Management and Equalization of Energy Storage Devices for DC Microgrids Using a SoC-Sharing Function

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ABSTRACT This paper presents a method for Energy Storage Systems (ESSs) equalization and energy management in dc microgrids (MGs) with slow dynamic sources, such as Fuel Cells (FCs). The three main features of this method are the ESSs equalization, the energy management between the ESSs and the FC, and the ability to suppress fast transients of load, preventing damages in the FC. The equalization is performed using a State of Charge (SoC)-Sharing Function, which is based on a Sigmoid Function (SF). The SoC-Sharing Function is designed similarly to the droop controller, therefore, it is suitable for operation in droop based MGs. Additionally, the ability to suppress fast transients of load is performed by adding a low pass filter in the FC control loop. The main advantages of this method are the SF smooth behavior and the lack of need for a high-speed link of communication between the sources. To evaluate the MG stability, the Lyapunov’s Indirect Method is applied in the MG model considering different scenarios varying the SoC and load connected to the dc-link. Finally, the model is validated by comparing simulation and experimental results supplied by a lab-scale prototype.

INDEX TERMS Energy storage system, dc microgrid, equalization method, fuel cell, energy management.

I. INTRODUCTION

The integration of alternative energy sources for grid-tied or standalone operation modes have increased the use of power converters in the worldwide energy matrix. However, the operation of these new devices may produce instabilities due to the alternative energy source nonlinearities, i.e. the wind and solar power are affected by the environmental conditions, while the electrical power produced on the fuel cells (FCs) terminals depends on the chemical reactions between hydrogen (H₂) and oxygen (O₂) [1]–[5].

Additionally, the microgrids (MGs) are the integration of power converters and alternative energy sources with high levels of power quality and stability. In this context, a single alternative energy source connected close to the end-users is named as distributed generation system (DG), while the integration of a considerable number of alternative energy sources is described in the literature as a hybrid power generation system [6]–[8].

The main benefits of a MG is the improvement of power quality, efficiency, stability and economical operation [9]. The replacement of ac to dc DG systems demand financial support as strategy of government and new economical perspectives. However, dc MGs are on continuous rising in comparison with ac MGs because there is no concern to reduce the reactive power and harmonic currents that improves the overall grid performance [3]. For instance, the efficiency of a building energy, that changes from ac to dc technologies rises from 10% to 28% [10].

In addition, dc MGs reduce the conversion losses because the power production is close to the end-users, and it is not required synchronization methods for connect them to a
common dc-link or to other dc generators [11]. Furthermore, if the dc MG is connected to the main grid, any blackout or voltage sag on the ac-side will not affect the power sources placed on the dc-side [11].

The different rates of wind and solar light may influence the power production on a MG that leads to voltage fluctuation and power unbalances on the dc-side [3]. Thus, Energy Storage Systems (ESSs) are the most suitable solution to mitigate the impacts aforementioned, guaranteeing the reliability, safety and stability [3], [12].

Moreover, there are another benefits that ESSs bring to a dc MG. Among the most important are the compensation of load transients, support for black-start and electrical faults [1], [4], [13], [14]. Although the use of ESSs improve some drawbacks related to the MG operation, they demand a coordination among all sources and ESSs. Otherwise, they may cause deep discharge or over-charge that result in degradation and reduction of their life-cycle [15].

Therefore, a State of Charge (SoC) management promotes a balancing among ESS units to prevent different rates of charge/discharge and consequently damages to them [3], [5], [16]. The most effective solution has been widely proposed to improve the dc MG operation to speed up the charge and to reduce the uneven degradation in ESSs [4].

Additionally, the SoC equalization can be implemented among their cells or stacks according to the method used on the energy management system [9], [17]. Considering the possibilities, this paper focus on SoC battery pack equalization with decentralized strategy, which it does not need a high speed communication link.

In the process of balancing, the units with SoC closer to 0% will provide a low amount of power (current), while the units with SoC closer to 100% will supply a larger level of power (current) to the dc-link. Moreover at the end of the equalization process, the battery SoCs will converge to a similar value.

