Holistic Control Approach for the Grid-Connected Converter of a Battery Energy Storage System

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ABSTRACT This paper introduces a holistic control approach applied to a grid-connected converter of a Battery Energy Storage System (BESS). The BESS is mainly used for power peak shaving, frequency supporting, and islanded operation mode which implies multiple control transitions depending on the operation mode. One existing challenge is related to the multiple tuning controllers for the grid-connected converter required for each operation mode, including the rectifier operation. Moreover, when the rectifier operation is running the system is naturally nonlinear which motivates the use of nonlinear controllers. From this standpoint, a strong motivation for this research is the seeking of a holistic control to face all the operation-mode changes seamlessly. Hence, the merit of the proposed holistic control approach consists of using a unique tuning process based on the linear technique of state feedback with integral action for all operation modes, which are: 1) grid-connected mode as an inverter, 2) grid-connected mode as a rectifier, and 3) islanded mode. Of special attention is the grid-connected mode as rectifier since the proposal avoids the introduction of the PWM rectifier model which increases the model order and is inherently nonlinear. A thorough analysis of eigenvalues in open loop and closed loop with the same tuning gains is presented to demonstrate the stability and feasibility of the proposal. An affordable tuning methodology is proposed considering the physical restrictions of the grid-connected converter related to the LCL-filter bandwidth and the switching frequency. To demonstrate the merits of the holistic control approach, several simulations are presented using PSCAD/EMTDC on a 100 kW, 480 V rated BESS using a delta-connected LCL filter for interconnecting with the grid. Simulation results show that the seamless capability with steady-state and transient state operation runs smoothly.

INDEX TERMS BESS, holistic control, LCL-filter, power peak shaving, islanded mode.

I. INTRODUCTION Today, the increasing of distributed energy, the participation of renewable energy with its intermittent nature, and the requirement of shave power demand have made the BESS an element whose incorporation to the grid is being increasingly weighed. Thus the use of BESS is oriented to improve the capabilities of the grid by adding flexibility to the operation of the transmission and distribution infrastructure, increasing the profitability and robustness of the electrical supply [1]–[3]. In [4]–[7], several applications for BESS can be found, and their scopes are explained. Usually, one primary application for BESS is selected and combined with a secondary and even tertiary application in order to increase its profitability. For the purposes of this paper, three modes of operation have been selected: 1) grid-connected mode as an inverter for peak power shaving, 2) grid-connected mode as a rectifier for battery charging, and 3) islanded-mode for voltage and frequency regulation.

Once the applications have been selected, it is important to address the different approaches to control this kind of systems. Figures 1 (a) and (b) show the two approaches most quoted in the state-of-the-art. Figure 1(a) plots the block diagram of the so-called hybrid control approach [8]–[15]. This strategy requires a PQ/Droop control [2], [8], which provides to the V/I stage (enveloped by a dashed line) the necessary references for the BESS. Within the V/I dashed line there are usually two control blocks, each one with different
tuning gains, which means that when a change of operation mode occurs, the selector should select the operation mode, the proper reference, and the control scheme. Most of the literature related to hybrid control does not present the mode when the BESS works as a battery charger. However, this finding does not mean that authors do not face that operation mode.

An improvement over the hybrid approach is illustrated in Figure 1 (b), where the so-called unified control is presented. In this approach, a modified PQ/Droop control is proposed to unify the reference calculation and then a single V/I control is required [16], [17]. Several strategies are reported within the unified approach. For instance, [16]–[19] present different strategies such as saturation of control gains, usage of offsets, or selection blocks to deactivate parts of the control scheme; all of them imply changes in the controller tuning. In [20], a unified controller is proposed using PI compensators that contain inner current and voltage loops and outer loops for real power and reactive power control. The use of dq transformation is also widely used. For example, in [21] a unified control based on a PI current compensator and a P voltage compensator in the dq frame for a BESS with LC filter is presented. In the islanded-mode the voltage is not determined by the grid; therefore, the voltage controller is automatically activated. A similar approach with this strategy is presented in [22] and [23] but using an LCL filter. Other perspectives to address the inherent bidirectionality of this kind of systems are reported in [24] and [25] where the authors present an approach based on fuzzy logic.

