POWER CONTROL STRATEGY FOR GRID-CONNECTED INVERTERS IN STATIONARY REFERENCE FRAME

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Abstract – The control of grid-connected converters in stationary reference frame has been investigated in several works of literature. One of the challenges of this method is in the computation of the current controlling current references as a function of power references. In some works, this issue has been solved based on instantaneous power theory equations described in the stationary reference frame. However, this approach can lead to steady-state errors in the injected power if there is an error in the current control loop, which is the focus of this investigation. Firstly, analytical expressions are derived to investigate the effect of current loop steady-state error in the active and reactive power injected into the grid. Then, this paper proposes a closed-loop power control for grid-connected inverters controlled in the stationary reference frame. This strategy is experimentally investigated in two power conversion system configurations for battery energy storage systems. The results indicate that the proposed scheme guarantees zero steady-state error in the injected power even when the current control loop presents an amplitude and phase steady-state error.

Keywords – Active Power Control, Battery Energy Storage Systems, Instantaneous Power Theory, Reactive Power Control, Square Voltage Control, Stationary Reference Frame

I. INTRODUCTION

The cost reduction of battery technologies and high penetration level of photovoltaic and wind energy generation in the electrical power systems contribute to the growth of battery energy storage systems (BESS) installations around the world [1]. Furthermore, the BESS can contribute to several grid services, which increases the hosting capacity of distributed generation (DG) [2]. The main services are time-shifting (arbitrage), peak shaving, load leveling, spinning reserve, voltage support, support of intermittent renewable generation plants and reactive power support [3].

All these services involve the control of active or reactive power in the grid. Generally, the reactive power is controlled in the outer-loop of the inverter control strategy, which composes the dc/ac stage of the power conversion system.
of the PCS are cascaded connected. This PCS structure has been gaining attention for BESS application due to the low step-up ratio if compared to the parallel converter structure [10]. In this case, the dc-link voltage is controlled by dc/dc converters, and the inverter directly controls the active and reactive power exchanged with the grid. Therefore, a closed-loop control strategy is also required for the active power component control.

Given the above discussions, the main contributions of this paper are listed below:

- Mathematical analysis of the error in the power components if the open loops are used;
- Proposal of a closed-loop for active power applied in the control strategy based on stationary reference frame and IPT;
- Experimental validation of reactive power closed-loop applied in dc-link voltage-based method along with stationary reference frame and IPT.

It is worth noting that the proposal of this work apply to any system that presents grid-connected inverters, such as photovoltaic, wind, and battery energy storage systems. In this work, proposed control strategies are studied and applied in battery energy storage systems due to their current importance for distributed generation.

This paper is organized into six sections. Section II presents the power structure where the control strategies are studied and validated. In Section III, the control strategies proposed in this work are detailed. Section IV shows the control design of the proposed control strategies. The error modeling on the active and reactive power is performed in Section V. Experimental results are presented in section VI. Finally, the conclusions are presented in section VII.

II. Power Electronics Structures for BESS realization

The proposed reactive and active power control strategies based on stationary reference-frame and instantaneous power theory are applied and analyzed in the control structures shown in Fig. 2. These structures are grid-connected BESS, which present PCS of two stages. The first stage is composed by the inverter and the second stage is composed by dc/dc converters.

In the first stage, a two-level inverter is used to interface the BESS system with the grid. In the second stage, a multiport power electronic concept is used in [11]. With this approach, it is possible to associate different sources and battery technologies and operate in different power levels, improving power management and flexibility.

This work uses two approaches to multiport converters with interleaved bidirectional dc/dc converters, which is interesting to reduce the input and output current ripple [12],[13]. In this work, three legs are used for each dc/dc converter.

The first analyzed multiport converter structure uses two interleaved bidirectional dc/dc converters connected in parallel, as shown in Fig. 2(a). The association of dc/dc converters in parallel mode is widely discussed in literature [14]–[16]. The voltage outputs of the dc/dc converters are equal to the dc-link voltage, which is generally regulated by the inverter control scheme. In this scenario, each dc/dc converter can inject power independently and the typical outer-loop of the control strategy have the following characteristics:

- The inverter control strategy presents the dc-link voltage ($V_{dc}$) and reactive power ($Q$) control. The control references for both quantities are $V_{dc}^*$ and $Q^*$, respectively.
- The dc/dc converters control the active power ($P_1$) and ($P_2$) processed by each one independently, according to the references are ($P_1^*$) and ($P_2^*$).