For the equalization process, one of the main techniques proposed in the literature focus is on the adaptive droop control that changes the virtual resistance according to the SoC of each battery in dc MGs. Thus, in [16] a coefficient is responsible to modify the droop slope using the SoC and the battery power demand. [18] determines a virtual resistance using the SoC and the battery power demand, and [3] applies a fuzzy controller with SoC and the voltage error as parameters to calculate the virtual resistance in the strategy of management.

In ac MGs, the equalization presented in [4] proposes an adaptive droop control with a weighting factor obtained from fuzzy inference system with SoC as input, while [5] uses a coefficient that depends on the rate that the SoC changes.

Moreover, [19] elaborates a different strategy applying SoC based droop control that sums a factor to complement the voltage reference from droop management, allowing the balancing process in the dc MG.

For stability analysis, [16] and [19] consider only the management control without include the dc-dc converter model while [10] and [18] apply the influence of ESSs connected to their dc-dc converters without evaluate others DG behaviors. In this paper, Lyapunov’s Indirect Method contemplates the nonlinear interactions between each dc-dc converter by modeling not only the physical circuit but also the control loops. Additionally, the droop control is not continuously differentiable, thus it is not suitable for proving the level of stability in the whole range of operation.

The comparison of some methods found in literature are shown in Table 1 with the alternative sources presented in the MG, the equalization method and the technology dc or ac.

| Reference | Alternative Sources | Equalization Method | MG Technology |
|-----------|---------------------|---------------------|---------------|
| [3]       | PV panels and wind turbine | Adaptive droop control | dc            |
| [4]       | PV panels and wind turbine | Adaptive droop control | ac            |
| [5]       | PV panels and wind turbine | Adaptive droop control | ac            |
| [10]      | Not mentioned        | Adaptive droop control | dc            |
| [16]      | Not mentioned        | SoC based droop control | dc            |
| [18]      | PV panels and wind turbine | Adaptive droop control | dc            |
| [19]      | PV panels            | SoC based droop control | dc            |

This paper: Fuel cell SoC-Sharing Function dc

The voltage reference from droop management, allowing the balancing process in the dc MG.

TABLE 1. Equalization methods found in literature.
This method of energy management in association with the ESSs, reduces the FC speed response during maneuver of load, and it allows the ESSs to supply power at steady-state to the dc-link.

Finally, Lyapunov’s Indirect Method is applied to prove the dc MG stability around the operation region through the dc MG average model, considering the closed loop average model of each dc-dc converter connected to the common capacitor. Therefore, the nonlinear interaction between the modules and control structure are not neglected and the droop control management in the FC is also approximated by a SF to apply the Lyapunov’s Indirect Method. The first analysis relates the range of loads that the dc MG was designed to operate. Afterwards, the stability is evaluated by analysing the dc MG eigenvalues for different values of SoC. In addition, an experimental setup is used to demonstrate the effectiveness of the proposed approach.

The following paper is summarized as follows. Section II presents the topology of dc MGs in the standalone mode. Section III presents the function proposed for the dc MG energy management with droop control applied on the FC and the SoC-Sharing Function method to equalize the ESSs. In section IV, the dc MG stability is evaluated using the Lyapunov’s Indirect Method. Section V shows the results obtained from the experimental setup in comparison with the computational simulations and numerical solution of MG model using differential equations.

II. MICROGRID CONFIGURATION
Fig. 1 shows the MG selected as case of study, which is composed by a FC, two groups of ESSs and dc loads ($R_1 \ldots R_n$) that represent the local costumers and the equivalent model of the ac-side.

In this context, the main source is a 1 kW proton-exchange membrane (PEM) FC supplied by a tank of $H_2$ with high levels of purity (around 99.999%). The electronic interfaced connected to the FC terminals is an IBVM with high voltage gain, high efficiency and low ripple level on the current absorbed from the energy source. Furthermore, the architecture of the ESS considered is composed by a BBB converter and battery stacks of two Li-Po in series connection, 5 Ah of capacity and rated voltage of 22.2 V each, resulting in 44.4 V of terminal voltage per stack, as indicated in Fig. 1 [3].