Analyzing the findings of the state of the art, unified control shows an improvement on the control approaches, however different tuning gains for the corresponding control loops in each mode, and sometimes, combined with dq transformations, are always required. Additionally, findings do not reveal the performance of a hybrid control or a unified control when the BESS is operating as a battery charger what implies that the grid-connected converter works as a PWM rectifier. PWM rectifier boosts the grid voltage towards a DC bus capacitor and the analysis considers a nonlinear mathematical model, and the order of system state increases [26], [27]. Furthermore, the controllers are different to those used for delivering energy from the battery to the grid, adding an additional control stage [8], [28].

In this paper, a formulation aimed to fully unify the control of a BESS for all operation modes, including the PWM rectifier, is presented. This formulation is named “Holistic control approach” where it means that the gains established in a unique control tuning, for a linear state feedback with integral action controller, are used for all the operation modes, including the PWM rectifier operation; without using the dq transformation. The formulation of the proposal is analytically demonstrated. Also, extensive simulations of a 100 kW, 480 V BESS with operation mode changes and load transients are conducted to reveal the validity of implementing the holistic control approach in a BESS.

Once the previous arguments have been established; the paper is organized as follows. Section II presents a description of the BESS system under study and establishes operative considerations. Section III describes the modeling for each operation mode, the LCL-filter design, and the control design. An eigenvalue analysis for open and closed loops is presented as well as a tuning methodology. Simulations of the electrical performance of the system to support the effectiveness of the proposal are shown in Section IV. In Section V a discussion about the characteristics of this proposal is contrasted with respect to the traditional control approaches. The conclusions and further research of this contribution are presented in Section VI.

II. BESS SYSTEM DESCRIPTION

Figure 2 shows the proposed BESS, identifying by colors the power stage (red), sensors and control stage (green), and the grid (black). It is important to highlight that the holistic control approach is designed for the three-phase full bridge converter, which includes the delta-connected LCL filter. Due to that, the DC/DC converter along with the battery bank are considered as an ideal DC voltage source.

III. MODELING, LCL FILTER AND CONTROL DESIGN

Mathematical model, LCL filter and the control approach are addressed in the same section because they are complementary to introduce the holistic control approach.

According to Figure 1(c), the structure of three-phase full bridge converter should be able to operate coordinately with an LCL filter using the same control scheme for each one of the operation modes which are: a) grid-connected mode (inverter), b) grid-connected mode (rectifier), and c) islanded-mode. Hence for the LCL filter design and the control tuning, the first decision to be taken is to select the mode of operation. To attend this decision, let state the following assumptions:

**FIGURE 1. Typical unified control scheme and proposed holistic control scheme.**
A. MATHEMATICAL MODEL OF EACH OPERATION MODE

For mathematical modeling, the following assumptions are established:

1) The three-phase system is balanced.
2) A line-to-line modeling is considered.
3) The complete analysis is based on the average mathematical model.
4) The link capacitor voltage is not considered as a state variable. Additionally, this voltage $V_{DC}$ is always bigger than the peak input voltage $V_{AB}$.
5) The grid-connected converter works as an inverter if the current $i_{AB}$ is in phase with the input voltage $V_{AB}$. In this case, the active power flows from $V_{DC}$ to the grid and the capacitor is not discharged because of the action of the DC/DC converter and the battery bank.
6) The grid-connected converter works as a rectifier if the input current $i_{AB}$ is shifted 180° with respect to the input voltage $V_{AB}$. In this case, the active power flows from the grid to $V_{DC}$, and the link capacitor is not overcharged because the DC/DC converter is charging the battery bank.
7) The complete analysis is done considering the phase AB.

Taking advantage of assumption 1) the rest of the control signals are obtained by shifting their phase by 120° and 240°, respectively.

1) ISLANDED OPERATION MODE

Considering assumptions 2) and 3), the line-to-line equivalent circuit for islanded operation mode, seen from the three-phase circuit, is shown in Figure 3 in the black line.

A. Holistic Control Approach for the Grid-Connected Converter of a BESS

Let us define from Figure 3 the following variables:

- $v_{ab}, v_{bc}, v_{ca}$ are the delta-connected output voltages of the power converter.
- $v_{cAB}, v_{cBC}, v_{cCA}$ are the delta-connected capacitors voltages.
- $i_a, i_b, i_c$ are the currents through inductors $L_f 1$.
- $i_{ab}' i_{bc}' i_{ca}'$ are the delta-connected capacitors currents.
- $i_A, i_B, i_C$ are the currents through inductors $L_f 2$.
- $v_{AB}, v_{BC}, v_{CA}$ are the delta-connected grid voltages.