An advantage of the parallel connection lies in the fact that if one converter fails, it can be removed from the system effortlessly due to the natural independence connection between the converters With penalties on power rating. A disadvantage is the high voltage step-up ratio required for a low input voltage, reducing the efficiency.

The second multiport dc/dc converters is the cascaded connection of two interleaved bidirectional dc/dc converters, as shown in Fig. 2(b) [10], [17], [18]. The advantage of this structure is the sum of the output voltage of the converters,
allowing the lower voltage step-up ratio required if compared to the parallel structure [19]. However, there are challenges in the control and power structure of this strategy. This structure requires an equal output current in each dc/dc converter. Therefore, bypass diodes are required for this structure to remove a converter in case of failure [10]. For simplicity, these diodes are not shown in Fig. 2(b).

Furthermore, the output voltage of each converter cannot be fixed by the inverter control, as performed in the parallel structure. Therefore, each dc/dc converter controls its output voltage and the power control is transferred for the inverter control strategy. In this scenario, the independent operation between the dc/dc converters is achieved by changing their output voltages [19]. Therefore, if the dc-link is kept constant, the output voltages of the dc/dc converter must be changing proportionally to the power operation point in each one. For this structure, the typical outer loop of the control strategy has the following characteristics:

- The inverter control strategy have the active (P) and reactive power (Q) control;
- The dc/dc converters control the output dc voltage ($V_{dc1}$) and ($V_{dc2}$), which follows the references ($V_{dc1}^*$) and ($V_{dc2}^*$).

It is important to highlight that inner loops of both structures are similar, and they are responsible for controlling the inverter output current and current of each arm of the interleaved dc/dc converter. However, the focus of this work is on the outer loop of the inverter control strategy and this discussion is deepened in the next section.

### III. Control Structures

The typical inverter control structure discussed in literature are based on the dc-link voltage square $V_{dc}$ in outer-loop and stationary reference-frame, the current control is shown in Fig.3(a) [9], [20], [21]. This control strategy can integrate the inverter control structure shown in Fig. 2(a), since this is responsible for dc-link voltage control.

The modeling of the outer-loop based on the $V_{dc}$ squared method is carried out from the stored energy in the dc-link capacitor, detailed in [22]. A proportional-integrator (PI) controller calculates the power which is required in the dc-link capacitor bank to regulate the dc-link voltage to the reference $V_{dc}^*$. Therefore, through the external power $P_{ext}$ measured in the battery bank terminals, the inverter active power reference ($P^*$) is calculated.

The inverter current references ($i_{a,b}^*$) in the stationary reference frame are calculated by the instantaneous power theory, given by [23]:

$$
\begin{bmatrix}
    i_{a}^* \\
    i_{b}^*
\end{bmatrix}
= \frac{1}{\sqrt{\alpha^2 + \beta^2}}
\begin{bmatrix}
    v_{a} & v_{b} & v_{c} \\
    v_{b} & v_{c} & v_{a}
\end{bmatrix}
\begin{bmatrix}
    P^* \\
    Q^*
\end{bmatrix},
$$

where $Q^*$ is the reactive power reference to perform some grid service such as Low-Voltage-Ride-Through, or voltage regulation [24], [25]. The positive sequence on the fundamental frequency of the point of common coupling (PCC) voltage in stationary reference ($v_{a,b}$) is calculated by

$$
\begin{cases}
    v_{a} &= v_{dc} \cos(\omega t) - v_{ac} \sin(\omega t) \\
    v_{b} &= v_{dc} \cos(\omega t) - v_{ac} \sin(\omega t)
\end{cases}
$$

$\omega$ is the resonant frequency. The PR controller design is described in [28]. Finally, the feedforward voltage terms ($v_{a,b}$) are included, generating the inverter reference voltages synthesized using a space vector modulation (SVPWM).

