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ABSTRACT

Here goes the abstract

1. Introduction

According to the International Renewable Energy Agency (IRENA) and the International Energy Agency (IEA), renewable energy sources (RES) are projected to account for at least 70% of global electricity generation by 2050 [1, p. 267]; [2, p. 20]. The increased penetration of RES — as exemplified by inverter-based resources, where the installed capacity of solar power generation alone already surpassed the total installed hydropower capacity by 2023 [3, pp. 18 and 33] — underscores the critical importance of researching grid converters to facilitate the integration of these energy resources. Operating primarily as controlled current sources [4, p. 3-4], these converters are designed to ensure efficient power injection, comply with low-voltage ride-through (LVRT) requirements, and potentially provide ancillary services such as dynamic voltage support and frequency regulation [5, p. 5-6]. Despite their advantages, grid-connected converters face significant challenges in offering dynamic grid support under fault and disturbance conditions, underscoring the necessity for advanced control strategies and optimized design methodologies to maximize efficiency [6, p.3-8], [7, p. 9-18].

Voltage sags are prevalent disturbances in power systems and represent one of the most frequently reported short-duration power quality issues worldwide [8, p. 12, 15, 22], [9]. To mitigate these effects, grid converters are expected to remain connected and provide positive-sequence reactive current injection (RCI) to stabilize voltage conditions at the point of common coupling (PCC) according to grid codes [10, p. 43-44], [11, p. 3, 5-6, 10, 18-19, 29-31]. As dictated by the generalized instantaneous reactive power theory (GIRPT), this compensation introduces substantial fluctuations in active (\tilde{p}) and reactive (\tilde{q}) power, typically at twice the frequency of the grid, which can propagate through the network [12, p. 3-4, 6-7]. These oscillations exert considerable stress on the power transformers that connect the converter to the main grid, resulting in increased thermal and magnetic stress, core saturation, and a general reduction in operational lifespan [13, p. 4-5]. Furthermore, voltage sags

induce second-harmonic oscillations in the DC-link voltage of grid-connected converters, producing significant ripple across capacitors. This ripple exacerbates thermal stress, accelerates capacitor degradation, and ultimately reduces the reliability and lifespan of these critical components [14, p. 1-2].

Since the establishment of grid codes in the early 2000s, several techniques have been proposed to address power control in grid-connected converters during voltage sags. The five different sinusoidal current control strategies — average active-reactive control (AARC), positive-negative sequence compensation (PNSC), balanced positive-negative sequence control (BPSC), active power oscillation cancellation (APOC), and reactive power oscillation cancellation (RPOC) — power oscillation profiles have been systematically analyzed in [14, 15, 16]. Nonetheless, novel approaches that incorporate sophisticated techniques, such as model predictive control (MPC) [17], sliding mode control (SMC) and adaptive control, have demonstrated improved dynamic response and LVRT capability. Additionally, emerging data-driven strategies, including machine learning-based adaptive power compensation and fuzzy logic controllers designed to enhance system resilience against grid disturbances, have gained attention. Although these new control paradigms may offer better performance, they generally entail a significantly higher computational cost and design complexity.

This paper aims to provide a thorough experimental quantification of the second harmonic component in power, introduced by the aforementioned strategies, through frequency analysis under both lightly and heavily unbalanced conditions. Furthermore, key active and reactive power set points are examined to assess the theoretical conditions for oscillation cancellation as established in the literature. Lastly, a direct comparison between the power ripple magnitude equation proposed in [18] and the experimental results is conducted.

The remainder of this work is organized as follows. In Section 2, the fundamental instantaneous characteristics of each power control strategy and their relationship to the unbalanced factor are analyzed. Section 3 presents a typical grid-connected converter control system structure. Section 4 details the experimental setup employed in this work. Section 5 presents and discusses the experimental results, and Section 6 states the main conclusions.