Besides considering that:

$$ i_{ab} = \frac{1}{3} (i_a - i_b) $$

$$ i_{AB} = \frac{1}{3} (i_a - i_B) $$

$$ v_{cAB} = \frac{1}{3} (v_{ab}' - v_{bc}') $$

With the previous variables definition, and the circuit of Figure 3, the mathematical model for islanded mode is as follows:

$$ \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} = \begin{pmatrix} 0 & 0 & -1 \\ 0 & \frac{1}{3 L_f 1} & \frac{1}{3 L_f 2} \\ \frac{3}{L_f 1} & -\frac{3}{L_f 2} & 0 \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} + \begin{pmatrix} \frac{1}{3 L_f 1} \\ 0 \\ 0 \end{pmatrix} v_{ab} $$

$$ y = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} $$

(4)

2) GRID-CONNECTED MODE (INVERTER)

In this mode, the control objective is the sinusoidal current tracking of $i_{AB}$ in phase with $v_{AB}$. This rated current $i_{AB}$ corresponds with an active power flux from the grid-connected converter to local loads to contribute to the grid to achieve peak shaving or support the equilibrium of the rate of change of frequency (ROCOF). To illustrate the procedure to obtain
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the mathematical model, let consider the circuit of Figure 4, where local loads represented by resistances are included in the grid-connected mode (inverter). Hence \( i_{AB} = i_{AB-BESS} \).

The Figure 4 shows that the grid has the capability to deliver the power of 1 \( \text{pu}_{\text{grid}} \) while the BESS has another capability to deliver the power of 1 \( \text{pu}_{\text{BESS}} \). As long as the load is within the grid capability, the BESS’s current reference will be zero. However, when the load exceeds the grid capability, the BESS delivers power to the load as long as that power does not exceed the BESS capability. For delivering that power, an \( i_{AB} \) current should be calculated as a reference and supplied by the BESS through \( L_{g2} \). This abstraction of the BESS operation does not mean that this is the unique purpose of the BESS operation, but it can be used to obtain the mathematical model for control purposes.

Hence, considering the previous explanation and the circuit of Figure 4, the mathematical model is:

\[
\begin{bmatrix}
\dot{x}_1 \\
\dot{x}_2 \\
\dot{x}_3
\end{bmatrix} =
\begin{bmatrix}
0 & 0 & -\frac{1}{L_{f1}} \\
0 & -\frac{Z_{AB-BESS}}{L_{f2}} & 0 \\
\frac{3}{L_f} & \frac{3}{L_f} & 0
\end{bmatrix}
\begin{bmatrix}
x_1 \\
x_2 \\
x_3
\end{bmatrix} +
\begin{bmatrix}
\frac{1}{L_{f1}} \\
0 \\
0
\end{bmatrix} v_{ab}
\]

\[y = \begin{bmatrix} 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}\]  (5)

3) GRID-CONNECTED MODE (RECTIFIER)

To analyze this mode, let consider the equivalent average circuit of Figure 5, where it can be observed that the load at the DC side is denoted as \( Z_{ch} \). This load consumes the battery bank active power to charge it until the state of charge (SOC) reaches 100%. It is important to remark that the current \( i_{ch} \); is requested by a DC/DC stage which is not part of the scope of this paper. The relevance of this contribution lies in the fact that the voltage in \( C_{DC} \) is not considered as a state variable; however, one-third of the power demand will be coped by the current \( i_{AB} \) shifted 180° with respect to \( v_{AB} \) and with the required amplitude to maintain regulated \( V_{DC} \).

Once the circuit of Figure 5 is established, its mathematical model is:

\[
\begin{bmatrix}
\dot{x}_1 \\
\dot{x}_2 \\
\dot{x}_3
\end{bmatrix} =
\begin{bmatrix}
0 & 0 & -\frac{1}{L_{f1}} \\
0 & 0 & \frac{1}{L_{f2}} \\
\frac{3}{L_f} & \frac{3}{L_f} & 0
\end{bmatrix}
\begin{bmatrix}
x_1 \\
x_2 \\
x_3
\end{bmatrix} +
\begin{bmatrix}
1 \\
0 \\
1
\end{bmatrix} v_{ab} +
\begin{bmatrix}
0 \\
0 \\
0
\end{bmatrix} v_{AB}
\]

\[y = \begin{bmatrix} 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}\]  (6)

B. LCL FILTER DESIGN

The LCL filter is the passive stage of the system, which supplies the energy to be delivered either for the grid or the battery. In this paper, the filter synthesis approach developed by [29] is used because of its directness, normalized design, and feasibility to be used either for communications or grid-connected filters.