As can be seen, the reactive power is essential in the open-loop in this scheme. This approach presents steady-state error in the reactive injection and leads to poor performance of the reactive services performed by the inverter. For this reason, reference [8] proposes the reactive power control loop for the control structure that uses $V_{dc}$, squared based method for dc-link voltage control and stationary reference-frame in the current control, as shown in Fig 3(b). This control technique adds the measured inverter reactive power ($Q$) and compares it with the reference ($Q^*$). An integrator controller ($k_i/s$) processes the error between these two components and the output is added to the reference $Q^*$, equaling this reference to the measured component in steady-state. This control strategy is applied in the power structure shown in Fig. 2(a), where the inverter controls the dc-link voltage and the parallel dc/dc converters control the system power.
When the cascaded dc/dc converters are employed, as shown in Fig. 2(b), the dc-link voltage control is transferred to the dc/dc converters and the active power is performed by the inverter. This approach allows using the stationary reference frame in the current control with instantaneous power theory and ensures an easy saturation of power components processed by the inverter. Therefore, this work extends the method proposed for the reactive power control to the active power control, as shown in Fig. 3(c). In the next section, a control analysis is performed for both the reactive and active power loops.

Active and active power is measured through the voltage and current components of the inverter in the stationary reference frame, given by [29]:

\[ P = \frac{1}{2}(v_{a}i_{a}^{*} + v_{b}i_{b}^{*}) \]  
\[ Q = \frac{1}{2}(v_{b}i_{a}^{*} - v_{a}i_{b}^{*}) \]

IV. Error Modelling on the Active and Reactive Power

The power components error can be modeled as a function of phase and amplitude errors in current control loops. For this purpose, considering the active \( P \) and reactive \( Q \) power components injected by the inverter given by:

\[ P = \frac{3}{2}(v_{a}i_{a} + v_{b}i_{b}) \]  
\[ Q = \frac{3}{2}(v_{b}i_{a} - v_{a}i_{b}) \]

where \( v_{a\beta} \) is the grid voltage in stationary reference frame, \( i_{a\beta} \) is the output current of the inverter. These voltage and current components are substituted by:

\[ v_{a} = V\cos(\alpha t), \]  
\[ v_{b} = V\cos(\alpha t - 90), \]  
\[ i_{a} = (I + \Delta I)\cos(\alpha t + \delta + \Delta \theta), \]  
\[ i_{b} = (I + \Delta I)\cos(\alpha t - 90 + \delta + \Delta \theta), \]

where \( V \) is the peak value of grid phase voltage, \( I \) is the peak value of the inverter current, \( \Delta I \) is the amplitude error of current controller, \( \Delta \theta \) is the current controller phase error and \( \delta \) is the angle of the power factor (PF) the current controller phase error.

Therefore, errors in active and reactive power are given by, respectively:

\[ \Delta P = P^{*} - P = \frac{3}{2}V[(I + \Delta I)\cos(\delta + \Delta \theta) - I\cos(\delta)], \]  
\[ \Delta Q = Q^{*} - Q = \frac{3}{2}V[(I + \Delta I)\sin(\delta + \Delta \theta) - I\sin(\delta)], \]

Considering same current and voltage amplitudes, the errors depend on PF angle, the amplitude and phase error of the current power error for PF close to 0.

![Fig. 4 Active and reactive power error in relation to the phase and amplitude errors of the current control, considering different power factors. (a) Reactive power error for PF = 0.707. (b) Active power error for PF = 0.707. (c) Active power error for PF = 1. (d) Reactive power error for PF close to 0.](image)

V. Design of the Power Controls

The current reference frame addressed in this work is stationary and thus the current controller must be able to track signal with a specific frequency. In this scenario, the use of a proportional-integral controller leads to magnitude and phase errors [30]. Because of that, the proportional-resonant controllers (PR) have been spread used in this scenario [31].

The active and reactive power errors in steady-state, using the open-loop approaches are mainly due to phase or amplitude error from current control. These errors can occur even if current control strategy is well-tuned. For example, if proportional-resonant (PR) controllers, tuned at 60 Hz, are used, in case of grid voltage and frequency instabilities the active and reactive power error arises. To overcome this drawback, adaptive PR controller tuning can be used [31]. However, this approach requires considerable computational time processing since recommended discretization based on Tustin, with pre-warping, requires the calculation of trigonometric functions in all execution steps [32].

This drawback can be better understood through the bode diagram of the inverter current closed-loop, shown in Fig. 5. In this example, the PR controller is designed to track the 60
HZ current, however, there are magnitude and phase errors if the signal frequency changes, for example, to 60.5 Hz. To overcome this drawback, the second solution is to use the proposed closed-loop strategies for power components control. However, an important step in using this technique is the design of the controllers. can be seen in Fig. 3(c), both active and reactive power control loops have a similar structure. Therefore, these control loops have the same design and, consequently, the same stability analysis.

