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Efficient multiple-reference-frame controller for harmonic suppression in custom power devices

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ABSTRACT

Tracking harmonic currents and voltages in electric power systems with custom power devices exceeds the capabilities of conventional Proportional+Integral controllers and more sophisticated algorithms are required, especially under grid-frequency variations. This paper presents a control method based on multiple reference frames for harmonic control in the context of a series active power filter. The proposed scheme allows recursive calculation when referring signals to reference frames rotating synchronously with harmonic equivalent space vectors whilst a minimum of trigonometric-function evaluations are required. Furthermore, the control of each harmonic can be dealt with using simple integral controllers applied to the transformed signals. The paper presents the closed-loop-stability analysis and experimental results of a series active power filter. A scenario with grid-frequency variations is considered to show the intrinsic adaptation capability of the proposed controller.

Introduction

Steady-state voltages and currents in electric power systems (balanced or unbalanced) consist of a fundamental component of 50 or 60 Hz plus harmonics with frequencies which are integer multiples of the fundamental one. Voltage and current harmonics are important concerns in electric power systems because they produce additional power losses, equipment heating, fuse and breaker malfunction and torque pulsations in electrical motors. Voltage harmonics are produced by non-linear devices such as DC-to-AC converters, arc furnaces, saturated transformers, etc.

Nowadays, active power filters (APF) based on power electronics devices are a flexible alternative to compensate current and voltage disturbances [1]. This paper deals with the controller for a series active filter to protect sensitive loads from grid harmonic voltages. The test arrangement together with the controller to be spelt out later on are shown in Fig. 1.

Proportional+Integral (PI) controllers using Park's Transformation of three-phase electrical variables into the so-called synchronous reference frame is often used for power-flow control in power electronics devices. The reference frame is made synchronous with the positive sequence of the fundamental frequency so that all variables of that frequency are DC in steady state and this is the reason why simple PI controllers are effective [2]. However, harmonics are still seen as sinusoids in that frame and cannot be tackled so easily.

Harmonic control was first addressed using resonant terms (selective controllers) as in [3–5]. This control method guarantees zero-error in steady-state at the selected frequencies and adaptation to frequency variations could be included. However, one resonant term must be designed and added for each harmonic to be suppressed, increasing the effort at the design stage. Furthermore, an anti-windup mechanism, adaptation and a precise implementation in discrete time, are difficult to achieve [6].

A comprehensive approach was later found with the so-called "repetitive controller" which is implemented using a delay of one period of the grid frequency [7]. A repetitive controller deals with some drawbacks of the selective controller: delays can be easily implemented in discrete time and it works as multiple selective controllers for all the harmonics within the specified bandwidth. However, flexibility is lost from the point of view of individual harmonics and the controller is very sensitive to frequency variations. The latter problem requires attention always and has been addressed in power electronics in [8] where a promising approximate solution is presented.

The use of multiple reference frames for active filters was already proposed in [9]. In this approach, Park's Transformation is applied several times to the three-phase magnitudes using, each time, the position of a reference frame which rotates with respect to the fundamental-frequency $d-q$ reference frame with an angular speed related to a harmonic frequency. Consequently,

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several reference frames rotating synchronously with the harmonic space vectors (harmonic synchronous reference frames or HSRFs) are used. In this scenario, PI controllers can be designed independently for each harmonic once the output to be controlled is referred to the appropriate HSRF where a given harmonic should look like a DC variable. In order to avoid harmonic interaction, the transformed variable is filtered by a low-pass filter in each HSRF to extract its DC value. This procedure is very attractive from the design viewpoint but has always been considered as cumbersome due to the fact that many trigonometric functions have to be calculated in real-time. In [10], a PLL structure for each HSRF is proposed. Therefore, one *sin* and one *cos* function have to be calculated for each HSRF giving a large computational effort.

Unlike conventional MRF techniques, [11] proposes a modified harmonic extraction method: the positive and negative sequences at the fundamental frequency of the variable of interest are subtracted from the measurements before transforming those measurements into the HSRFs as required. This does not guarantee perfect decoupling amongst harmonics but, at least, disturbances at the main frequency are avoided in each HSRF. Positive and negative sequences are estimated using signal processing of the measured variables. Although, interaction amongst harmonics is theoretically possible it does not seem to have caused much trouble in practice [12]. However, the computational effort of extracting the harmonic components and the reconstruction of the signal in each HSRF is still very high.

A comparison between HSRF-based controller and resonant controller is described in [13] where the authors conclude that, when the same number of harmonics are compensated, the HSRF-based controller needs more elementary operations but less memory resources compared with the resonant controller. However, the two controllers compared in [13] are not strictly equivalent and show different performance during transients. The authors do not explore the possibility of grid-frequency adaptation in any of the two controllers leaving the question opened for discussion.