The input parameters to design the LCL filter considering the use of SPWM are:

i) Switching frequency \( (f_{sw} = 12,060 \text{ Hz}; \omega_{sw} = 75.7 \text{ krad}/s) \).

ii) Modulation index in amplitude \( m_a = 0.85 \).

iii) Desired attenuation of first relevant harmonic for THD compliance \( < 1.0\% \) of the fundamental component at \( m_a = 0.85 \).

v) Load value \( (Z_{load} = Z_{AB} = Z_{AB-BESS} = 6.912 \Omega) \) for rated power. It is important to notice that the approach considers a resistance as load, it means, active power transference. Of course, the BESS operates in different modes and operation conditions, and the filter should be able to transfer the required energy in both directions.

The normalized characteristic equation to synthesize a Butterworth third order filter polynomial is \( s^3 + 2s^2 + 2s + 1 = 0 \); being the normalized passive values to fulfill the polynomial
Let consider the islanded operation mode to design the controller. Table 1 summarizes the open-loop matrixes of: parameter, inputs, outputs, and the eigenvalues as well.

Table 1. Open-loop matrixes and eigenvalues.

| Operation mode | State matrix | Input matrix | Output matrix | Eigenvalues (rad/s) |
|----------------|--------------|--------------|---------------|--------------------|
| Islanded-mode  | $A_{im}$     | $B_{im}$     | $C_{im}$      | $\sigma_{1,im} = -15.70 \times 10^3$ |
|                |              |              |               | $\sigma_{2,im} = (-7.85 \pm j13.6) \times 10^3$ |
| Grid-connected mode inverter | $A_{gci}$    | $B_{gci}$    | $C_{gci}$     | $\sigma_{1,gci} = -15.70 \times 10^3$ |
|                |              |              |               | $\sigma_{2,gci} = (-7.85 \pm j13.6) \times 10^3$ |
| Grid-connected mode rectifier | $A_{gcr}$    | $B_{gcr1}$   | $B_{gcr2}$    | $C_{gcr}$          |
|                |              |              |               | $\sigma_{1,gcr} = 0$|
|                |              |              |               | $(\pm j22.21) \times 10^3$ |

Where:

\[
A_{im} = \begin{bmatrix} 0 & 0 & -1,515 \\ -31.41 \times 10^3 & 4,545 & 0 \end{bmatrix} \\
B_{im} = \begin{bmatrix} 1,515 \\ 0 \\ 0 \end{bmatrix} \\
C_{im} = [0 0 1] \\
A_{gci} = \begin{bmatrix} 0 & 0 & -1,515 \\ -31.41 \times 10^3 & 4,545 & 0 \end{bmatrix} \\
B_{gci} = \begin{bmatrix} 1,515 \\ 0 \\ 0 \end{bmatrix} \\
C_{gci} = [0 1 0] \\
A_{gcr} = \begin{bmatrix} 0 & 0 & -1,515 \\ -31.41 \times 10^3 & 4,545 & 0 \end{bmatrix} \\
B_{gcr1} = \begin{bmatrix} 1,515 \\ 0 \\ 0 \end{bmatrix} \\
B_{gcr2} = \begin{bmatrix} -4.5451 \\ 0 \end{bmatrix} \\
C_{gcr} = [0 1 0] \\
\]

Observe that in islanded mode and grid-connected mode (inverter), the eigenvalues are the same; also, it is important to notice that $|\sigma_{1,im,gci}|$ coincides with the bandwidth in the same manner that $|\sigma_{2,3,im,gci}|$.

Once the previous observation was done, the controller proposal is based on state feedback plus integral action. Figure 7 shows the block diagram of the proposal applied for the islanded mode.

