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Flexible harmonic current compensation strategy applied in single and three-phase photovoltaic inverters

Heverton A. Pereira[a,*], Guilherme L.E. da Mata[a], Lucas S. Xavier[c], Allan F. Cupertino[b,c]

[a] Department of Electrical Engineering, Federal University of Viçosa, Av. P. H. Rolfs, s/n, 36570-000 Viçosa, MG, Brazil
[b] Department of Materials Engineering, Federal Center for Technological Education of Minas Gerais, Av. Amazonas, 5253, 30421-169 Belo Horizonte, MG, Brazil
[c] Graduate Program in Electrical Engineering, Universidade Federal de Minas Gerais, Av. Antônio Carlos 6627, 31270-901 Belo Horizonte, MG, Brazil

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ABSTRACT

Non-linear loads connected to power system have increased considerably in the recent decades. Traditional generation based on hydro and thermal power plants cannot mitigate harmonic currents. However, due to the increased connection of photovoltaic into the power system, its power electronic converter can be used to perform ancillary services such as harmonic current compensation. This work presents a dynamic method based on the Second Order Generalized Integrator coupled with a phase locked loop structure to detect and compensate the most predominant harmonic current components from the power system. It is also presented an extension to detect multiple harmonics, according to the amplitude. Technical issues related with the harmonic current compensation strategy, and its implementation for both single and three-phase PV inverters are explored to demonstrate the functionality and efficiency of the method. The results show the harmonic current compensation being compensated by a PV inverter. Finally, a losses analysis were performed in the LCL filter. The magnetic and damping resistor losses are more impacted due to high harmonic current compensation.

1. Introduction

The classic infrastructure of electrical power systems consists on large scale centralized generation, distributed over long transmission lines [1]. Nowadays, distributed generation (DG) systems have changed this traditional conception. DG systems are receiving more attention whereas environmental concerns and energy demand grow over the world [2]. Furthermore, DG systems may be installed inside consumer units, which reduces losses over distribution and transmission systems [3]. Such benefits brought huge development in renewable energy sources in recent years, especially photovoltaic (PV) energy, whose cost was reduced in 75% in less than 10 years [4].

Compared with hydro and thermal power plants, PV systems have electronic converters that inject high order harmonic current components into the power system. [3,5]. These high order harmonic component can be minimized using passive filters. On the order hand, the growing presence of nonlinear loads, generally, injecting low order harmonic current components, can reduce the distribution system power quality [6].

Since solar irradiance varies during the day, inverters usually work below their nominal operation point [7], as illustrated in Fig. 1. Thus, whenever the inverter current does not exceed its nominal value, it can be used to improve the power quality [8,9]. Ancillary services, such as reactive power compensation [10,11], reactive injection during faults [12], voltage and frequency regulation [12] and harmonic current compensation [6,10] are some of the contributions that PV inverters can aggregate to improve the power system stability.

Current total harmonic distortion (THD) level is an important index in power systems harmonic analysis. Some standards define that the current THD level must be below 5% [13,14]. Some methods to reduce the grid harmonic current distortions can be found in literature. The most conventional ones use passive [15] and active [16,17] filters, or associations of both to decrease the THD level. However, once the PV plant is already installed, the use of the inverter in multifunctional operation is an economic alternative more viable than passive or active filters [18].

The detection method is an important issue to compensate harmonic current components. Some of the methods commonly found in literature realize the harmonic current detection through second order generalized integrators (SOGI) [1], instantaneous power theory [11,17], conservative power theory [3,7,18], Fourier transform [19] and delayed signal cancellation [20]. Nevertheless, most of these strategies detect the whole harmonic content from the load, increasing the controller tuning complexity.

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[*] Corresponding author.
E-mail addresses: heverton.pereira@ufv.br (H.A. Pereira), lucas.xavier@ufv.br (L.S. Xavier), afcupertino@ieee.org (A.F. Cupertino).

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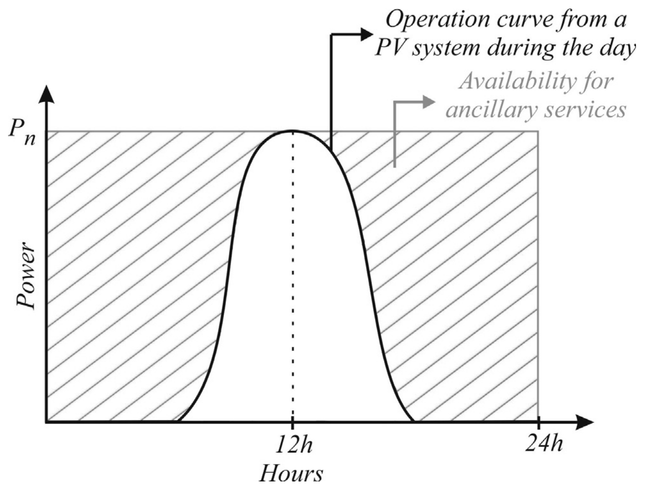

Fig. 1. Power generated by a PV system during a sunny day.

