b). When the frequency drops below a lower threshold ($f_{\text{min}} = 49$ Hz), the DESS is connected releasing active power. The aim is to restore the frequency to the preassigned operating range (target frequency is set to 49.01), according to [27]. Control is performed through a closed loop employing PI controller:

$$I_d = K_{pd1} (49.01 - f) + K_{id1} \int (49.01 - f) dt. \quad (6)$$

A similar control philosophy is adopted for defining the reactive power. When the voltage magnitude drops below a threshold ($V_{\text{min}} = 293$ V), the converter of DESS injects reactive power. The reactive current signal is defined by

$$I_q = K_{pq1} (293 - V_n) + K_{iq1} \int (293 - V_n) dt. \quad (7)$$

If the DESS is not fully charged, and the microgrid frequency is higher than 50 Hz it charges with a current equal to 1/10 of the nominal battery capacity.

The SoC of the DESS is constantly measured, as

$$\text{SoC} = \frac{Q_o - \int i_{\text{bat}} dt}{Q_{\text{tot}}}, \quad (8)$$

where Q_o is the initial charge of the battery, Q_{tot} the maximum charge of the battery, and i_{bat} the output current of the battery. The SoC limits for the usual charge-discharge cycle, ensuring an extended lifetime, are considered among 20% and 90%.

FIGURE 1: DGU converter control strategy.

FIGURE 2: Nonlinear control.

The reference for the active and reactive current injected by each DESS is modified by the ratio of the respective SoC to the aggregated SoC levels of all DESSs. In this way, the sharing of the active and reactive power demand among the DERs is performed proportional to their SoC. The active (I_{dref}) and reactive (I_{qref}) current reference signals are given by

$$I_{dqref,i} = I_{dq,i} \cdot \frac{\text{SoC}_i}{\sum_{j=1}^N \text{SoC}_j}, \quad (9)$$

where SoC_i is the SoC of the i -battery and N is the amount of the connected batteries. In order to ensure that the SoC will always remain within the predefined limits (20%–90%), once it reaches the lower limit, no more energy is released. Respectively, when the SoC of the battery reaches the upper limit, no more energy is absorbed. In this way, the SoC cannot exceed either the upper or the lower limit. Similar to the

control of the DGU, the SPWM method is used in the output of the current controller, as shown in Figure 3(a).

3. Battery Management Control Strategy

3.1. Key Principles of the Proposed Method. In order to ensure that each battery of the microgrid will have comparable number of charging/discharging cycles, the SoC should be effectively controlled. The SoC range is divided into equal levels, each representing 10% of the charge capacity. The proposed method is based on the superimposition of a sinusoidal distortion at 175 Hz in the injected output current of each DESS, when the SoC changes by 10%. More specifically, two distortions with different time durations are implemented in order to represent the 10% increase and 10% decrease of the SoC, respectively. Furthermore, in order to distinguish the origin of the distortion, each DESS uses different time

FIGURE 3: (a) DESS converter control strategy and (b) dq-PLL.

durations. The time duration of each injected distortion is described by an integer defining the number of periods ($T = 1/175$ sec). Two unique integers are assigned to each DESS, in order to differentiate the SoC increase from the SoC decrease. Therefore, by counting the number of periods, the origin of the distortion signal can be classified to the corresponding DESS.

Beginning from a black start, the SoC level of a DESS is considered to be zero. Therefore, the DESS will send a number of sequential current distortions, each representing an increase of 10% in the SoC (e.g., if the SoC is 70%, seven sequential distortions will be transmitted). Another issue concerns the conflict among the simultaneous transmissions. For this reason, a time delay is also inserted. Thus, when a DESS identifies a distortion, the transmission control is deactivated.

In order to implement the proposed methodology, the internal control strategy of the DESS is modified. The SoC increase or decrease information is transmitted in form of a sinusoidal distortion at 175 Hz, superimposed in the output current. The parameters of this distortion, such as the amplitude and frequency, are the same regardless of its origin. The information is contained on its time duration (number of periods).

