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A NOVEL ADAPTIVE CURRENT HARMONIC CONTROL STRATEGY APPLIED IN MULTIFUNCTIONAL SINGLE-PHASE SOLAR INVERTERS

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Abstract – The inverter multifunctional operation is based on the harmonic current compensation, generated by nonlinear loads. The traditional harmonic detection methods tracks all harmonic contents of the load current and the control tuning tends to be complex with low flexibility. In many works, the proportional resonant (PR) controllers are used to control the inverter current reference. However, one PR controller needs to be designed for each harmonic frequency and this fact increases the control algorithm complexity. Therefore, this work proposes a novel adaptive current harmonic control strategy applied in multifunctional single-phase solar inverters. The strategy is based on a novel detection method of the harmonic load current. The harmonic current detection method is frequency adaptive and able to detect the load harmonic current with higher amplitude. This method consists in a cascade association of two phase-locked loop based on second order generalized integrator (SOGI-PLL). The detected frequency is used as feedback by the proportional resonant controller. Therefore, only two PR controller are required: one to track the fundamental component and another to track the harmonic component with higher magnitude. Simulation and experimental results show the performance of the proposed control strategy, improving significantly the grid current quality.

Keywords – Adaptive control, harmonic compensation, harmonic current detection method, multifunctional operation, proportional resonant controller, SOGI-PLL.

I. INTRODUCTION

For the first time in four decades, the global carbon emissions related to energy consumption remained stable in 2014, while the global economy grew [1]. The high penetration level of renewable energy sources in the global electrical system is the reason associated with this stabilization [1]. However, the growth of renewable energy sources integration (especially wind and photovoltaic sources) with the electrical system are bringing some concerns for researchers, such as: quality in the energy injected into the grid due to use of power electronic converters [2],[3]; the security and support in an installation under fault in the grid [4]–[6].

Although the use of electronic converters as interface between renewable source and grid brings challenges in relation to the injected power quality into the electrical system, these devices have potential to improve the power quality index of an installation. For example, photovoltaic inverters have been employed to control the harmonic current compensation generated by nonlinear loads connected at the point of common coupling (PCC). In this way, the solar inverter becomes multifunctional [7]–[10].

In the multifunctional operation of photovoltaic inverters, the detection method of the nonlinear load harmonic current is an important issue. Most methods are not designed to detect just one harmonic component of the load current [7],[8],[11]–[15]. The proposed strategy can be interesting in order to compensate only harmonic with higher amplitude, increasing efficiency and reducing the control complexity.

In single-phase applications, many works use proportional-resonant (PR) controllers [16],[17], because references of the current loop are sinusoidal and have high index of harmonic distortion. In these conditions, the conventional proportional-integral (PI) controller has steady state error due to its limited current tracking capability [16]. On the other hand, PR controller can compensate only one frequency. Thereby, one PR controller needs to be designed for each harmonic frequency [17]. This fact increases the control algorithm complexity. Therefore, if the PR controller becomes adaptive to the system, it is possible to obtain an efficient controller with low implementation complexity, this fact is approached in [18],[19] for grid frequency fluctuations.

In this context, this work proposes a novel adaptive current harmonic control strategy applied in multifunctional single-phase solar inverters. The strategy is based on a novel detection method of the harmonic load current. The harmonic current detection method is frequency adaptive and able to detect the load harmonic current with higher amplitude. The detection method consists of two-cascaded phase-locked loop based on second order generalized integrator (SOGI-PLL) proposed in [2],[20]. This proposed detection method is based on the frequency adaptive characteristic of the SOGI structure [2],[13], tuning in the frequency detected by PLL.

The novel detection method is applied in a single-phase photovoltaic system shown in Figure 1. The control system is based on proportional multi-resonant (PMR) controller composed by: a proportional controller, a resonant controller tuned at fundamental frequency and another resonant controller dynamically tuned at harmonic frequency detected by the proposed detection method. The PMR controller transfer function is:
The control strategy is shown in Figure 3(b). A PI compensator is used in the dc-bus voltage control. This compensator calculates the active current amplitude. The Figure 3(b) shows the detected frequency $\omega_f$ being used as feedback for ($R_h$).