The kind of controller affects both precision and control complexity. Proportional integral (*PI*) controllers are easier to implement, however, it presents steady state errors, due to their limited bandwidth. This results in a lower tracking capacity and consequently loss of precision. On the other hand, proportional resonant (*PR*) controllers are more accurate [21], even though the need of one PR tuned in each frequency to be compensated, increasing the control complexity. An alternative to obtain low complexity and precise control is making the controller adaptive to the harmonic components. Thus, it can follow the harmonic load variations [22].

In this work, for both single-phase and three-phase systems, a harmonic current detection is proposed through a cascade association of a SOGI and a synchronous reference frame phase-locked loop (SRF-PLL) structure. This detection structure proposed in [23] was used to synchronize the converter with the grid voltage phase angle. We have extended this concept to detect harmonic current components. Furthermore, this work shows the SRF-PLL flexibility when n-stages are cascaded. Finally, the load harmonic current components of higher amplitude are compensated with a PV inverter.

Therefore, the present work provides the following contributions:

- a flexible harmonic current detection strategy based on *n*-stage SOGI-PLL structure with negative feedback;
- proposal of a fast algorithm to select the highest harmonic current components;
- losses in the LCL filter are computed to show the impact of the harmonic current compensation in the cooper and magnetic losses.

This paper is structured as follows: Section 2 describes the main parts of the PV system, including the control strategies used in both single-phase and three-phase systems. Section 3 describes the harmonic detection topology and its extension for multiple harmonic components detection. Section 4 presents the case studies for both single and three-phase systems. In Section 5, the proposed harmonic detection method is verified through simulation results. Finally, the conclusions are stated in Section 6.

2. Grid connected PV system

In this work, two PV systems are analyzed: a single-phase and a three-phase. Fig. 2 presents a general connection scheme between the PV plant and the power system.

2.1. Photovoltaic panel, maximum power point tracking and LCL filter

Based on the photovoltaic effect, the PV panel transforms sunlight energy into electricity. A mathematical model proposed by [24] is used to simulate a photovoltaic panel. Furthermore, the Maximum Power Point Tracking (MPPT) algorithm is extremely important for the PV system control efficiency. The Incremental Conductance (IC) method is able to extract more power than the Perturb and Observe (P&O) method [25], and it is used in this work.

The LCL filter is the structure most used to attenuate harmonics generated by the inverter switching [26]. Although LCL filter is a simple passive structure, its design requires special attention. The capacitor value is limited by the power factor at rated power (generally less than 5% of the inverter nominal power) [26]. A resistor is connected in series with the capacitor in order to reduce the resonant peak [27]. The resonant frequency should be in a range between ten times the line frequency and one-half of the switching frequency, to avoid resonance problems in the lower and upper parts of the harmonic spectrum [26]. Besides, passive damping must be sufficient to avoid oscillation, however, losses should reduce slightly the converter efficiency [27].

The losses in LCL filter can be classified in the following groups: capacitor losses, damping losses and inductor losses. LCL filters employ film capacitors with a very low series resistance and thereby negligible losses [28]. Therefore, only damping and inductor losses are considered in this work. In order to evaluate inductor losses, its physical design needs to be accomplished. The design methodology employed is based on [29].

The inductor copper losses is calculated as function of the rms current I_r:

$$P_{cp} = R_L I_r^2, \tag{1}$$

where R_L is the inductor resistance. As observed, the skin and distribution effects are not considered in this work. Finally, the magnetic losses are estimated by the improved generalized Steinmetz equation method (iGSE) [30], given by:

$$P_m = \frac{V_c}{T}\int_0^T k_i \left|\frac{dB}{dt}\right| (\Delta B)^{\beta-\alpha} dt, \tag{2}$$

$$k_i = \frac{K}{(2\pi)^{\alpha-1}\int_0^{2\pi} |cos\theta|^{\alpha}\, 2^{\beta-\alpha}}, \tag{3}$$

where V_c is the magnetic core volume and K, α and β are the Steinmetz parameters, which are provided in the datasheets [29]. As observed, the flux density waveform must be known, thus the magnetic losses can be computed. $B(t)$ can be obtained from the voltage at the inductor terminals $v_L(t)$, as follows:

$$B(t) = \frac{1}{NA_c}\int v_L(t)dt. \tag{4}$$

where A_c is the cross sectional area of the inductor core.

2.2. Control strategies

The PV inverter control strategies have two forms, the dc/dc stage, with boost converter, and the dc/ac stage, with the inverter.

2.2.1. Dc/dc stage

The dc/dc stage converter is commonly used for booster the input voltage level of the inverter, ensuring the acceptable voltage level for startup and extending its operation range during low irradiance conditions. In single-phase system, the use of dc/dc is even more important due to power oscillation in the 2nd harmonic frequency. This power oscillation results in dc-link voltage fluctuation and reduces the MPPT efficiency, when the PV modules are connected directly to the dc-link. For this reason, it is advisable to perform MPPT algorithm in dc/dc stage control for single-phase applications. The boost converter is widely used for these cited purposes [31].

The connection of the PV array to the boost converter is shown in Fig. 3. The PV array model is linearized around the nominal maximum