In the context of active power filters, [14,15] established the equivalence between controllers in a stationary reference frame (resonant controllers) and controllers in HSRFs (PI controllers). After weighting advantages and disadvantages, they suggest designing the controllers using HSRF whilst implementing them as resonant controllers in a stationary reference frame to ease the computational burden.

Harmonic control can also be tackled using a DFT (Discrete Fourier Transform) or a DCT (Discrete Cosine Transform) as in [16–18] for harmonic extraction. Both strategies have several drawbacks. First of all, the sampling frequency for the harmonic controller is slower than the one for the main voltage and current controller (bringing a slow transient response) and it has to be chosen carefully as a multiple of the fundamental frequency of the signals to be sampled in order to extract harmonics properly. Otherwise leakage appears and accuracy in steady-state deteriorates. Furthermore, under grid frequency variations, the harmonic-extraction window has to be adapted to avoid leakage. Finally, the storage of the DFT coefficients and the management of the data buffers required for each harmonic complicate the implementation.

In this paper, the strategy based on HSRFs will be revisited showing that its implementation can be greatly eased avoiding nearly all the trigonometric functions whilst maintaining excellent performance. Furthermore, only one single gain has to be adjusted in the proposed control approach. Variations of the grid frequency will be considered here to show the implicit frequency-adaptation capability of the algorithm without any additional modification. Experimental results of the proposed controller will be presented in the context of voltage-harmonic suppression with a three-phase series active power filter (Fig. 1).

Efficient use of harmonic synchronous reference frames

When controlling voltage source converters (VSCs) connected to the grid in an APF, three-phase currents and voltages (*abc*) can be transformed into vector signals (*0dq*) using Park's Transformation. For a generic three-phase variable:

$$\boldsymbol{f}_{0dq}(t) = \boldsymbol{P}(\theta)\boldsymbol{f}_{abc}(t) \tag{1}$$

where

$$\boldsymbol{P}(\theta) = k_1 \begin{bmatrix} k_2 & k_2 & k_2 \\ cos(\theta) & cos(\theta - \frac{2\pi}{3}) & cos(\theta + \frac{2\pi}{3}) \\ -sin(\theta) & -sin(\theta - \frac{2\pi}{3}) & -sin(\theta + \frac{2\pi}{3}) \end{bmatrix} \tag{2}$$

$\boldsymbol{f}_{abc}(t)$ is a column vector containing the instantaneous values of the three-phase magnitude and $\boldsymbol{f}_{0dq}(t)$ is a column vector with the so-called 0*dq* components which, ideally, will have constant $d-q$ components in steady state if $\theta = \theta_0 = \omega_0 t$ in (2) with ω_0 equal to the frequency of the positive sequence of the grid frequency. It is then said that the electrical variables are referred to a synchronous reference frame (SRF) where the zero component (0) is often ignored because it is decoupled from the *d* and *q* components and the zero current component is always zero in three-wire systems. This properties lead to the common representation of the positive sequence of electrical magnitudes as space vectors ($d-q$ components) which rotate with an angular speed ω_0. A $d-q$ axis coordinate system which rotates synchronously with these vectors can also be defined and all variables can be referred to this new system.

If there are harmonics in the electrical variables, each one will be seen as a rotating space vector in the SRF used so far. Its angular speed will be (see Fig. 2):

$$\omega_n = \overbrace{(i \cdot m - 1)}^{n}\,\omega_0 \tag{3}$$

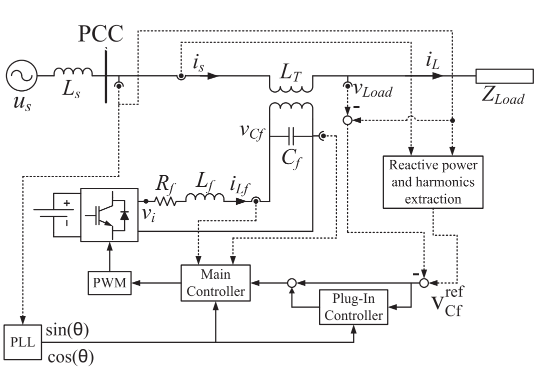

Fig. 1. Active power filter and control scheme.

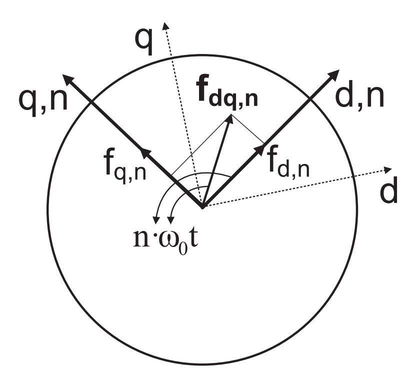

Fig. 2. Synchronous reference frame for each harmonic.