Only two resonant controllers are required: The first one ($R_f$) is responsible to track the fundamental component and the second one ($R_h$) is adaptive to track the harmonic component with higher magnitude. The Figure 3(b) shows the detected frequency $\omega_f$ being used as feedback for ($R_h$).

The complete control strategy is shown in Figure 3. The dc/dc stage is responsible for maximum power point tracking (MPPT) of the solar panels. The electrical model of the solar panel is based on the mathematical model proposed in [22]. The MPPT algorithm is based on perturb and observe (P&O) method [23]. The boost stage is used to ensure inverter bus stability [2]. As shown in Figure 3(a), the boost control loop has an outer loop, responsible for dc-bus voltage control of the solar plant $v_{pv}$ and an inner loop, responsible for current control of the dc/dc stage inductor $I_{ind}$.

The inverter control strategy is shown in Figure 3(b). A PI compensator is used in the dc-bus voltage control. This compensator calculates the active current amplitude $I^*$, which needs to be injected into the power system. This signal is synchronized with PCC voltage through the SOGI-PLL structure [2]. The synchronization results in a sinusoidal wave $i^*(t)$ for the internal control loop. This current reference is added to harmonic component of the load current detected by proposed detection structure. As result, $i^*_L(t)$ is compared with the inverter current $i_L(t)$ and the PMR compensator calculates the modulation index $v^*$ of the inverter.

In order to compensate just one harmonic component of the load current, this work proposes a detection method able to detect the harmonic component of the load current with higher amplitude. This strategy is based on SOGI-PLL structure, as shown in Figure 4. The complete description about SOGI-PLL can be found in [2], [20].

The adaptive filter SOGI is tuned at resonant frequency detected by PLL, the closed-loop transfer functions of the SOGI are defined in (2) and (3). This feedback frequency is achieved locking the PLL in order to ensure the rotation of the space phasor orthogonal to the q-axis.

$$H_d(s) = \frac{i_L(s)}{i_L(s)} = \frac{k\omega s}{s^2 + k\omega s + \omega^2}$$

$$H_f(s) = \frac{i_L(s)}{i_L(s)} = \frac{k\omega^2}{s^2 + k\omega s + \omega^2}$$

where:

- $i_L$ - generated phase current;
- $i_L$ - generated quadrature current;
- $\omega$ - adaptive filter resonance frequency;
- $k$ - adaptive filter damping factor.

SOGI has a bandpass filter characteristic, with adjustable resonance frequency. These transfers function shows that the bandwidth of the SOGI only depends on the damping factor [2]. These SOGI characteristics are explored in the current proposed detection method.

The current harmonic detection method is composed by two-cascaded SOGI-PLL, as detailed in Figure 5. The first stage consists to detect the load fundamental current component $i_L(t)$. In steady state, the measured load current $i_L(t)$ is filtered by the SOGI at fundamental frequency detected
by PLL. Usually, as the fundamental component has a higher amplitude in relation to the other harmonics, the adaptive filter damping factor \( k \) is set to \( \sqrt{2} \) which results in an admissible settling time [2]. The current component of the load \( i_f(t) \) is detected by (4). Therefore, the load current harmonic content \( i_{hf}(t) \) is detected subtracting the measured load current by the fundamental component.

\[
i_f(t) = I_{f,peak} \cos(\theta_f)
\]

(4)

The second stage consists to detect the load current harmonic component with higher amplitude. The second stage PLL extracts the angle and frequency of the harmonic component with higher amplitude of the signal. This frequency is used as feedback to the SOGI and it provides two quadrature signals filtered at this frequency. This process eliminates the harmonics of low amplitude. The SOGI-PLL structure for harmonic component detection stage is similar to Figure 4.

For analysis, it is considered the load current content as \( i_{Lh}(t) \) in (5). It is composed of 3rd harmonic with amplitude \( I_3 \) and a 5th harmonic with amplitude \( I_5 \), wherein \( I_5 > I_3 \). From (2) and (5), the phase current (in steady state) of the SOGI output results in (6), considering the detected frequency by PLL as \( 3\omega_f \). In the same way, from (3) and (5), the quadrature axis current (in steady state) results in (7). Note that, the SOGI generates two quadrature signals filtered at the PLL feedback frequency, as can be seen in the first terms in (6) and (7). However, the second terms indicates that unwanted frequencies are not fully suppressed.

