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ABSTRACT

Here goes the abstract

1. Introduction

According to the International Renewable Energy Agency (IRENA), renewable energy sources~~, enabled by technologies such as inverter-based resources,~~ are projected to contribute over 80% of global electricity generation by 2050 [1]. This projection highlights the increasingly critical role of grid-following converters in facilitating the integration of these energy resources. ~~Functioning~~ primarily as controlled current sources [2], 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 [3]. Despite their advantages, grid-~~following~~ 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 [4].

Voltage sags and imbalances are widespread disturbances in power systems, accounting for most reported power quality issues worldwide [5]. To mitigate these effects, grid-~~following~~ converters are expected to inject positive-sequence reactive current (RCI) to stabilize voltage conditions at the point of common coupling (PCC) according to ~~local~~ grid codes [6]. As dictated by the instantaneous power theory, this compensation introduces substantial fluctuations in active and reactive power, typically at twice the frequency of the grid [7], which may propagate through the network. These oscillations exert considerable stress on the power transformers connecting the converter to the main grid, resulting in increased thermal and magnetic stress, core saturation, and an overall reduction in operational lifespan [8]. 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 [9].

2. Pliant power control strategies

The analysis 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 ~~inverter~~ so it can be ~~reliably~~ 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 $u = \frac{absV^-}{[illegible]}$ is a scalar between 0 and 1;
- Sequence-component phases are constant.

The generalized instantaneous power theory (GIPT) 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:

$$p = \mathbf{v} \cdot \mathbf{i} \tag{1}$$

$$\mathbf{q} = \mathbf{v} \times \mathbf{i} \tag{2}$$

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 $\mathbf{i_p}$ is aligned with $\mathbf{v}$ (null cross product). These properties imply in:

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

$$p = \underbrace{\mathbf{v}^+ \cdot \mathbf{i}_p^+}_{P^+} + \underbrace{\mathbf{v}^- \cdot \mathbf{i}_p^-}_{P^-} + \underbrace{\mathbf{v}^+ \cdot \mathbf{i}_q^+ + \mathbf{v}^- \cdot \mathbf{i}_q^-}_{0} \tag{4}$$

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

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

$$q = \underbrace{\|\mathbf{v}^+ \times \mathbf{i}_q^+\|}_{Q^+} + \underbrace{\|\mathbf{v}^- \times \mathbf{i}_q^-\|}_{Q^-} + \underbrace{\mathbf{v}^+ \times \mathbf{i}_p^+ + \mathbf{v}^- \times \mathbf{i}_p^-}_{0} \tag{7}$$

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

As proposed by (WANG,DUARTE), $\tilde{p}$ and q̃ can be compensated weighting the different voltage and current sequence components products via a $k_{p,q}$ factor. Since $\mathbf{i_p}^{+,-}$ is collinear to $\mathbf{v}^{+,-}$, there is some scalars $\lambda^{+,-}$ such that:

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

$$\mathbf{v}^+ \cdot \mathbf{i}_p^- = k_p \mathbf{v}^- \cdot \mathbf{i}_p^+ \tag{10}$$

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

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

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

$$\mathbf{i}_p^- = \lambda^- \mathbf{v}^- = k_p \lambda^+ \mathbf{v}^- \tag{14}$$

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

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

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

$$\mathbf{i}_p^- = \frac{k_P P}{\|\mathbf{v}^+\|^2 + k_p \|\mathbf{v}^-\|^2} \mathbf{v}^- \tag{18}$$

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

$$\tag{20}$$

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

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

$$\mathbf{i}^* = \frac{P^*}{\|\mathbf{v}^+\|^2 + k_p \|\mathbf{v}^-\|^2} (\mathbf{v}^+ + k_p \mathbf{v}^-) + \frac{Q^*}{\|\mathbf{v}^+\|^2 + k_q \|\mathbf{v}^-\|^2} ({\mathbf{v}_\perp}^+ + k_q {\mathbf{v}_\perp}^-) \tag{22}$$

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

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

$$\|v\|^2 = \|v^+\| + \|v^-\| + 2\|v^+\|\|v^-\| \cos 2\omega t + \phi^+ \phi^- eqn \tag{25}$$

Table 1
Relationship between k_{pq} coefficients and the sinusoidal power control strategies

PARC		
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.

2.1. Non-sinusoidal

2.1.1. *Instantaneous Active-Reactive Control*

This strategy naturally arises from the GIPT geometric properties of $\mathbf{i_{p,q}}$. Computing $\mathbf{i_{p^*}}$ as orthogonal and $\mathbf{i_{q^*}}$ as parallel vectors to $\mathbf{v}$, the IARC can effectively cancel power oscillations for any u and active/reactive references:

$$\mathbf{i_{p^*}} = \frac{P^*}{\|\mathbf{v}\|^2} \mathbf{v} \tag{26}$$

$$\mathbf{i_{q^*}} = \frac{Q^*}{\|\mathbf{v}\|^2} \mathbf{v}_\perp \tag{27}$$

$$\tag{28}$$

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:

$$\mathrm{THD}_i = \frac{u}{\sqrt{1-u^2}} \tag{29}$$

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

2.2.1. *Average Active-Reactive Control (AARC)*

This strategy address the underlying problem present in the IARC: the second-order harmonics introduced by $\|v\|^2$ (**??**). 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:

$$: v_n orm \sqrt{\|\mathbf{v}^+\|^2 + k_{p,q}\|\mathbf{v}^-\|^2)} = \sqrt{\frac{1}{T}\int_0^T \|\mathbf{v}\|^2} \tag{30}$$

(31)

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 oposing 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 reciprical aproach 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. (32)) 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>.

$$G_c(s) = K_p + K_r \frac{s}{s^2 + w_f^2} \tag{32}$$

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 an 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.

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 µF
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	

5. Results

6.

CRediT authorship contribution statement

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