According to [30], $k_{eq}$ modifies the system performance, while the integrator assures the system robustness against constant disturbances. Let us introduce an extended model considering the islanded operation mode, as follows:

\[
\begin{bmatrix} \dot{x} \\ \sigma_{im} \end{bmatrix} = \begin{bmatrix} A_{im} & 0 \\ -C_{im} & 0 \end{bmatrix} \begin{bmatrix} x \\ \sigma_{im} \end{bmatrix} + \begin{bmatrix} B_{im} \\ 0 \end{bmatrix} v_{abim} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} x_s^* \tag{17}
\]

Figure 6 shows the Bode diagram of the third-order filter, considering the desired attenuation. Several findings can be obtained:

a) The open-loop bandwidth is 15.70 krad/s, what corresponds with $\omega_r$.

b) The desired attenuation of the first relevant harmonic is $-40 \text{ dB}$; which corresponds with a linear gain of $8.9125 \times 10^{-3}$. If the input is 0.85 (due to the modulation index $m_o$) then the output will be $7.5956 \times 10^{-3}$, which is $< 1.0\%$ of the input.

c) Also, from Figure 6, it can be established that the bandwidth in closed-loop should neither be greater than the switching frequency (or none attenuation will be achieved) nor minor than the open-loop bandwidth (or a conflicting tuning design will be forced).

Knowing $\omega_r$ and $Z_{load}$, the actual values of the LCL filter are:

$L_{f1} = 220 \text{ \mu H} \; \text{C}_{f} = 37 \text{ \mu F} \; \text{and} \; L_{f2} = 73 \text{ \mu H}$.

At this point, the LCL filter has been designed for islanded operation. However; the fundamental formulation of this paper is “a holistic control for the BESS can be designed for the three operation modes shown in Figure 1(c)”. Hence, the analysis of each mode should be clearly established to demonstrate the feasibility of the proposal.

C. HOLISTIC CONTROL DESIGN

Let consider the islanded operation mode to design the controller. Table 1 summarizes the open-loop matrixes of: parameter, inputs, outputs, and the eigenvalues as well.
where:
\[ x \] is the state vector.
\[ A_{im}, B_{im}, \text{ and } C_{im} \] are the matrices of state, input and output, respectively.
\[ \hat{\sigma}_{im} \] is the error between the voltage reference and measured voltage.
\[ v_{abim} \] is the control law which modifies the inverter output.
\[ k \] are the gain vector.
\[ k_t \] is the gain of the integral action.

Considering the control law as:
\[ v_{ab} = \begin{bmatrix} k_1 & k_i \end{bmatrix} \begin{bmatrix} x \sigma_{im} \end{bmatrix} \] (18)

The closed-loop system is:
\[
\begin{bmatrix}
\dot{x}
\dot{\sigma}_{im}
\end{bmatrix} = \begin{bmatrix} A_{im} - B_{im}k & B_{im}k_i \
-C_{im} & 0 \\
0 & 1 \end{bmatrix} \begin{bmatrix} x 
\sigma_{im} \end{bmatrix} + \begin{bmatrix} 0 
1 \end{bmatrix} x^* (19)
\]

Theoretically, if the matrix \( \hat{A} \) is Hurwitz, then the linear system is asymptotical and exponentially stable. Nevertheless, this theoretical concept is restricted by the physical limitations of the system. Hence, let us introduce the following practical formulation for tuning the control scheme.

The lower limit for establishing the closed-loop eigenvalues is denoted by the open-loop LCL-filter bandwidth, which is 15.70krad/s. Any eigenvalue below that limit will be wasteful in terms of energy since the system would tend to be slower than its own dynamic, what does not make sense. The upper limit for establishing the closed-loop eigenvalues is given by the switching frequency of 77.5krad/s. Any eigenvalue above that limit will be inconsequential; since the system would not be able to follow those dynamics.

Once the previous limits have been established then, a constant multiplier \( M \) is introduced to multiply the open-loop eigenvalues for the state feedback. To place the closed-loop eigenvalue introduced by the integral action is obtained by multiplying \( \omega_r \times M \). In this paper, \( M = 2 \) (it fulfills the previous limits considerations); therefore, the proposed closed-loop location of eigenvalues is:
\[
\alpha_{imcl}(\text{states feedback}) = M \times (\alpha_{1,im}, \alpha_{2,3,im})
\]

Then, the tuning constants of (18) are:
\[
k = [-5.1825, 926.00] \\
k_i = -62.8319 \times 10^3
\] (21)