3.2. Distortion Signal Characteristics. The frequency of the distortion is selected at 175 Hz, which is an intermediate frequency, in order to prevent any interference with the harmonics of the basic frequency 50 Hz, that is, 250 Hz, 350 Hz, and so forth. Moreover, the selection of a high frequency has been avoided, in order not to be attenuated by the low-pass filters.

The Standard EN 50160 does not define the exact permissible amplitude for the intermediate frequency signals. However, it specifies the maximum allowable amplitude of the communication signals, as shown in Figure 4. Around the frequency of 175 Hz, the upper limit for the amplitude is 9% of the maximum nominal grid phase voltage. For this reason, the amplitude of the distortion is selected at 1%, that is, 3.2 V. This value is rather small, in order not to encumber the microgrid bus with additional harmonics.

3.3. Method Implementation. The implementation of the proposed method requires a transmitter and receiver for the distortion in each DESS, implemented in the battery management control block. The battery management control is placed before the PWM control of the DESS converter (Figure 3). Figure 5(a) presents the control of the transmitter, placed before the SPWM control. This control is divided into

FIGURE 4: Allowable amplitude of intermediate harmonic for communication.

4 steps: the SoC control, the delay control, the reference signal control, and the resonant controller.

The first step (SoC control) is activated, when the SoC level of the battery varies by 10% (charging or discharging). Then, a sinusoidal reference signal of 3.2 V magnitude and 175 Hz frequency is produced. In case the transmitter has detected a distortion signal from another DESS, the delay control is activated to prevent conflicts raised by the simultaneous transmission of two or more distortion signals. Finally, the R-controller is responsible for the signal superimposition at each phase of the system. In the meantime, the transmitter counter block counts the periods of the output signal and deactivates the SoC transmitter control, when the signal reaches the predefined time duration. The transfer function of the R-controller is

$$H(s) = \frac{2k_i\omega_c s}{s^2 + 2\omega_c s + \omega^2}, \quad (10)$$

where ω_c is considered within 5–15 rad/s, ω is the resonance angular frequency, and k_i is a gain.

The receiver control is divided into 2 steps, as presented in Figure 5(b). Initially, the distortion is detected and its time duration is measured, by using the dq -PLL in each DESS, as presented in Figure 3. The inputs of the PLL are the phase voltages at the terminals of the DESS. The output of the PLL in the q -axis (V_q) is fed in a band-pass filter, that is tuned at 175 Hz, in order to isolate the distortion. The bandwidth of the band-pass filter is selected equal to 20 Hz. In this way, the distortion signal is extracted from the voltage waveform. The time duration of the distortion is measured in the receiver counter block, by counting the number of its periods. In the next step, the origin of the distortion is identified in the identification block, by comparing the time duration of the distortion with the predefined number of periods corresponding to each DESS.

4. Simulation Tests

4.1. Simulation Model. The microgrid consists of two converter-interfaced DGUs, three DESSs with DC-batteries, a constant power linear load, and two nonlinear loads (NL₁ and NL₂), as it is shown in Figure 6. The parameters of the system are listed in Table 1, while the electrical parameters

TABLE 1: System parameters.

Items	DGU ₁	DGU ₂
Rated power S (kVA)	10	5
Frequency droop coefficient m	$2 \cdot 10^{-4}$	$4 \cdot 10^{-4}$
Derivative frequency coefficient m_d	10^{-5}	10^{-5}
Amplitude droop coefficient n	$3.25 \cdot 10^{-3}$	$6.5 \cdot 10^{-3}$
Derivative amplitude coefficients m_d, n_d	10^{-5}	10^{-5}
Virtual inductor L_o (mH)	4	10

TABLE 2: Transmitter/receiver characteristics.