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2. Pliant power control strategies

The analysis and results presented in this work rely on the following assumptions:

- The active and reactive power delivered at the PCC is constant in a grid voltage period;
- The inverter is connected through a three phase three wire system and thus there is no zero-sequence voltage and current component at the PCC;
- The system operates as an ideal grid-following converter so it can be modeled as a current controlled source;
- The instantaneous voltage sequence components are known and their absolute values are constant during the dip. Therefore, the unbalanced factor $u = \frac{|V^-|}{|V^+|}$ is a scalar between 0 and 1;
- The phase angles of voltage and current sequences are constant during the sag

The GIRPT states that, for any three-phase system, the instantaneous active and reactive power can be expressed, respectively, in terms of the scalar and cross-vector products of the instantaneous voltage and current column vectors[13, p. 1]:

$$p = \mathbf{v} \cdot \mathbf{i} \quad (1)$$

$$\mathbf{q} = \mathbf{v} \times \mathbf{i} \quad (2)$$

Consequently, the current vector \mathbf{i} can be decomposed into two mutually orthogonal components: the instantaneous active current vector (\mathbf{i}_p) and the instantaneous reactive current vector (\mathbf{i}_q). Using this definition, \mathbf{i}_q is orthogonal to \mathbf{v} (null dot product), whereas \mathbf{i}_p aligns with \mathbf{v} (null cross product). These properties imply in:

$$p = (\mathbf{v}^+ + \mathbf{v}^-) \cdot (\mathbf{i}_p^+ + \mathbf{i}_p^- + \mathbf{i}_q^+ + \mathbf{i}_q^-) \quad (3)$$

$$p = \underbrace{\mathbf{v}^+ \cdot \mathbf{i}_p^+}_{P^+} + \underbrace{\mathbf{v}^- \cdot \mathbf{i}_p^-}_{P^-} + \underbrace{\mathbf{v}^+ \cdot \mathbf{i}_q^+ + \mathbf{v}^- \cdot \mathbf{i}_q^-}_0 \quad (4)$$

$$+ \underbrace{\mathbf{v}^+ \cdot \mathbf{i}_p^- + \mathbf{v}^- \cdot \mathbf{i}_p^+}_{\tilde{p}} \quad (5)$$

$$q = \|(\mathbf{v}^+ + \mathbf{v}^-) \times (\mathbf{i}_p^+ + \mathbf{i}_p^- + \mathbf{i}_q^+ + \mathbf{i}_q^-)\| \quad (6)$$

$$q = \underbrace{\|\mathbf{v}^+ \times \mathbf{i}_q^+\|}_{Q^+} + \underbrace{\|\mathbf{v}^- \times \mathbf{i}_q^-\|}_{Q^-} + \underbrace{\mathbf{v}^+ \times \mathbf{i}_p^+ + \mathbf{v}^- \times \mathbf{i}_p^-}_0 \quad (7)$$

$$+ \underbrace{\|\mathbf{v}^- \times \mathbf{i}_q^+ + \mathbf{v}^+ \times \mathbf{i}_q^- + \mathbf{v}^- \times \mathbf{i}_p^+ + \mathbf{v}^+ \times \mathbf{i}_p^-\|}_{\tilde{q}} \quad (8)$$

As proposed by (WANG,DUARTE), \tilde{p} and \tilde{q} can be compensated by weighting the different products of the

voltage and current sequence components through a $k_{p,q}$ factor. Since $\mathbf{i}_p^{+, -}$ is collinear to $\mathbf{v}^{+, -}$, there is some scalars $\lambda^{+, -}$ such that:

$$\tilde{p} = \mathbf{v}^+ \cdot \mathbf{i}_p^- + \mathbf{v}^- \cdot \mathbf{i}_p^+ \quad (9)$$

$$\mathbf{v}^+ \cdot \mathbf{i}_p^- = k_p \mathbf{v}^- \cdot \mathbf{i}_p^+ \quad (10)$$

$$\mathbf{v}^+ \cdot (\lambda^- \mathbf{v}^-) = k_p \mathbf{v}^- \cdot (\lambda^+ \mathbf{v}^+) \quad (11)$$