To allow tracking of the harmonic component with higher magnitude, as will be discussed, the adaptive filter damping factor at second stage is set to \( \sqrt{2} \). Thus, Figure 6 shows the time response (in steady state) of (6) and (7) for \( (\omega_f = 2\pi \times 60 \text{ rad/s}) \). The amplitude \( (i_{Lh}) \) of the current component filtered by SOGI is given in (8). Note that, once the signal is being filtered in \( 3\omega_f \), the expected amplitude value is of \( I_3 \). However, due to the second terms of (6) and (7), oscillations appear around \( I_3 \), as illustrated in Figure 6. These fluctuations can influence the harmonic detection and unwanted harmonics can be injected at the system. For this reason, it is used a low-pass filter (LPF) in the detected amplitude (Figure 6) and at PLL feedback frequency.

\[
i_{Lh}(t) = I_3 \cos(3\omega_f t) + I_5 \cos(5\omega_f t)
\]

(5)

\[
i_{Lha}(t) = I_3 \cos(3\omega_f t) + \frac{15I_5k[16\sin(5\omega_f t) + 15\cos(5\omega_f t)]}{225k^2 + 256}
\]

(6)

\[
i_{Lhb}(t) = I_5 \sin(5\omega_f t) + \frac{9I_5k[16\cos(5\omega_f t) - 15\sin(5\omega_f t)]}{225k^2 + 256}
\]

(7)

\[
i_{Lh, peak} = \sqrt{i_{Lh}\text{a}(t)^2 + i_{Lh}\text{b}(t)^2}
\]

(8)

Therefore, the harmonic component with higher amplitude \( i_{Lh}(t) \) presents in the load current is detected by (9) and it is sent to the control strategy for harmonic compensation.

\[
i_{Lh}(t) = I_{hf,peak} \cos(\theta_{hf})
\]

(9)

For analysis of SOGI bandwidth influence at detection method, considers that in a time \( t \), the harmonic content amplitudes changes from \( I_3 > I_5 \) to \( I_5 > I_3 \) in (5). However, in the next sample time the SOGI frequency feedback is still tuned in \( 3\omega_f \) by PLL. For this reason, if the SOGI bandwidth is too small, the fifth harmonic is suppressed. Thus, the PLL continues to detect the third harmonic component in steady state. For second stage damping factor equal to 0.1, the Figure 7(a) shows the SOGI output and the unwanted suppression of fifth harmonic in the next sample time after of the load change.

The ideal damping factor does not allows that the SOGI bandwidth suppresses the harmonic with higher amplitude during the load harmonic component variations, as depicted in Figure 7(b). In this case, the damping factor is set to \( \sqrt{2} \). The fifth harmonic has higher amplitude than third harmonic even in the next sample time after of the load change. Therefore, in the next samplings, the frequency detected by PLL tends to the fifth harmonic. These interactions, between of SOGI-PLL bandwidths suppress the third harmonic at steady state.

IV. RESULTS

A. Simulation Results

The case study presents a solar array with 3 parallel strings of 13 panels of 48 W in series. The solar irradiance is maintained in 500 W/m² during the study. The boost and
The resonance frequency of the grid is 10 kHz. Voltage at point of common couple is 220 V. The inverter dc-bus voltage (Vdc) is controlled in 420 V. The discrete simulation was implemented in Matlab/Simulink environment with sample time of twice the inverter switching frequency.

The adaptive PMR controller is discrete by Tustin with prewarping method to avoid deviations at resonant frequency caused by the discretization, as depicted in [24]. The PMR parameters design is done using stability analysis by means of Nyquist diagrams, as proposed in [21], [24]. Therefore, the PMR parameters is set to \( K_F = 0.9 \), \( K_I = 1000 \) and \( K_H = 5000 \). The resonance frequency of \( R_F \) is fixed at fundamental frequency \( (\omega_F = 2\pi f_0) \) and the resonance frequency of \( R_H \) \( (h\omega_F) \) is provided by the proposed detection method of the load harmonic current with higher amplitude.