A. SYSTEM DESCRIPTION
In Fig. 2, the ESS terminal voltages and currents are $v_{bat1}$ and $i_{bat1}$ for ESS1 and $v_{bat2}$ and $i_{bat2}$ for ESS2, respectively. Additionally, the BBBs input low pass filters $L_{bat1}$ $C_{bat1}$ and $L_{bat2}$ $C_{bat2}$ are designed to reduce the ESSs current ripple. In addition, through BBB inductances $L_{bat1}$ and $L_{bat2}$ are flowing $i_{bat1}$ and $i_{bat2}$, while $v_{bat1}$ and $v_{bat2}$ are the voltages on $C_{bat1}$ and $C_{bat2}$, respectively.

Also in this figure, the FC terminal voltage and current are $v_{fc}$ and $i_{in,fc}$ and the voltages $v_{C1}$ and $v_{C2}$ are measured on the capacitances of the doubler-voltage $C_1$ and $C_2$, respectively.

Through the IBVM inductances ($L_1$ and $L_2$) are flowing $i_L1$ and $i_L2$, thus, the converter input current is defined by $i_{in,fc} = i_L1 + i_L2$.

In the same picture, the voltage on the common capacitance $C_o$ is $v_{link}$ and $i_{link}$ is the current through the dc load ($R_1$, $R_2$, $R_3$, ..., and $R_n$). Furthermore, $i_{fc}$, $i_{bat1}$ and $i_{bat2}$ are the differences between the current reference and the current measured on the FC, ESS1 and ESS2, respectively, while the terminal capacitance of each dc-dc converter connected in parallel are represented by the equivalent capacitor $C_o$ (considering ”n” dc-dc converters, the equivalent capacitor $C_o$ is $C_1 + C_2 + \ldots + C_n$).

B. CONTROL DESCRIPTION
The ESS current references ($i_{ref, bat1}$ and $i_{ref, bat2}$) are produced according to the dc-link voltage ($v_{link}$) and the ESS SoC (SoC1 or SoC2) values, i.e. $v_{link}$, SoC1 or SoC2 are processed through the SoC-Sharing Function to generate the ESS current references as shown in Fig. 2. Later, the ESS current references ($i_{ref,bat1}$ and $i_{ref,bat2}$) are compared with the current measured on the ESS terminals ($i_{in,bat1}$ and $i_{in,bat2}$) and processed through the battery controllers, which, in general, are the classical proportional-integral (PI) controller [13].

Additionally, in Fig. 2, the FC control structure is based on the classical droop control with $v_{link}$ as input and $i_{droop,fc}$ as output. Taking into account the FC characteristics, the power sharing management is used to control the FC dynamic response by adjusting the low pass filter coefficients in the transfer function ($n_d(s)$). Thus, the output current of droop controller ($i_{droop,fc}$) is processed through the low pass filter to produce the FC current reference ($i_{ref,fc}$) that is compared
FIGURE 2. MG control diagram.

with the FC measured current \((i_{\text{in, fc}})\) and applied as input in the FC controller (PI compensator).

III. MANAGEMENT AND EQUALIZATION METHODS

The MG controller is responsible to coordinate the current injected or absorbed from the dc-link, where the main challenge is the MG management and equalization considering the ESS fast dynamic and the FC slow dynamic response at transitory regime. To achieve the main requirements of stability, the droop controller is applied on the FC and the SoC-Sharing Function defines the current reference of each battery in order to promote the ESS equalization.

A. DROOP CONTROL APPLIED ON THE FUEL CELL MANAGEMENT

The FC energy management function is based on the droop control technique. Therefore, the current reference is defined according to \(v_{\text{link}}\) [22], [23]. Fig. 3 clarifies the droop control concept, which presents graphically the relationship between the current \((i_{\text{droop, fc}})\) in p.u. (per unit) and the dc-link voltage \((v_{\text{link}})\). As a result, it is created the concept of the virtual resistance \(r_{\text{droop}} = \Delta v/i_{\text{max}}\) [11].

