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Detailed analysis of the implementation of frequency-adaptive resonant and repetitive current controllers for grid-connected converters

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ABSTRACT

Current control is a common feature in power electronics voltage source converters connected to the grid. In this scenario frequency drifts can entail a big loss in performance of these controllers, significantly worsening the quality of the power delivered to the grid. This article focuses on the study and implementation of current control algorithms for DC–AC voltage source converters (VSCs) that are able of both reducing the harmonic contents of the grid current and maintaining the selectivity of the current control against frequency drifts, so that the stability of the system is preserved. Two types of current control techniques are investigated here, namely, resonant and repetitive controllers. A thorough study of alternative implementation structures is carried out whilst spelling out the frequency-adaptive algorithm in each case. Besides, basic guidelines for their software implementation are given and the computational load for each alternative is analyzed.

1. Introduction

Current control for VSCs is of paramount importance in today's application of power electronics in electric power system. Some of these applications include: tracking of grid current harmonics, rejection of grid voltage harmonics, operation in islanded systems likely to suffer grid frequency variations, microgrids for operation as grid generator or grid tracker, connection of energy storage systems to the grid, etc. As for these latter applications, it is mandatory to ensure the power supply of the auxiliary systems irrespective of the possible grid perturbations. Noticeably, frequency drifts may take place in weak grids, seriously affecting the controller's performance above all when considering tracking current harmonics where the relative error is more important.

Among the existing techniques for implementing the current control for harmonic compensation, two of the most commonly used are resonant and repetitive controllers.

The Generalized Integrator (GI) [1] was one of the first proposals of resonant control. A single GI was capable of compensating both positive and negative sequences and several resonant controllers could be placed in parallel to tackle multiple harmonics. This GI derived in the well-known Second Order Generalized Integrator (SOGI).

The SOGI introduces an infinite gain at the resonant frequency which can make the closed-loop system unstable as it does not make any control in the phase lag introduced. Thus, the addition of a lead-lag network to the original SOGI was proposed in the literature in order to control the phase shift nearby the resonant frequency [2,3]. In this article, this technique receives the name of Second Order Generalized Integrator with lead-lag network (SOGI-LLN).

Another technique of resonant control is the so-called Adaptive Feedforward Cancelation (AFC). A discrete time AFC was designed to control the output voltage of a full-bridge DC–AC inverter in [4] following the loop-shaping approach presented in [5].

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Repetitive control has its origins in the works of Inoue et al. [6,7] in the early 80s, where the authors provided the first discussion of this new method of control. The plug-in repetitive controller consists of a generator of the reference input, a low-pass filter to stabilize the system and a user-defined function. The latter is based on the inverse of the plant model, if the plant is a minimum-phase system [8–10].

A repetitive controller based on the Discrete Cosine Transform (DCT) filter was proposed in [11]. The specific harmonics to be tackled can be selected by means of an offline calculation of the DCT coefficients; therefore, its complexity is independent of the number of harmonics to be compensated.

Another implementation is discussed in [12,13]. This repetitive controller is capable of compensating only the typical harmonics in power systems, i.e. those of order $6k \pm 1 (k \in \mathbb{Z})$. The new repetitive controller was based on two feedback delay paths and a feedforward delay path.

A similar scheme to the above was developed in [14]. It is also based on feedback and feedforward delay paths but it is capable of compensating the harmonics of order $6k (k \in \mathbb{Z})$. Moreover, it is combined with a proportional + resonant controller in stationary reference frame.

The frequency-adaptive versions of all current controllers mentioned in the preceding paragraphs are capable of working both in grid-connected or islanded scenarios. Furthermore, they allow a smoother reconnection to the grid because during the process of phase locking the current controller may experience frequency variations.

This article compares the performance of these controllers under frequency steps and analyzes computational load issues. It is organized as follows: Section 2 covers the three mentioned resonant controllers as well as their frequency-adaptive version; Section 3 does the same job with the repetitive control, with an emphasis on its digital implementation; Section 4 shows an overview of the experimental setup that has been used; also presents the experimental results and, finally, Section 5 summarizes the conclusions of the work.