Battery (number)	Initial SoC (%)	10% SoC increase (number of periods)	10% SoC decrease (number of periods)
1	80	7	10
2	40	13	16
3	60	19	22

of the connection line are overhead ACSR 16 mm² lines with $R = 1.268 \Omega/\text{km}$ and $X = 0.422 \Omega/\text{km}$. The length of each connection line is $L_1 = 100$ m, $L_2 = 200$ m, $L_3 = 150$ m, $L_4 = 300$ m, $L_5 = 100$ m, and $L_6 = 50$ m. Each battery converter has 5 kVA nominal apparent power and is composed of 400 OPzS-type lead-acid batteries of 2 V nominal voltage. The battery bank is modelled as a variable DC voltage source in series with internal resistance [28]. The switching frequency of all converters is 9.95 kHz, while the DC voltage of all DGUs is 800 V. All the simulation tests are carried out in the time domain with the PSIM Software.

The characteristics of each battery management controller are presented in Table 2. Each DESS owns two unique-duration signals: one for the state of 10% increase in SoC and the other for 10% decrease.

4.2. Simulation Results

4.2.1. Case 1: Power Sharing (with Linear Load Increase). Initially, the power combination of the two DGUs feeds the linear and nonlinear load with active power of 7 kW and 4 kW, respectively. At $t = 1$ s the linear load increases by 7 kW. The DGUs adapt the injected active power trying to fulfill the load demand, according to the droop control method. As a result, the frequency drops below 49 Hz, since the aggregated load demand is larger than the aggregated available power of the two DGUs. The battery converters measure a frequency lower than 49 Hz and are connected to the microgrid. The active power sharing among the batteries is performed proportional to their SoC, according to the proposed strategy, described in Section 2.3. Therefore, the frequency is restored above the acceptable limit of 49 Hz. Figure 7(a) presents the power sharing of the two DGUs, while Figure 7(b) presents the formed microgrid frequency. The active power injected by each DESS is presented in Figure 7(c), while the respective SoC is presented in Figure 7(d). As it is obvious, Bat₂ has the lowest SoC and consequently injects less power than the other two batteries. At $t = 5.2$ s, the SoC of Bat₂ becomes

FIGURE 5: Battery management control: (a) SoC transmitter control and (b) SoC receiver control.

FIGURE 6: Microgrid scheme.

20% (which is considered the lowest permissible limits). As a result, its active power injection is zeroed, as can be seen in Figure 7(c). The other two DESSs undertake the load demand, in order to maintain the frequency within the limits defined by EN 50160. Evaluating this method, a comparable number of charging/discharging cycles for all batteries will be achieved and at the meantime they are protected from deep discharges. In case the proposed SoC control was not applied, each DESS would inject the same amount of active power, leading to the depletion of the battery with the lowest SoC.

In order to perform the power sharing according to the SoC, each DESS integrates a battery management control. The control is implemented by injecting a distortion at 175 Hz each time the SoC decreases by 10%. In Figure 8(a), the number of periods of the distortion signal transmitted by each DESS is presented, which is in accordance with Table 2. When the batteries are feeding the microgrid with active power, their SoC is reduced, as they discharge. At $t = 2.6$ s, the SoC of battery Bat_2 becomes 30%. This means that its SoC is reduced by 10% in respect to the initial SoC (Table 2) and as a result a distortion signal with 16-period time duration is propagated (blue curve in Figure 8(a)). This distortion signal is identified by all DESSs, as it is indicatively shown for Bat_1 in Figure 8(b). In a respective manner, distortion signals with different number of periods for each DESS are generated, transmitting the information of their SoC variation. According to the counter measurements, each DESS can identify the origin of the distortion and adjust the initial SoC. Figure 8(c) presents the SoC for each

battery as they are perceived by Bat_1. By implementing the proposed battery management control each DESS can effectively identify the SoC of the other batteries without implementing physical communication.