In this formulation \(\Delta v = v - v_{\text{DC0}}\), with \(v\) being the voltage when \(i_{\text{droop, fc}} = 0\) and \(v_{\text{DC0}}\) the voltage when \(i_{\text{droop, fc}} = i_{\text{max}}\), with \(i_{\text{max}}\) representing the maximum current produced by the FC, thus the FC current reference is controlled according to the \(v_{\text{link}}\) behavior. Additionally, the virtual resistance and the limit of current \(i_{\text{max}}\) have to be in accordance with the FC limits. Thus, the droop curve from Fig. 3 is defined analytically in (1), where \(a\) is the curve slope (the inverse of virtual resistance) in \(p.u./V\) and \(b\) is the linear coefficient in \(p.u.\).

\[
i_{\text{droop, fc}} = -\frac{v_{\text{link}}}{r_{\text{droop}}} + \frac{\Delta v + v_{\text{DC0}}}{r_{\text{droop}}} = -a v_{\text{link}} + b \quad (1)
\]

In this context, it is integrated the ESSs and the FC, proposing the ESS dynamic response at transitory regime faster than the FC time response as illustrated in Fig. 4 [24]. To achieve these requirements, the ESS current \((i_{\text{in, bat}})\) has to show a complementary behavior in comparison with the FC current \((i_{\text{in, fc}})\) when a step of load is applied on the dc-link. In other words, the ESS current response has to be faster than the FC current response during load transients.

After that, the FC current achieves the steady-state regime slowly, while the ESS current returns to zero as shown in Fig. 4. The case that the ESS is absorbing the transients and sharing power at steady-state regime will be explained in III-C. Also in Fig. 4, it is important that the ESS has the capacity to supply enough power to mitigate the load transients, avoiding permanent damage to the FC membrane and ensuring the dc-link stability.

To control the FC speed response (2), the authors include a low pass filter \(n_d(s)\) in series with the droop controller to speed up or slow down the FC current response [13].

\[
n_d(s) = \frac{1}{(\tau s + 1)} \quad (2)
\]
In (2), $\tau$ is the time-constant predefined by the designers or adjusted dynamically to match the FC dynamic, which is related to the speed response that the reaction takes to reach an equilibrium.

To evaluate the effectiveness of the FC control scheme, the authors apply the final value theorem (3) on the step response of $i_{\text{droop, fc}}(s)$ in series with the low pass filter $n_d(s)$. The result shows that the low pass filter does not affect the solution at steady-state regime. As consequence, the FC current reference is equal to the FC droop output at steady-state ($I_{\text{ref, fc}} = I_{\text{droop, fc}}$).

$$I_{\text{ref, fc}} = \lim_{s \to 0} I_{\text{droop, fc}} \frac{1}{s \tau + 1} = I_{\text{droop, fc}} \quad (3)$$

Therefore, it is proved that $n_d(s)$ does not produce alteration in the MG management control structure at steady-state. In addition, as the communication link among the sources is not mandatory, a simple PI is enough to maintain the IBVM at the reference of current according to $v_{\text{link}}$.

For this project, as shown in Fig. 5, it is considered $v_{\text{DC0}} = 150 \text{ V}$, $\Delta v = 20 \text{ V}$, $v_{\text{link}}$ in the range of 150-170 V and the maximum current supplied by the FC is $20 \text{ A}$ ($1 \text{ p.u.}$), thus it is followed (4).

$$i_{\text{droop, fc}} = -0.05v_{\text{link}} + 8.5 \quad (4)$$

**B. SoC-SHARING FUNCTION FOR THE ESS EQUALIZATION**

According to the previous sections, the ESSs operating with SoCs numerically equivalents improve the MG efficiency and avoid damage on them. To achieve the aforementioned requirements, the SoC of each ESS is estimated with a classical real time algorithm (Coulomb Counting Method), then, they are used as input of the equalization method. In addition, to calculate a new value of $i_{\text{ref, bat}}$ properly the equalization method also applies the dc-link voltage ($v_{\text{link}}$) as input, as described in (5).

$$i_{\text{ref, bat}} = \frac{2}{1 + e^{e_{factor} - \text{SoC}}_{10}} - 1 \quad (5)$$

where $e_{factor}$ is the equalization factor defined according to (6).

$$e_{factor} = \frac{v_{\text{link}} - v_{\text{DC0}}}{\Delta v} \quad (6)$$

In accordance with voltage range of droop control, it is defined the range of $e_{factor}$ as 150-170 V, as shown in Fig. 6. From this analysis, if $e_{factor}$ is closed to zero, there is a smoothly equalization process to avoid the MG instability because the dc-link approaches to the maximum capacity of operation (minimum dc-link voltage). However, the ESS balancing is easily achieved when $v_{\text{link}}$ is close to 170 V, because the load demand on the dc-link is slight.