$$\lambda^- (\mathbf{v}^+ \cdot \mathbf{v}^-) = k_p \lambda^+ (\mathbf{v}^- \cdot \mathbf{v}^+) = \lambda^- = k_p \lambda^+ \quad (12)$$

$$\mathbf{v}^+ \cdot \mathbf{i}_p^+ = \mathbf{v}^+ \cdot (\lambda^+ \mathbf{v}^+) \longrightarrow \lambda^+ = \frac{\mathbf{v}^+ \cdot \mathbf{i}_p^+}{\|\mathbf{v}^+\|^2} \quad (13)$$

$$\mathbf{i}_p^- = \lambda^- \mathbf{v}^- = k_p \lambda^+ \mathbf{v}^- \quad (14)$$

$$\mathbf{i}_p^- = \frac{k_p \mathbf{v}^+ \cdot \mathbf{i}_p^+}{\|\mathbf{v}^+\|^2} \mathbf{v}^- \quad (15)$$

$$P \|\mathbf{v}^+\|^2 = (\|\mathbf{v}^+\|^2 + k_p \|\mathbf{v}^-\|^2) (\mathbf{v}^+ \cdot \mathbf{i}_p^+) \quad (16)$$

$$\mathbf{i}_p^+ = \frac{P}{\|\mathbf{v}^+\|^2 + k_p \|\mathbf{v}^-\|^2} \mathbf{v}^+ \quad (17)$$

$$\mathbf{i}_p^- = \frac{k_p P}{\|\mathbf{v}^+\|^2 + k_p \|\mathbf{v}^-\|^2} \mathbf{v}^- \quad (18)$$

$$\mathbf{i}_p^* = \frac{P^*}{\|\mathbf{v}^+\|^2 + k_p \|\mathbf{v}^-\|^2} (\mathbf{v}^+ + k_p \mathbf{v}^-) \quad (19)$$

$$(20)$$

A similar deduction exploiting the equivalent collinear property between \mathbf{i}_q^* and \mathbf{v}_\perp is presented in the same article, yielding:

$$\mathbf{i}_q^* = \frac{Q^*}{\|\mathbf{v}^+\|^2 + k_q \|\mathbf{v}^-\|^2} (\mathbf{v}_\perp^+ + k_q \mathbf{v}_\perp^-) \quad (21)$$

$$\mathbf{i}^* = \frac{P^*}{\|\mathbf{v}^+\|^2 + k_p \|\mathbf{v}^-\|^2} (\mathbf{v}^+ + k_p \mathbf{v}^-) \quad (22)$$

$$+ \frac{Q^*}{\|\mathbf{v}^+\|^2 + k_q \|\mathbf{v}^-\|^2} (\mathbf{v}_\perp^+ + k_q \mathbf{v}_\perp^-)$$

$$\|\tilde{p}\| = u \sqrt{\left(\frac{(1+k_p)P^*}{1+k_p u^2}\right)^2 + \left(\frac{(1-k_q)Q^*}{1+k_q u^2}\right)^2} \quad (23)$$

$$\|\tilde{q}\| = u \sqrt{\left(\frac{(1+k_q)Q^*}{1+k_q u^2}\right)^2 + \left(\frac{(1-k_p)P^*}{1+k_p u^2}\right)^2} \quad (24)$$

$$\|v\|^2 = \|v^+\|^2 + \|v^-\|^2 + 2\|v^+\|\|v^-\|\cos 2\omega t + \phi^+ \phi^- \quad (25)$$

2.1. Non-sinusoidal current strategy

2.1.1. Instantaneous Active-Reactive Control

This strategy naturally arises from the GIPT geometric properties of $\mathbf{i}_{p,q}$. Computing $\mathbf{i}_{p,q}^*$ as orthogonal and $\mathbf{i}_{q,p}^*$ as

Table 1

Relationship between k_{pq} coefficients and the sinusoidal power control strategies