Therefore, the control law for the islanded mode has the form:
\[
\begin{align*}
v_{abim} &= k_1x_1 + k_2x_2 + k_3x_3 + k_i\sigma_{im} \\
\hat{\sigma}_{im} &= x_1^* - x_3
\end{align*}
\] (22)

Following the holistic control concept, the controller for the other modes are:
\[
\begin{align*}
v_{abgci} &= k_1x_1 + k_2x_2 + k_3x_3 + k_i\sigma_{gci} \\
\hat{\sigma}_{gci} &= x_2^* - x_2 \\
v_{abgcr} &= k_1x_1 + k_2x_2 + k_3x_3 + k_i\sigma_{gcr} \\
\hat{\sigma}_{gcr} &= x_2^* - x_2
\end{align*}
\] (23) (24)

Table 2 summarizes \( \hat{A} \) and the closed-loop eigenvalues for each mode. As it can be observed, all the eigenvalues have a negative real part and fulfill with physical limits established by the application.

### TABLE 2. Closed-loop matrices and eigenvalues.

| Operation mode | Closed-loop matrix | Eigenvalues (rad/s) |
|----------------|--------------------|---------------------|
| Islanded-mode  | \( \hat{A}_{im} \)  | \( \alpha_{1,im} = -7.85 \times 10^3 \) |
|                |                    | \( \alpha_{2,3,im} = (-15.70 \pm 27.20) \times 10^3 \) |
|                |                    | \( \alpha_{4,im} = -31.41 \times 10^3 \) |
| Grid-connected mode (inverter) | \( \hat{A}_{gci} \) | \( \alpha_{1,gci} = -30.19 \times 10^3 \) |
|                |                    | \( \alpha_{2,gci} = (-19.75 \pm 28.56) \times 10^3 \) |
|                |                    | \( \alpha_{4,gci} = -966.92 \) |
| Grid-connected mode (rectifier) | \( \hat{A}_{gcr} \) | \( \alpha_{1,gcr} = (-13.53 \pm 26.06) \times 10^3 \) |
|                |                    | \( \alpha_{3,gcr} = (-6.09 \pm 11.91) \times 10^3 \) |

Where:
\[
\begin{align*}
\hat{A}_{im} &= \begin{bmatrix} -39.27 & 7.85 & -10.60 & 95193 \\
0 & -31.416 & 4.54 & 0 \\
81.43 & -81.43 & 0 & 0 \\
0 & 0 & -0.001 & 0 \end{bmatrix} \times 10^3 \\
\hat{A}_{gci} &= \begin{bmatrix} 0 & -31.416 & 4.54 & 0 \\
81.43 & -81.43 & 0 & 0 \\
0 & 0 & -0.001 & 0 \\
-39.27 & 7.85 & -10.60 & 95193 \end{bmatrix} \times 10^3 \\
\hat{A}_{gcr} &= \begin{bmatrix} 0 & 0 & 4.54 & 0 \\
81.43 & -81.43 & 0 & 0 \\
0 & 0 & -0.001 & 0 \\
-39.27 & 7.85 & -10.60 & 95193 \end{bmatrix} \times 10^3
\end{align*}
\] (25) (26) (27)

### IV. SIMULATION RESULTS OF GRID-CONNECTED CONVERTER

Once the holistic control feasibility has been analytically confirmed, the next is to establish a test protocol applied to
the grid-connected converter of a BESS, including all the operation modes analyzed in the previous Section.

Figure 8 shows the whole BESS scheme used for simulations using PSCAD/EMTDC software. Observe that the red dashed line envelopes a schematic circuit which acts emulating the DC/DC converter and the battery. This emulation is justified because the scope of the simulation is focused on the three-phase full bridge converter connected to the grid. Besides, what we want to show is that the \( V_{DC} \) regulation is achieved by using the control proposing as follows. Opening \( SW_1 \) and provoking load changes with \( SW_2 \) and \( SW_3 \), the DC voltage regulation is maintained.

In Table 3 the grid-connected converter electrical parameters to be fulfilled and the LCL-filter parameters are put together.