In this simulation, the load current harmonic contents are changed to validate the proposed harmonic detection method and the proposed adaptive control strategy. In the first 4 seconds, the nonlinear loads connected to the PCC are represented by current sources, injecting harmonics in the system. Between \( 0 < t < 2 \) seconds, the load current has a 3rd and 5th harmonic of 2 A and 0.5 A, respectively. Between \( 2 < t < 4 \) seconds, the load current has a 3rd and 5th harmonic of 1 A and 3 A, respectively. After 4 seconds, a load with rectifier diodes is connected at the PCC, generating odd harmonics on the grid.

Current spectra during harmonic compensation of load harmonic current component with higher amplitude are shown in Figure 8. Between \( 0 < t < 2 \) seconds, the 3rd harmonic of the load current is detected and strongly reduced in the grid current. Between \( 2 < t < 4 \) seconds, the 5th harmonic of the load current is detected and compensated by inverter. After 4 seconds, the 3rd harmonic of the rectifier diodes is detected and compensated.

To validate the harmonic current detection method, the Figure 9 shows the detection of load fundamental component and harmonic component with higher amplitude. Note that, the control does not destabilize even at frequency feedback during load harmonic content variation, as illustrated in Figure 10.

The Table I details the total harmonic distortion (THD) of the grid current \( (i_G) \) with and without harmonic compensation. Note that, a strong improvement in the grid power quality index. Between \( 0 < t < 2 \), e.g., the grid current THD reduces from 15.38% to 4.19%.

**Fig. 7. SOGI output in the next sample time after of the load change from \( I_3 > I_5 \) to \( I_5 > I_3 \) in (5). (a) For \( k = 0.1 \). (b) For \( k = \sqrt{2} \).**

**Fig. 8. Current spectra during harmonic compensation of load harmonic current component with higher amplitude. (a) Grid current spectrum. (b) Inverter current spectrum. (c) Load current spectrum.**

**Fig. 9. Fundamental and harmonic component of the load current detected. (a) Fundamental current frequency. (b) Fundamental current amplitude. (c) Harmonic current component frequency. (d) Harmonic current component amplitude.**

**Fig. 10. Adaptive PMR controller error.**

<table>
<thead>
<tr>
<th>Time Intervals</th>
<th>( i_G ) THD without Harmonic Compensation (%)</th>
<th>( i_G ) THD with Harmonic Compensation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 0 &lt; t &lt; 2 )</td>
<td>15.38</td>
<td>4.09</td>
</tr>
<tr>
<td>( 2 &lt; t &lt; 4 )</td>
<td>23.00</td>
<td>9.06</td>
</tr>
<tr>
<td>( 4 &lt; t &lt; 6 )</td>
<td>19.52</td>
<td>7.93</td>
</tr>
</tbody>
</table>

**TABLE I**

Total Harmonic Distortion (THD) of the Grid Current \( (i_G) \)
B. Experimental Results

To validate the adaptive current harmonic control strategy, experiments are carried for single-phase inverter. The initial load is an rectifier diodes. Figure 11 shows the initial state of the grid, inverter and load current waveforms. Figure 12 illustrates the spectrum of these currents. Note that, the inverter supplies a peak fundamental current of 1 A for load and 2 A for grid, approximately. The nonlinear load harmonic content has a 3rd harmonic component with higher amplitude and there is no harmonic compensation, as can been seen in the grid current spectrum.

The harmonic compensation is enabled and the harmonic detector tracks the 3rd harmonic component. Figure 13 shows the harmonic mitigation of the 3rd harmonic on the grid current.

In a second scenario, the load is changed and the 5th harmonic becomes the component with higher amplitude. The harmonic detector tracks the 5th harmonic and tunes the PMR at the related frequency. Figure 14 illustrated the harmonic mitigation of the 5th harmonic on the grid current.

V. CONCLUSIONS

This work presented a novel adaptive current harmonic control strategy applied in multifunctional single-phase photovoltaic inverters with proportional multi-resonant (PMR) controller. This strategy is based on the proposed harmonic current detection method of the nonlinear loads which consists in a cascade association of two phase-locked loop based on second order generalized integrator (SOGI-PLL).

The harmonic current detection method is frequency adaptive and able to detect the load current harmonic with higher amplitude and its frequency. Thereby, the PMR current controller can be tuned for specific harmonics, increasing efficiency and reducing the control algorithm complexity.

Simulation and experimental results show performance of the proposed control strategy and the improvements in the grid power quality index through harmonic compensation generated for nonlinear loads connected to the point of common coupling.

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