4.2.2. Case 2: Power Sharing (with Load Increase and Decrease). In this test case, the proposed power sharing method is examined under varying load conditions. Initially, the linear load demand is 7 kW, while the nonlinear load demand is 4 kW. At $t = 1$ s, the linear load increases by 7 kW and the microgrid frequency decreases below 49 Hz (Figure 9(b)), since the DGUs supply their maximum available active power (Figure 9(a)). Therefore, the DESSs inject active power in order to satisfy the load demand and restore the frequency within the permissible limits. At $t = 3$ s, the linear load is decreased by 3 kW. The DESSs contribute to less active power, as can be seen in Figure 9(c). This is reflected in the rate of SoC decrease of each battery (Figure 9(d)). A successive load increase of 2 kW takes place at $t = 6$ s. The DESSs increase again their active power injection in order to control the microgrid frequency. The power sharing among the DESSs is performed proportional to their SoC, proving the effectiveness of the proposed method, even under load variations.

4.2.3. Case 3: Harmonic Attenuation. In an islanded microgrid with both linear and nonlinear loads, the voltage is polluted with harmonics of higher order. This test case demonstrates the effectiveness of the proposed voltage harmonic

FIGURE 7: (a) DGU active power injection, (b) microgrid frequency, (c) DESS active power injection, and (d) battery actual SoC.

FIGURE 8: (a) Number of periods of distortion signal transmitted, (b) number of periods of distortion signal as measured by the receiver counter, and (c) battery SoC measured by DESS.1.

attenuation method under increase of the nonlinear active power absorption. The increase of the active power implies the change in the microgrid frequency. In the following simulations scenarios, the nonlinear load is simulated as a three-phase diode rectifier with resistance. Initially, the linear load and the nonlinear load NL_1 are connected to the microgrid, as it is shown in Figure 6. The active power absorption is 7 kW for the linear load and 4 kW for NL_1 . The microgrid operates with frequency equal to 49.52 Hz.

At $t = 0.5$ s, the switch sw_{NL} is activated and the nonlinear load NL_2 is connected, adding 9 kW of active power. As a result, the frequency changes to 49.09 Hz. Figures 10(a) and 10(b) present the phase voltage profile (phase a) at the terminals of the linear load without the action of the proposed harmonic attenuation method. In this case, the total harmonic distortion (THD_v) is equal to 5.3% (only NL_1 is connected) and 8.12% (both NL_1 and NL_2 are connected), respectively. The same simulation test is performed after the

FIGURE 9: (a) DGU active power injection, (b) microgrid frequency, (c) DESS active power injection, and (d) battery actual SoC.

FIGURE 10: Voltage (phase a) at the terminals of the linear load: (a) with NL_1 connected and deactivated the proposed control, (b) with NL_1 and NL_2 connected and deactivated the proposed control, (c) with NL_1 connected and activated the proposed control, and (d) with NL_1 and NL_2 connected and activated the proposed control.

activation of the proposed control method. As can be noticed from Figures 10(c) and 10(d), THD_v decreases significantly to 3.25% and 4.75%, respectively. The effectiveness of the proposed method is verified even under severe nonlinear load and frequency deviations.

5. Conclusions

In an islanded microgrid with several DESSs, the SoC balancing problem should be effectively addressed, in order to

ensure a prolonged lifespan. In contrary to communication-based techniques, this paper proposes a new decentralized method in order to define the injected current of each DESS. According to this methodology, a sinusoidal distortion at 175 Hz is superimposed in the output current of every DESS and propagated in the microgrid bus. This distortion indicates the increase or decrease of the SoC. In this way, the information of the SoC is indirectly communicated to the other DESSs, which adapt their internal control and regulate the power sharing proportional to their SoC. The target is

to achieve a comparable number of charging/discharging cycles. The proposed method is integrated in the control of each DESS, without requiring any additional communication infrastructure leading to reduced installation cost. Since the islanded microgrid may also contain nonlinear loads, an effective harmonic attenuation method is also proposed. This method is applied to each DGU and is implemented in the dq rotating frame. Thus, the harmonic attenuation control is immune to frequency deviations. The simulation results show the effectiveness of the proposed control method, in an islanded microgrid with several DGUs and batteries as DESS.

Competing Interests

The authors declare that they have no competing interests.

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