Fig. 7 shows the surface formed by plotting (5), where the ESS current reference ($i_{\text{ref, bat}}$) is defined from $-1 \text{ p.u.}$ to $1 \text{ p.u.}$, considering negatives values for charging and positives for discharging, while SoC varies from 0% to 100% and $v_{\text{link}}$ is in the range of 150-170 V.
In order to improve the analysis, Fig. 8 shows the SoC-Sharing Function in 2-D (two dimensions) according to 3 different dc-link voltages, with the maximum capacity of load ($v_{\text{link}} = 150 \, \text{V}$), with half capacity ($v_{\text{link}} = 160 \, \text{V}$) and without load connected to the MG ($v_{\text{link}} = 170 \, \text{V}$). In these scenarios, the ESSs can supply power (delivery current) when the maximum load is connected to the MG or absorb power (absorb current) when the dc-link has not load connected to its terminals.

Finally, Fig. 9 shows the SoC-Sharing Function surface in 2-D according to 3 cases of SoC: 0%, 50% and 100%. Note that there is an unique possibility of charging in the whole range of the dc-link with ESS completely discharged, while the ESS can only supply current when its SoC is around 100%, avoiding over charging.

According to Fig. 8 and Fig. 9, the ESS with SoC numerically high can absorb or deliver current in accordance with the dc-link load. For this case, if $v_{\text{link}}$ is around 170 V, the battery is charged because the load demand on the dc-link is slight; otherwise, if $v_{\text{link}}$ is around 150 V, a heavy load is connected to the dc-side and the ESS must increase the discharging current to avoid the dc-link collapse.

In the opposite case, when the ESS is completely discharged, indicating a SoC numerically low, it can be charged by the extra power available on the dc-link. To become a simple evaluation of the proposed method, Table 2 presents the logic applied for the management of the dc MG using the SoC-Sharing Function for ESS equalization.

Therefore, the SoC-Sharing Function guarantees that the storage devices balance their SoCs in the MG, and then the ESSs are operated with a similar charging current. Because of the SoC is a parameter that establishes a long time to change (depends on battery capacity) [5], [25], the SoC-Sharing Function is also responsible for the dc-link current management, as illustrated in Fig. 10 that presents $i_{\text{ref, bat}}$ vs. $v_{\text{link}}$ according with level of SoC (from 0% until 100%).

### C. SoC-SHARING FUNCTION FOR THE TRANSITORY AND STEADY-STATE REGIMES

As mentioned in subsection II-B, the FC current is associated with a low pass first order filter that leads to a slower response when the loads are changed on the dc-side. To improve the MG stability, the ESSs are used to compensate/absorb transients on the dc-link. This feature is associated with the $v_{\text{link}}$ measurement in the SoC-Sharing Function, then, any load variation on dc-link implies on changes in $i_{\text{in, bat}}$. As a result, the SoC-Sharing Function maintains the equalization and leads the ESS to a fast response at transitory
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IV. DC MICROGRID STABILITY

Due to an enormous variety of DGs with different dynamics behavior, a stability analysis is important to ensure that any load variations does not lead the MG to an unstable operation on the dc-side [26]. In this work, it is considered the complete interactions between the dc-units, i.e. the dc-dc converter’s close loop average model (CLAM) coupled with the dc-link capacitor ($C_o$) via differential equation is calculated. Later, the eigenvalue analysis on the CLAM via Lyapunov’s Indirect Method is performed considering two cases: variations on the dc loads with constant SoC of all ESSs and the changes on SoC according to their balancing with constant dc load. Thus, the subsections IV-A and IV-B evaluate a detailed control loop of the FC and the ESS, respectively, and then, the subsection IV-C considers the coupled model of all DGs units on MG.

A. FC CONTROL LOOP

Fig. 12 shows the FC control loop considering that in the inner loop the IBVM current ($i_{in, fc}$) is controlled by a proportional-integrator (PI) controller with $k_{p, fc}$ and $k_{i, fc}$ as the controller gains. Also in Fig. 12, the outer loop applies the droop technique integrated with the low pass filter ($n_d(s)$). 

while it shares, at steady-state regime, the amount of power injected in the dc-link in contribution with the FC, as shown in Fig. 11.
Finally, if the dc-link voltage is below 150 V, employs the droop setpoint \( i_{\text{ref,bat}} \) as calculated according to [27].