PARPC		
Strategy	k_p	k_q
AARC	1	1
BPSC	0	0
PNSC	-1	-1
APOC	-1	1
RPOC	1	-1

Table 2

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Elaborated by the author.

parallel vectors to \mathbf{v} , the IARC can effectively cancel power oscillations for any u and active/reactive references:

$$\mathbf{i}_{p^*} = \frac{P^*}{\|\mathbf{v}\|^2} \mathbf{v} \quad (26)$$

$$\mathbf{i}_{q^*} = \frac{Q^*}{\|\mathbf{v}\|^2} \mathbf{v}_\perp \quad (27)$$

However, as eq. <ref-eq> states, the current references are proportional to $\|\mathbf{v}\|^2$. Since this norm is time-variant and directly linked to the symmetric-sequence components norms, the resulting current reference is inherently non-sinusoidal. Furthermore, when only active power is delivered to the grid ($Q^* = 0$), the total harmonic distortion (THD) of the current can be approximated as:

$$\text{THD}_i = \frac{u}{\sqrt{1-u^2}} \quad (28)$$

This undesired harmonic content, which is heavily dependent on the unbalance factor, may not meet grid power quality requirements even for low u values, especially if the inverter is connected to grid through a transformer.

2.2. Sinusoidal current strategies

2.2.1. Average Active-Reactive Control (AARC)

This strategy address the underlying problem present in the IARC: the second-order harmonics introduced by $\|\mathbf{v}\|^2$ (eq. (25)). To counteract the cosine oscillation, the squared denominator in eq. (23) must enclose all the voltage sequence components delivered in one grid period i.e the RMS voltage:

$$\sqrt{\|\mathbf{v}^+\|^2 + k_{p,q}\|\mathbf{v}^-\|^2} = \sqrt{\frac{1}{T} \int_0^T \|\mathbf{v}\|^2} \quad (29)$$

$$(30)$$

As a result, $\mathbf{i}_{p,q}$ are time-aligned with \mathbf{v} and \mathbf{v}_\perp , generating instantaneous power oscillations that are decoupled from each other's reference values. A important feature of this strategy is the lower conduction losses, whereas a drawback is necessary null reference to cancel \tilde{p} or \tilde{q} .

2.2.2. Positive-Negative-Sequence Compensation (PNSC)

While the previous strategy tries to align the respective currents and voltages components respectively responsible for $i_{p,q}$, the PNSC introduces the negative sequence voltage vector as subtracted quantity, producing a complementary characteristic: \mathbf{i} orthogonal components are time-aligned to their opposing voltage orthogonal vectors. This weighting links \tilde{p} and \tilde{q} to their counterpart power reference aiming to cancel the oscillation when one of them is zero.

2.2.3. Balanced Positive-Sequence Control (BPSC)

In the Balanced Positive-Sequence Control strategy, only the positive-sequence voltage vector is employed to compute the reference currents. Since no negative-sequence component current is injected, both P^- and Q^- are zero, indicating that the average active and reactive power depend exclusively on P^+ and Q^+ , respectively. Nonetheless, as pointed in , the inner and cross products of \mathbf{i}_p^+ and \mathbf{v}^- introduce power oscillations of equal magnitude in p and q , which are directly proportional to their respective reference values. Although these power oscillations are not eliminated for any reference value, this strategy is unique as it produces a perfectly balanced current set for any unbalance factor.

2.2.4. Active Power Oscillation Cancels (APOC)

As the \tilde{p} equation highlights, active power oscillation is a product of the inner product of \mathbf{v}^{+-} and \mathbf{i}^{+-} , which is exactly what APOC tries to compensate for alligning \mathbf{i}_p and \mathbf{v}_\perp maximums values. Thus, a constant p is obtained for whatever u factor and power references values. Nevertheless, \mathbf{i}_q is precisely collinear to \mathbf{v} , yielding the highest \tilde{q} possible.

