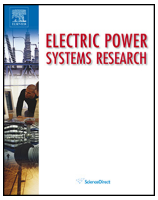
Electric Power Systems Research 106 (2014) 226–231

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr



Lower order grid current harmonics for a voltage-source inverter connected to a distorted grid

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ARTICLE INFO

Article history:
Received 13 May 2013
Received in revised form 20 August 2013
Accepted 22 August 2013
Available online 25 September 2013

Keywords:
Grid current distortion
PLL
ZCD
VSI
THD
Grid codes

ABSTRACT

As a result of lower order grid voltage harmonics, the grid current injected by a voltage-source inverter will also be partially distorted. In large-scale applications, active harmonic filters or notch filters are used to reduce the grid current distortion. For small-scale units, this may not be economically viable. In this article, two different grid phase tracking methods are evaluated with respect to the grid current distortion. The first method uses the zero-crossing detection (ZCD) method together with a look-up table (LUT), to generate a perfectly sinusoidal voltage synchronized with the grid. The second method uses a single-phase phase-locked loop (PLL). This method will reflect the grid harmonics in the inverter output, resulting in either cancellation or superposition of the harmonics of the grid current. A theoretical expression for the grid current as a function of the grid voltage harmonics is derived. Individual grid current harmonics as well as the total harmonic distortion (THD) are experimentally evaluated for both ZCD and PLL, and compared with theory. Results are presented for different power flows into the grid and compared with grid codes.

1. Introduction

Renewable energy sources have gained an increased interest for the last decades. These are often small-scale, such as wind or solar power, and distributed in the grid rather than in a conventional radial grid structure with unidirectional power flow. Due to the intermittent characteristics of the energy sources, the voltage-source inverter (VSI) with constant DC-link is often used. A sinusoidal voltage synchronized with the grid is generated by pulse-width modulation (PWM) of the DC-voltage. The inherent switching frequency harmonics of the grid current are filtered by putting an inductor in series with the grid, or more effectively by the use of an LCL-filter [1,2]. Lower order harmonics, however, will not be removed by the general LCL lowpass filter. On the contrary, they may even be reinforced if coinciding with the filter resonance peak depending on the filter design [3]. For large-scale units, the LCL-filter may be replaced by active harmonic suppression (AHS) equipment to improve the efficiency of the system [4]. AHS can be programmed to cancel out both switching frequency harmonics as well as lower order harmonics. In high-voltage direct current (HVDC) topologies, individual notch filters are tuned to remove these harmonics individually [5,6].

In an electric grid with distributed small-scale generation, AHS or notch filtering may not be an economically viable alternative. As a result, lower-order grid voltage harmonics will be reflected in the injected grid current, even if the inverter output voltage is perfectly sinusoidal. An alternative approach is to let the grid harmonics be reflected in the inverter output voltage. This will result in either cancellation or superposition of the resulting grid current, depending on the harmonic phase shift and the load angle.

In this article, two grid phase tracking methods are evaluated. In the first, zero-crossing detection (ZCD) is used to track the zero-crossings of the grid phase twice per period. This information is used to reset the phase in a look-up table (LUT), which will produce a perfectly sinusoidal waveform for the inverter control. The only harmonic source in this case is the grid itself, and should be independent of the power flow. In the second, the single-phase phase-locked loop (PLL) is used. Depending on the tuning of the PLL coefficients, the grid voltage harmonics will to some extent be reflected in the inverter output voltage, resulting in either cancellation or superposition of the grid current harmonics. Both methods are implemented for single-phase and extended to three-phase assuming symmetry in the grid. Theoretical expressions are derived for the grid current as a function of the grid voltage harmonics. Experiments have been carried out for a grid-connected VSI, and grid current harmonics are measured for different power flows into the grid. THD is calculated and the experimental results are compared with theory.

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http://dx.doi.org/10.1016/j.epsr.2013.08.018

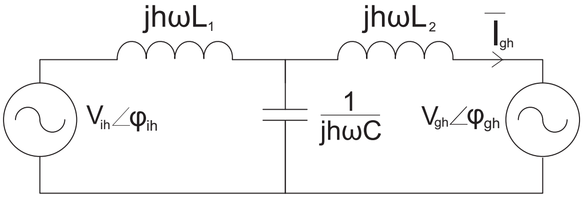

Fig. 1. The *h*th harmonic of a VSI connected to the grid via an LCL-filter.

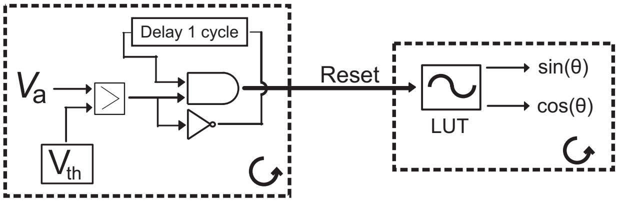

Fig. 2. ZCD structure.

2. Grid current harmonics

A commonly used standard on grid current harmonic limits is the IEEE Std.519-1992 [7]. This sets the maximum recommended limits of individual currents, as well as the total harmonic distortion (THD), calculated as

$$THD = \frac{\sqrt{\sum_{h=2}^{N}(I_h)^2}}{I_1} \tag{1}$$

where h is the harmonic number and I_1 the current fundamental. In the medium or low voltage grid, the total demand distortion (TDD) is used instead, dividing by the load demand current in the grid rather than the internally generated current. Using the TDD results in more generous grid codes and this may give problems in future smart grids where the number of small producers increase. Throughout this article, the THD will be used as it is the more stringent recommendation.