### Table 3. Grid-connected converter electrical parameters and passive values.

| Parameter                        | Value                        |
|---------------------------------|------------------------------|
| Grid voltage (ac: L-L, RMS)     | 480 V                        |
| Rated power                     | 100 kW                       |
| Power factor                    | Near to unity                |
| \( V_{DC} \)                    | 920 V (±3%)                  |
| THD of current \( i_{AB}, i_{BC}, i_{CA} \) | < 5%                    |
| THD of voltage \( v_{AB}, v_{BC}, v_{CA} \) | < 5%                    |
| Duty class                      | 1.1 p.u. for 1 h            |
|                                | 1.25 p.u. for 2 min         |
|                                | 1.5 p.u. for 10 s           |
| Switching frequency            | 12060 Hz                     |
| Delta-LCL filter \( L_{L1}, L_{L2}, C_f \) | (220 \( \mu \)H, 73 \( \mu \)H, 37 \( \mu \)F) |

To follow the test protocol, consider Table 4 where a timeline is broken down. The mode changes are controlled by the breakers \( BRK_1, BRK_2, \) and \( BRK_3. \) Since islanded mode detection techniques are not considered in this paper. However, to approach the effect of islanded mode detection delay, an intentional delay of one cycle of grid between changes from grid-connected mode to islanded operation mode are included in order to reveal that kind of effect.

Once the test protocol has been described the simulations are presented as follows:

#### A. TIMELINE FROM 0 TO 1.1 s

First, it can be seen that the converter works in open loop in the lapse \( 0 - 0.1 \) s. Second, at \( 0.1 \) s the converter starts to work in grid-connected mode (inverter) with a power demanded of \(-156.5 \) kW (the minus sign is used when the power is delivered to the grid). Third, a change of current reference occurs at \( t = 0.3 \) s being \(-106.2 \) kW the power injected to the grid. Next a change from grid-connected mode (inverter) to islanded mode at \( t = 0.5 \) s, where the \( P_{PCC} \) is 0 and the \( P_{inverter} \) is \(-148.8 \) kW as can be seen in Figure 9.
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Then, a local load change occurs at $t = 0.7\, s$ being $-99.40\, kW$ the power delivered to the local loads.

Finally, a change from islanded mode to grid connected mode occurs at $t = 0.9\, s$ with $P_{\text{PCC}} = P_{\text{inverter}} = -106.2\, kW$.

Another relevant electrical parameter to be fulfilled is the power factor. Figure 10 shows the performance of that parameter. It is important to notice that during the islanded mode operation the power factor reaches the unity. This is because the load is purely resistive.

Another parameter, which is related with power quality, is the THD of voltage and current. Figure 11 at the top shows the voltage THD while Figure 11 at the bottom shows the current THD. It can be seen that in steady state both values are within the limits of Table 3. The voltage THD is lower during grid-connected mode than islanded mode. This is due to the influence of the grid which is stronger than the inverter.

Figures 12 and 13 show the transient that occurs in voltage and current for mode changes between grid connected and islanded mode respectively. It can be observed the effect of the introduced delay time from grid connected to islanded mode to represent the islanded detection.

To illustrate the grid-connected performance when load steps occur, Figure 14 and 15 display the evolution of the voltage and current respectively. The left side of those figures shows the performance facing load steps during the grid-connected mode (inverter) while the right side shows the islanded mode behavior.

**B. SIMULATIONS FOR TIMELINE FROM 0.9 TO 2 s**

According to the analysis presented in Section III-C, the grid-connected converter (inverter) can operate as a rectifier when such mode is required for charging the battery bank, shifting the current reference $180^\circ$.

Hence, to calculate the current reference the power balance between the AC and DC side should be maintained. In reference [26] is obtained the current peak value to guarantee the power balance for a three-phase PWM rectifier, this method permits to maintain a regulated $V_{\text{DC}}$ avoiding the use of a second control loop for the capacitor voltage. By using the same procedure, the three-phrase references are:

$$i^*_{AB} = I^* p \sin (2\pi ft + 180^\circ)$$  \hspace{1cm} (28)

$$i^*_{BC} = I^* p \sin (2\pi ft - 120^\circ + 180^\circ)$$  \hspace{1cm} (29)

$$i^*_{CA} = I^* p \sin (2\pi ft + 120^\circ + 180^\circ)$$  \hspace{1cm} (30)
FIGURE 14. Voltage transients when load changes occur.

FIGURE 15. Current transients when load changes occur.

FIGURE 16. Voltage $V_{DC}$, for timeline from 0.9 s to 2.0 s.

with the $f = 60$ Hz and considering $V_{DC}^\ast = 922$ V.