Regarding the BBB model, \( A_{\text{bat}0}, B_{\text{bat}0}, C_{\text{bat}0}, D_{\text{bat}0}, D_{\text{bat}0,b} \) are the state, input, output and feed-forward matrices at steady-state regime. Furthermore, \( A_{\text{bat}1}, B_{\text{bat}1}, C_{\text{bat}1}, D_{\text{bat}1}, D_{\text{bat}1,b} \) are the state, input, output and feed-forward matrices around the operation point, as calculated according to [27].

Also in Fig. 14, \( \dot{x}_{\text{bat}}, y_{\text{bat}}, u_{\text{bat}} \) and \( k_{\text{bat}} \) are the ESS vector of states, output, input and the ESS duty-cycle, respectively. Additionally, it is considered that the output vector is defined by \( y_{\text{bat}} = [i_{\text{in,bat}}, v_{\text{link}}]^T \), the state vector is \( x_{\text{bat}} = [v_{\text{Bat}1}, i_{\text{Bat}1}, v_{\text{link}}]^T \) and the input vector is \( u_{\text{bat}} = [v_{\text{bat}}, i_{\text{link}}]^T \).

**C. DC MICROGRID AVERAGE MODEL**

Finally, the dc MG average model (8) is obtained by considering the closed loop average model of each dc-dc converter described in the subsections IV-A and IV-B.

In (8), the first differential equation, \( \dot{v}_{\text{link}} \), is related to the dc-link voltage. As there are three dc DG systems integrated on the MG, the load contribution has to be decremented twice \( 2(-\frac{\dot{v}_{\text{link}}}{R_{\text{C2}}C_{\text{av}}}) \) to avoid superposition. The next three differential equations consists of \( \dot{x}_{\text{bat}}^{(1/2)}, \dot{e}_{\text{bat}} \) and \( \dot{x}_{\text{ref,bat}} \). In addition, the fifth and the sixth equation \( (\dot{x}_{\text{bat}1}^{(1/2)} + \dot{e}_{\text{bat}1}) \) are related to the ESS1 with \( x_{\text{bat}1} = [v_{\text{Bat}1}, i_{\text{Bat}1}, v_{\text{link}}]^T \). The seventh and the last equation \( (\dot{x}_{\text{bat}2}^{(1/2)} + \dot{e}_{\text{bat}2}) \) are associated to the ESS2 with \( x_{\text{bat}2} = [v_{\text{Bat}2}, i_{\text{Bat}2}, v_{\text{link}}]^T \). Finally, the ESS1 input vector is \( u_{\text{bat}1} = [v_{\text{Bat}1}, i_{\text{Bat}1}, v_{\text{link}}]^T \) and ESS2 input vector is \( u_{\text{bat}2} = [v_{\text{Bat}2}, i_{\text{Bat}2}, v_{\text{link}}]^T \).

It is important to notice that in the matrix indices for the FC and ESS state vectors are \((1:4)\) and \((1:2)\), respectively. These indices are used to avoid repetition of the dc-link voltage differential equation.

**V. STABILITY ANALYSIS**

In the stability analysis, the real part of the eigenvalues are calculated using the Jacobian’s matrix of (8). Additionally,
to avoid damages on the FC and ESSs, it is considered that the maximum FC current ($I_{fc_{\text{max}}}$) is 20 A and the maximum ESS current ($I_{bat_{\text{max}}}$) is 5 A.

Firstly, it is addressed the effect of the load variations in the dc-link considering the other parameters as constants. Afterwards, it is analyzed the stability during the equalization process. Considering that the dynamic response associated with the rate of SoC is much slower when compared with the current and voltages variables in (8), as shown at the bottom of this page, the stability analysis is performed and presented for constant values of SoC.

For this purpose, the MG is analyzed in two different cases. In the first case, the ESS1 is practically discharged with SoC$_1 = 10\%$, while ESS2 is charged at medium range with SoC$_2 = 40\%$. In the second case, the ESS1 presents SoC$_1 = 20\%$, while ESS2 is almost fully charged with SoC$_2 = 80\%$.