The simplified closed-loop block diagram of the active and reactive power controls is shown in Fig. 6, where $Y$ represents both power components and $k_i/s$ is the integral controller. $G_c$ is the inner loop controller, which is designed to be faster than the outer-loop control. In such conditions, $G_c \approx 1$. $\Delta Y(s)$ is the disturbance that causes steady-state error in the power components concerning the references. The output dynamic stiffness, which indicates the effect of the disturbance $\Delta Y(s)$ in the output power component $Y$, can be found as:

$$\frac{\Delta Y(s)}{Y(s)} = 1 + \frac{k_i}{s},$$

where $k_i$ is the integrator gain. This relationship describes the effect of the disturbance in the output $Y(s)$. Fig. 7 shows the dynamic stiffness magnitude concerning the frequency for range values of $k_i$. It is important to note that $k_i = 0$ represents the case when the power components are in an open loop, presenting a poor dynamic stiffness. In this case, a unitary magnitude of $\Delta Y$ causes a unitary magnitude error in the output $Y$ in all frequency spectrums. As $k_i$ increases, the dynamic stiffness increases for $s \to 0$ and still is unitary for $s \to \infty$. Therefore, theoretically, the higher the value of $k_i$, the better the dynamic stiffness.

Ignoring the constant term $Y^*$ adding to the output of the controller $k_i/s$ and $\Delta Y$, the closed loop transfer function reported in Fig. 6 is given by:

$$\frac{Y^*(s)}{Z(s)} = \frac{k_i}{s + k_i},$$

The pole of this transfer function is:

$$\omega_c = k_i,$$

Generally, the inner-loop control is designed one decade below the inverter switching frequency. The pole is placed three decades below the switching frequency, $k_i$ can be estimated by:

$$k_i = \frac{2\pi}{1000T_{sw}},$$

where $T_{sw}$ is inverter switching period.

Therefore, the control design of the power components is performed to take into account the maximum dynamics stiffness as possible, respecting the limited frequency response concerning the inner-loop.

**VI. Results**

A 6 kVA BESS is used in simulation and experimental setup to validate the control strategies of the power components shown in Fig. 3. The response of the proposed power control loops during frequency variations is shown in simulation results. Furthermore, a comparison between the proposed methodology and one already present in the literature is shown in the simulation results. In the experimental test bench, steady-state comparisons between the closed-loop of the power components and the open-loop approach are shown. In the simulation results, the topology is shown in Fig. 2(b) is used. In experimental results, both topologies of Fig. 2 are used.

The main parameters of the system for both simulation and experimental test setup are shown in Tab. I. the PR controllers are used in the current control, tuned at the 60 Hz rated frequency of the grid. The inner-loop control frequency of the inverter is designed a decade below the switching frequency. The outer-loop reactive and active power components control are designed three decades below the switching frequency, given $k_i$ equal to 57.
### TABLE I
Simulation and Experimental system parameters.

<table>
<thead>
<tr>
<th>Power Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCL inductances</td>
<td>1 mH</td>
</tr>
<tr>
<td>LCL capacitance</td>
<td>25 µF</td>
</tr>
<tr>
<td>DC-link capacitance</td>
<td>4.7 mF</td>
</tr>
<tr>
<td>Interleaved dc/dc</td>
<td></td>
</tr>
<tr>
<td>Converter inductance</td>
<td>4 mH</td>
</tr>
<tr>
<td>Switching frequencies</td>
<td>9 kHz</td>
</tr>
<tr>
<td>Grid line Voltage</td>
<td>220 V</td>
</tr>
</tbody>
</table>

Fig. 8. Grid frequency variation for the simulation case study.

#### A. Simulation Results

The grid frequency is changed to demonstrate the performance of the proposed power control loops, as shown in Fig. 8. The frequency begins at 60 Hz. In 0.5 seconds, it is changed to 60.5 at a slope rate of 4 Hz/second. In 1 second, the frequency changes to 59.5 Hz at the same slope rate.

The time responses of active and reactive power during grid frequency variation is shown in Fig. 9(a) and 9(b), respectively. It can be noticed the disturbances during the frequency transitions and their rejection in steady-state, according to the controller design. The grid frequency transients occur when the active and reactive power is equal to 3000 W and 3000 var, respectively. Furthermore, there are transients in 1.5 and 2 seconds in both active and reactive power, respectively, dropping to half of the initial conditions. Results show a fast closed-loop response time.