2.2.5. Reactive Power Oscillation Cancels (RPOC)

A reciprocal approach to APOC is used in the Reactive Power Oscillation Cancels strategy, where \mathbf{i}_q is always perpendicular to \mathbf{v}_\perp objectiving a null cross product between them for arbitrary P^* and Q^* and unbalanced factor. Conversely, as predicted by IGPT, the second order oscillation superimposed on the active power will be at its peak.

3. System structure

3.1. Converter topology

The schematic of the three-phase, three-wire grid-connected inverter analyzed in this study is illustrated in ???. The DC/DC stage consists of a three-level interleaved bidirectional half-bridge converter that manages battery power flow and controls active power delivery. This is followed by a two-level, three-phase inverter responsible for DC-link voltage regulation and current characteristics injected into the grid through an LCL filter. Both stages employ cascade control.

3.2. Dc/ac control strategy

The inverter control strategy consists of two cascaded loops, being the faster inner-loop current control implemented in the $\alpha\beta$ stationary reference frame (SRF) through an ideal proportional-resonant (PR) controller (eq. (31))

tuned at the fundamental frequency of the grid. The LCL capacitor dynamics are ignored and thus i_s is presumably equal to i_{abc} . The outer voltage loop acts as a reference for the current loop and control power flow (Grid service) by compensating the DC-link voltage. This voltage regulation is modeled using the square voltage method and achieved through a PI controller, as proposed in <ref>.

$$G_c(s) = K_p + K_r \frac{s}{s^2 + \omega_f^2} \quad (31)$$

3.2.1. Sequence Detection

Accurate voltage sequence detection plays a crucial role in both reference current computation and grid synchronization. Therefore, a robust phase-locked loop (PLL) is essential. Considering that the current control is done in the SRF, the dual second order generalized topology (DSOGI-PNSC) arises as a convenient choice.

3.2.2. Power control

4. Experimental setup

To assess the performance of the proposed power control strategies, experimental validation was conducted using the laboratory test setup shown in (??). The system consists of a battery energy storage system (BESS) interfaced with a programmable three-phase regenerative grid simulator (NHR 9410), which was configured to simulate a voltage sag in A and B phases. Although the pq theory states that, theoretically, no energy storage element is required to compensate for \tilde{p} and \tilde{q} , this particular setup is valuable for validating the ripple magnitude at the PCC, as it offers the following advantages:

- Battery storage fast responding dynamics as a constant dispatchable active power source
- The ability to maintain (ideally) zero active power exchange, as the batteries' discharge current counteracts the active power required for PCS operation.

The instantaneous power waveforms were acquired at the DC/AC stage switching frequency using TMDSDOCK28379D development kits, which were employed to control the BESS power conversion system. The recorded data were then exported via Code Composer Studio to MATLAB for further analysis.

The key parameters of the case study are presented in table 3, while table 4 summarizes the selected unbalanced grid conditions and the active/reactive power reference values imposed on the converter for all u values.

5. Results

Table 3

Parameters of the experimental system

PCS Parameters	Values
Dc/dc converter inductance	4 mH
Dc/dc converter switching frequency	9 kHz
Dc/ac stage switching frequency	9 kHz
Number of interleaved dc/dc converter cells	3
Grid and dc/ac stage side LCL filter inductance	1 mH
Capacitance of each module	4.7 mF
LCL filter capacitance	25 μ F
LCL filter damping resistance	1.8 Ω
Grid voltage (RMS)	220 V
Grid frequency	60 Hz
Dc-link voltage	500 V
Nominal current (RMS)	16 A
Battery Parameters	Value
Rated Capacity (C/20)	36 A h
V_{nom}	12 V
V_{boost}	14.4 V
V_{float}	13.6 V
R_{bat}	7.2 Ω
Maximum charge current	7.2 A

Table 4

Grid voltages, unbalanced factors and converter power references

u	$V_{a,b}$ V	$V_{a,b}$ [pu]
0.18	76.21	0.8
0.33	50.80	0.6
0.57	25.40	0.4
Converter Power References		
Active W	Reactive VAr	
0	1500	
1500	0	
1000	1000	

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