### A. EFFECT OF THE LOAD POWER VARIATION ON THE DC MG STABILITY

For this analysis, Fig. 15 shows the eigenvalues of the Jacobian matrix for a specified range of load connected to the dc-link. For SoC$_1 = 10\%$ and SoC$_2 = 40\%$, without load connected implies in $v_{\text{link}} = 159$ V while the maximum value of load (680 W) leads to $v_{\text{link}} = 152$ V. However, for SoC$_1 = 20\%$ and SoC$_2 = 80\%$, without load connected implies in $v_{\text{link}} = 164$ V while the maximum value of load (680 W) leads to $v_{\text{link}} = 153$ V. As the first case have the ESSs with SoC$_1$ and SoC$_2$ lower than the second case, the power consumed by the batteries is higher for the first case. Thus, the dc-link voltage sweeps in a higher range for the second case.

Therefore, the load incremented moves the eigenvalues straightforward to the right side of the imaginary frame. Fortunately, this action is not sufficient to shift the eigenvalues of the dc MG to the region of instability. With the load increment in the specified range, the dc-link voltage sweeps range of operation on the droop line according with the SoC of both ESS.

### B. STABILITY ANALYSIS DURING THE EQUALIZATION PROCESS

To perform the stability analysis during the equalization process, the authors propose the SoC changing for each operation point. In this context, the difference of SoC$_2$ and SoC$_1$ ($\Delta$SoC) is decreased as the equalization process is reached.

In Fig. 16, the storage balancing process is not able to move the eigenvalues to the right side of the imaginary frame. Moreover, Fig. 17 shows the maximum real part of the eigenvalues ($\text{max}(|\lambda|)$). Although there is a slightly rising of $\text{max}(|\lambda|)$ as the equalization process occurs, this change is not sufficient to shift the dc MG to the instability.

### VI. RESULTS

The authors used an experimental test bed to verify the theoretical analysis proposed in this manuscript, as shown in Fig. 18. In this study, the main source is the H-1000 FC from Horizon Technologies with a rated power of 1 kW, while each ESS is represented by a group of two Li-Po batteries in series connection with rated voltage of 22.2 V each, resulting in a total of 44.4 V. Moreover, the maximum current supplied by the FC is 20 A, while the battery pack supplies/absorbs...
FIGURE 16. Movement of the eigenvalues in the complex plane for the equalization process. First case for SoC1 = 10% and SoC2 = 40%. Second case for SoC1 = 20%, SoC2 = 80%. In the both cases, there are 400 W connected to the dc-link that leads to $v_{\text{link}} = 158$ V.

FIGURE 17. Behavior of the maximum real part of the eigenvalues for the equalization process. First case for SoC1 = 10% and SoC2 = 40%. Second case for SoC1 = 20%, SoC2 = 80%. In the both cases, there are 400 W connected to the dc-link that leads to $v_{\text{link}} = 158$ V.

To evaluate the effectiveness of the proposed approach, this manuscript performs two types of analysis. In the first, the authors relate the equalization process obtained in the test bed with the simulation in the PSIM software. In the second, the experimental results are compared with the differential equations results (8) using the Matlab solver ODE23t.

A. COMPARISON BETWEEN THE EXPERIMENTAL AND SIMULATION TESTS PERFORMED IN THE PSIM

To speed up the time of analysis and avoid long periods of test, the experiments were scaled with 1 s corresponding to 200 s. Therefore, the real battery pack capacity in 10 Ah, $C_{\text{bat}}(\text{real})$, follows the simple model shown in (9), where $C_{\text{bat}}(\text{exp})$ is the experimental capacity of the ESS.

$$C_{\text{bat}}(\text{real}) = 200 C_{\text{bat}}(\text{exp}) \quad (9)$$

Fig. 19 shows the first experimental results considering initial SoC1 = 10% and SoC2 = 40%. In this test, the behavior of $v_{\text{link}}$, $i_{\text{in, fc}}$, $i_{\text{in, bat1}}$ and $i_{\text{in, bat2}}$ are indicated. The amount of switching load are present in Table 3, where ↑ represents an increase and ↓ a decrease.