The following simulations confirm the feasibility of the holistic control approach when the grid-connected converter works as a rectifier.

First, in Figure 16 the DC capacitor voltage $V_{DC}$ is shown to validate the capability of the proposed controller to maintain the DC voltage regulated around $V_{DC}^\ast$. It can be observed that as for mode changes as for load steps the DC voltage is regulated within the threshold of $\pm 3\%$ required in Table 3.

Second, in Figure 17 the power performance is plotted to show the capability to change from grid-connected mode (inverter) to grid-connected mode (rectifier) fulfilling the duty class. It is important to correlate Figures 16 and 17 and to observe the power transient maintaining the DC voltage regulation.

Next, the power factor is a relevant parameter to be accomplished in all the operation modes. Thus, Figure 18 presents the grid-connected mode (rectifier) power factor performance. It can be appreciated the capability to maintain a high power factor over 0.9 and near to 1.

Then, the voltage and current harmonic distortions are important in the grid-connected rectifier mode. Hence, Figure 19 shows at the top the THD voltage while at the bottom the THD current. It is possible to notice that during the steady state of the test, the limits established in Table 3 are satisfied.

Finally, in Figures 20 and 21, the instantaneous voltage and current when a mode change occurs at $t = 1.1$ s and when a load transient occurs at $t = 1.5$ s are shown, respectively.

Observe from Figure 21 the sudden phase shift of the current on $t = 1.1$ s. This shift corresponds to the change mode from the grid-connected inverter to the grid-connected rectifier.
rectifier revealing the success of the holistic control operation. Also, it should be highlighted that this change represents a flux power shift from -106.2 kW to 102.8 kW being a delta of power direction of 209 kW noticing the seamless transition from one mode to the other.

It can be appreciated the adequate response of the grid-connected converter for both, mode changes and load transients in rectifier mode.

Table 5 summarizes the electrical parameters achieved by using the holistic control approach. It can be observed the capability to fulfill each one of them for each mode.

Table 6 reveals the designed holistic control since all the relevant parameters of the controller are basically the same with exception of the reference although certainly, references are not part of the controller tuning.

V. DISCUSSION: PROPOSED CONTROL SCHEME VS. TRADITIONAL CONTROL SCHEME

In this paper a holistic control approach applied to the grid-connected converter for BESS applications has been analyzed, tuned and demonstrated its feasibility by simulations by using PSCAD. The converter features permit to obtain a linear model and design a state-feedback controller with integral action. The control formulation allows avoiding some usual complications that are common in the control of this kind of system such as dq transformations or the use of double control loops for regulating the DC voltage and tracking the AC current. The whole control is conceptualized to work in a single loop once the proper reference is established. An empirical proposal for tuning the controller is put into consideration. For the sake of clarity, two boundaries for placing the closed-loop eigenvalues are suggested; a lower limit which corresponds with the bandwidth of the LCL filter, and an upper limit which corresponds with the grid-connected converter switching frequency. Thus, a multiplier M is used to place the closed-loop eigenvalues and tune the controller, being careful of selecting the real part negative. The result is that with the same tuned controller, each mode fulfills the empirical proposal with closed-loop eigenvalues which guarantee exponential stability.

The main merit of this approach is that the grid-connected mode (rectifier) is incorporated to the whole analysis. If the rectifier modeling is incorporated considering the dc capacitor voltage as a state variable, a nonlinear model of fourth-order appears avoiding the holistic control conceptualization. Hence, by introducing a proper current reference shifted $180^\circ$ which maintains the power balance between AC and DC side, the third-order model of the grid-connected mode (inverter) can be used and the holistic control formulation can be preserved. Thereby, the same tuning for the same controller can be applied for the three operation modes and the proposed holistic BESS control concept is achieved.

The simulation results performed in a specialized software validate the feasibility of the proposal for fulfilling electrical parameters which includes mode changes and load steps accordingly with a duty class and power quality requirements.
VI. CONCLUSION
This paper studies the feasibility of implementing a fully unified control approach for the grid-connected converter contributing with a process for tuning the control considering physical restrictions. By using this approach, the grid-connected converter performance in the time domain is similar to those proposals that use the hybrid or unified control approaches. As further research, this holistic control can be evaluated under fault and unbalanced conditions in weak grids.

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