The limits are stricter for higher order harmonics, and the even harmonics are limited to 25% of their neighbouring odd harmonic. Even harmonics may cause e.g. excessive heating in the power transformers, thus the extra concern. The recommended limits are also dependent on the grid voltage level and its stiffness, defined as I_{sc}/I_L where I_{sc} is the short-circuit current and I_L is the rated load demand current. For a weak grid below 69 kV, the THD limit for both currents and voltages is set to maximum 5%.

The grid voltage $\overline{V}_g$ and the inverter voltage $\overline{V}_i$ may be decomposed into their respective Fourier components as:

$$V_g(t) = \sum_{h=1}^{N} V_{gh}\sin(h\omega t + \phi_{gh})$$

$$V_i(t) = \sum_{h=1}^{N} V_{ih}\sin(h\omega t + \phi_{ih})$$

The complex power into the grid at the fundamental frequency is:

$$S_{1\phi} = \frac{V_g V_i \sin(\delta) + j(V_g V_i \cos(\delta) - V_g{}^2)}{\omega_1 X} VA \tag{2}$$

where X is the inductive reactance between V_g and V_i and $\delta = \phi_{i1} - \phi_{g1}$ is the load angle. Neglecting the resistances in the circuit, the reactive power flow is controlled to zero by setting the amplitude of the inverter voltage to $|V_i| = |V_g|/\cos(\delta)$ for various δ.

The hth grid current harmonic $\bar{I}_{gh}$ of a single-phase grid-connected VSI with LCL-filter is displayed in Fig. 1, where $V_{ih}\angle\phi_{ih}$ is the inverter voltage harmonic and $V_{gh}\angle\phi_{gh}$ is the grid voltage harmonic. $\bar{I}_{gh}$ is calculated by:

$$\bar{I}_{gh} = \frac{V_{ih}\angle\phi_{ih} - V_{gh}\angle\phi_{gh}(1 - \omega_h{}^2 L_1 C)}{j\omega_h(L_1 + L_2 - \omega_h{}^2 L_1 L_2 C)} \tag{3}$$

Complete harmonic cancellation of $\bar{I}_h$ occurs when:

$$V_{ih}\angle\phi_{ih} = V_{gh}\angle\phi_{gh}(1 - \omega_h{}^2 L_1 C) \tag{4}$$

If the shunt capacitor is removed or neglected, this condition is fulfilled when $V_{ih}\angle\phi_{ih} = V_{gh}\angle\phi_{gh}$. Maximal harmonic superposition occurs when $\phi_{ih} = -\phi_{gh}$.

3. Grid phase tracking

Accurate grid phase tracking is crucial for any power utility producer, with respect to both safety and stability. Grid connection synchronization methods are discussed in [8–11]. A more detailed comparison of grid phase tracking methods is found in [12]. Most commonly discussed are the zero-crossing detection (ZCD), the Kalman filter and the PLL. ZCD is the simplest method, where the grid voltage zero-crossings are used to update the control loop. Though simple, this method is more sensitive to noise, and does not give any information of the grid phase in between the zero-crossings. The second method is using a predictive Kalman filter to estimate the grid phase. This gives good phase tracking at the expense of more heavy computations. The third is the phase-locked loop (PLL), which uses a feed-back PI-control loop to eliminate the phase error between the grid phase and the PLL output. Special focus on the PLL behaviour for distorted grids are discussed in [13–15]. Different PLL structures and reference frames are discussed in [16].

The simplified outline of the ZCD method is displayed in Fig. 2. The LUT memory block is able to generate both a sine wave and a cosine wave output with the desired fundamental frequency. A small analogue passive first-order filter is put on the measured grid voltage. At every voltage zero-crossing, the LUT is reset to avoid drifting from the grid voltage. In between, it is set to change with 50 Hz. To avoid erroneous resetting around the zero-crossings, due to noise, a hysteresis offset *V*th is introduced. The average noise level was measured in the lab, and *V*th was set to half of this, which in this case corresponded to around 0.1% of the nominal voltage. The drifting of the phase error, if not resetting the LUT, may occur for two reasons. Either the grid frequency is not exactly 50 Hz, or there may be a time drift within the controller unit itself. Since the LUT is updated twice per cycle, the error due to a non-nominal grid frequency becomes negligible. A grid frequency deviation of e.g ±0.1 Hz would correspond to an error of ±0.01% or ±0.035°. If the grid voltage spectra is known, the grid current harmonics may be calculated directly using Eq. (3), where V_i will be a sine wave.

The basic PLL structure using synchronous reference frame is depicted in Fig. 3. When only one grid voltage is detected, there is not sufficient information to create $V_{\alpha\beta}$. We set $V_\beta = V_a$, and V_α is obtained by introducing a delay of $\pi/2$ radians in V_a. The single-phase dq-components are calculated by the Park transformation [17]:

$$\begin{pmatrix} V_q \\ V_d \end{pmatrix} = \begin{pmatrix} \cos(\theta') & -\sin(\theta') \\ \sin(\theta') & \cos(\theta') \end{pmatrix} \begin{pmatrix} V_\alpha \\ V_\beta \end{pmatrix} \tag{5}$$

where θ' is the estimated grid phase. The PI-control block is tuned to minimize the PLL phase error, and also has the effect of a