As ESS1 is almost fully discharged, it receives a higher amount of current ($i_{\text{in, bat1}}$) than ESS2 ($i_{\text{in, bat2}}$). Thus, the equalization process is accomplished as shown in Fig. 20. It is important to notice that SoC estimation is based on the Coulomb Counting Method.

Batteries are charged only with a high voltage on dc-link while there is a slight load connected to the dc MG. Also in Fig. 20, the dashed line represents simulation results from
PSIM, while continuous line is obtained from experimental setup.

The second case considers initial values of SoC1 = 20% and SoC2 = 80%. The behavior of \(v_{\text{link}}, i_{\text{in, fc}}, i_{\text{in, bat1}}\) and \(i_{\text{in, bat2}}\) are followed in Fig. 21 with the load variation on the dc MG operation also according to Table 3. As shown, the equalization performance is related to \(v_{\text{link}}\), if there is a significant demand of load on the dc-link, the current reference of the batteries is lower, also according to their SoCs. Otherwise, if there is a considerable amount of current absorbed, then, the demand of load on the dc side has to be light. In Fig. 22, SoC estimation is also from Coulomb Counting Method and there is a comparison between experimental and simulation results.

For both results of experimental tests in Fig. 19 and Fig. 21, the highest value of FC current is below to the maximum limit of 20 A. Thus, in addition to protect the main source at transitional response, the management and equalization process also avoid damages on FC at steady-state regime.

B. COMPARISON BETWEEN THE EXPERIMENTAL TEST AND THE SOLUTION VIA DIFFERENTIAL EQUATIONS

This subsection presents the comparison between the MG analytical model (8) solutions using the ODE23tb Matlab solver and the experimental results. As the SoC changes in a slow rate, for the MG differential equations using ODE23tb, the SoC was considered as a constant while for the experimental results were addressed the real battery pack capacity, avoiding the relation (9) as the previous results.

Thus, the experimental results are presented in Fig. 23, which shows the \(v_{\text{link}}, i_{\text{in, fc}}, i_{\text{in, bat1}}\) and \(i_{\text{in, bat2}}\) with load variation according to Table 4. The comparison between the experimental results and the numerical solutions are presented in Fig. 24. In this figure, the numerical solutions were performed considering the SoC of the two batteries constant at SoC1 = 10% and SoC2 = 40%.

As shown in Fig. 24, there are some discrepancies in mathematical solution compared to experimental results because the model uses a SF as a reference of FC current control loop, instead of a droop curve. Apart from this, the ESS and FC voltages are considered as constant in mathematical calculation. According to Fig. 23 and Fig. 24, it is noted that ESS1 \(i_{\text{in, bat1}}\) delivers more current than ESS2 \(i_{\text{in, bat2}}\) because they have divergent values of SoC that implies on a distinct curves of management, as described in Fig. 10 on subsection III-B.
TABLE 5. Mean normalized absolute error between experimental and analytical test.

| Mean Normalized Absolute Error (p.u.) | \(v_{\text{link}}\) | \(i_{\text{in, fc}}\) | \(i_{\text{in, bat1}}\) | \(i_{\text{in, bat2}}\) |
|--------------------------------------|-----------------|-----------------|-----------------|-----------------|
|                                     | 0.0071          | 0.0990          | 0.1841          | 0.3217          |

FC related to the membrane humidity, temperature influence and others factors [28].

VII. CONCLUSION

This paper presented a ESS management using the SoC-Sharing Function. The proposed strategy fits to MGs that use droop based controllers, which does not require the use of fast links of communications between the sources. The SoC-Sharing Function relies on two main features: the transient compensation and ESS equalization. The transient compensation is useful mostly to applications with slow dynamic response sources, such as FCs. The equalization feature is implemented with the aim to equalize the available energy that the batteries connected to the MG can absorb or discharge.

The effectiveness of the proposed algorithm was evaluated using a dc MG with two Li-Ion batteries and one FC. In this context, the MG stability was performed by linearizing the full MG model using the Lyapunov’s Indirect Method. Finally, the experimental results, the computational simulation using PSIM and the numerical results solving in Matlab of the MG model were compared under different conditions of load and SoC to prove the effectiveness of the stability analysis and the proposed algorithm operation.

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