Fig. 10 shows the same time responses and transients for a power control strategy present in the literature [33]. This strategy controls the inverter current in the stationary reference frame, likely the proposed strategy in this work. However, it does not use the instantaneous power theory to calculate the reference current, since the response of the outer loop controller is the conductance. For a fair comparison, the outer loop controllers are adjusted to have the same bandwidth and dynamic stiffness as the strategy proposed in this work. It can be verified a similarity between the strategies during the transitions of the grid frequency and also in the power variation, showing the applicability of the proposed strategy near to the existing one.

Finally, Fig. 11(a) and (b) show the active and reactive power components considering the open-loop, respectively.

#### B. Experimental Results

A 6 kVA experimental BESS bench is used to validate the power components control strategies shown in Fig. 3.
This setup allows implementing both parallel connection and cascaded connection of dc/dc converters. The experimental setup overview is shown in Fig. 12. The main parameters of the BESS are shown in Tab. I. The control structures are implemented in two TMDSDOCK28379D experimental kits with the DSP F28379D from Texas Instruments.

The rms grid line voltage is 220 V and PR controllers used in the current control, tuned at the 60 Hz grid rated frequency. To demonstrate the errors that can happen in inverter current control, the test bench was supplied with a power source that imposes a frequency of 60.5 Hz. The Regenerative Grid Simulator NHR 9410 is used to perform a frequency variation. This scenario is suitable to validate the control strategies. It is important to highlight that this was the simplest manner of emulating a control error.

Lead-acid batteries 12MN36 of MOURA with a voltage of 12 V and charge of 36 A at 20°C are used. Each dc/dc converter presents 16 batteries in series. The dc-link voltage is controlled at 480 V during the experiment.

The inner-loop control frequency of the inverter is designed a decade below the switching frequency. The outer-loop reactive and active power components control are designed three decades below the switching frequency, given $k_i$ equal to 57.

The first analysis considers the structure shown in Fig. 2(a), with two interleaved dc/dc converters in parallel connection. In this case, the reactive power regulation considering control structure in open and closed loops for reactive power is shown in Fig. 3(a) and (b), respectively. Fig 13 shows reactive power profile considering PF equal to 0.707 and reference equal to 3000 var. It can be noticed that open-loop approach presents an error between measurement and reference equal to 48 var, while for closed-loop approach, the error of measured reactive power and reference is close to zero.

The reference and measurement current of inverter inner control loop are shown in Fig. 14, considering the reactive power open-loop approach. The phase error ($\Delta \theta$) between these two components is 0.84 degrees and the amplitude error ($\Delta I$) is 0.03 pu. These errors were estimated through the Fast Fourier transform. Through the mathematical analysis presented in previous section, the expected reactive power error is 50.25 var. This represents an estimation error of 4.7% concerning the measurement value of 48 var, as shown in Fig. 13.

Considering the same power structure, Fig 15 shows the reactive power profile with PF close to zero. The error of
the open-loop approach reduces to 9 var and this is in line with the analysis shown in Fig. 4(c) since the error variation, in this case, is less than the case of PF equal to 0.707. It is important to note that the closed-loop, leads to approximately zero steady-state error.

The second analysis considers the structure shown in Fig. 2(b), with two cascaded interleaved dc/dc converters. The control structure shown in Fig. 3(c), where both active and reactive power is in a closed-loop, is compared with the traditional scheme. Fig 16 shows the active power profile considering PF equal to 0.707 and reference equal to 3000 W. It can be noticed that open-loop approach presents an error between measurement and reference equal to 4.5 W, while for closed-loop approach, the error of measured active power and the reference is close to zero. Considering the same power structure, Fig 17 shows active power profile with PF equal to 1.

These results show that the proposed scheme ensures very low steady-state error in the active and reactive power.

VII. CONCLUSIONS

This paper approaches the active and reactive power control strategies applied to BESS. These strategies are applied in the inverter control along with the square dc-link voltage along with the stationary reference frame and instantaneous power theory. The experimental results, considering a deviation in the grid rated frequency, show that the steady-state error was reduced using the closed-loop for power components concerning the open-loop strategies addressed in the literature. Furthermore, it can be verified that the power component error depends on the power factor and the error of the current control loop. The control strategy proposed in this work is simple to be implemented and guarantees the reduction of the steady-state error in the power components. These errors can arise from several factors, such as discretization problems, bad control tuning, or grid frequency variation.

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REFERENCES

[1] REN21, Renewables 2020 Global Status Report, Ph.D.


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