2. Frequency-adaptive resonant controllers

2.1. Resonant controller based on Second Order Generalized Integrator (Res-SOGI)

The structure based in individual discretization of its integrators is usually considered as the most suitable for performing frequency-adaptation, since no explicit trigonometric functions are needed [15]. Nevertheless, current high-speed digital platforms are capable of carrying out a few trigonometric functions without jeopardizing the total execution time. It has already been proved that the discrete SOGI based on discrete integrators is not a suitable option when compensating high-order harmonics because, as the harmonic order increases, the poles displacement from their ideal locations is higher. This displacement also depends on the sampling period T_S.

This situation does not occur when the continuous transfer function of the SOGI is discretized with the techniques Tustin with prewarping (from now on, TPW) and Triangle approximation (non-causal First-Order Hold, FOH), which lead to the discrete transfer function of Table 1.

The way to implement the frequency-adaptive algorithms is quite straightforward once one has the equation for both TPW and FOH. Both discrete transfer functions $C_{\mathrm{TPW}}(z)$ and $C_{\mathrm{FOH}}(z)$ can be generally expressed as:

$$C(z) = \frac{a(1 - z^{-2})}{1 - bz^{-1} + z^{-2}} \tag{1}$$

Table 1
Discrete-time transfer functions of the SOGI.

Technique	z-domain equation
TPW	$C_{\mathrm{TPW}}(z) = \frac{\sin(\omega_0 T_S)}{2} \cdot \frac{z^2-1}{z^2-2\cos(\omega_0 T_S)z+1}$
FOH	$C_{\mathrm{FOH}}(z) = \frac{1-\cos(\omega_0 T_S)}{\omega_0 T_S} \cdot \frac{z^2-1}{z^2-2\cos(\omega_0 T_S)z+1}$

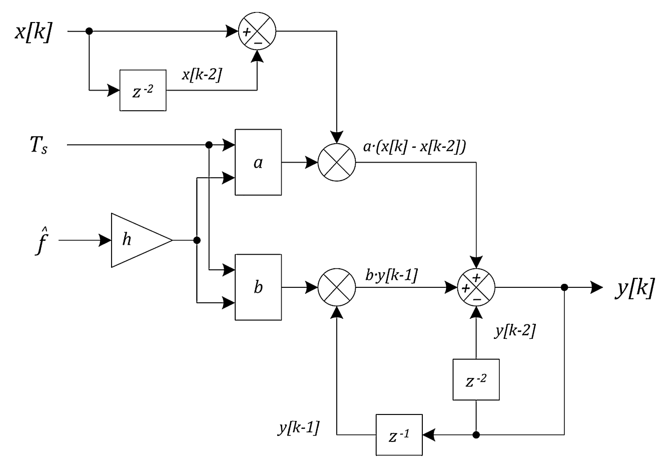

Fig. 1. Frequency-adaptive SOGI for both TPW and FOH discretization methods.

where coefficients a and b take the values $a|_{\mathrm{TPW}} = \sin(\omega_0 T_S)/2$, $a|_{\mathrm{FOH}} = 1 - \cos(\omega_0 T_S$, $b = 2\cos(\omega_0 T_S))$ for both techniques and $\omega_0 = h\hat{f}$, being $\hat{f}$ the estimated frequency. From (1), their difference equation is:

$$y[k] = a \cdot (x[k] - x[k-2]) + b \cdot y[k-1] - y[k-2] \tag{2}$$

whose schematic representation is depicted in Fig. 1.

In some cases, calculation of trigonometric functions can be avoided by using look-up tables. In the case at handle, the values of coefficients a and b are so small that tables with a very high accuracy would be necessary, i.e. with large sizes. If the digital platform has enough available memory, this option can be considered.

Regarding computational burden, both methods in this section multiply $\omega_o T_S = 2\pi h\hat{f} T_S$ n times and calculate a trigonometric function ($\sin(\omega_o T_S)$ or $\cos(\omega_o T_S)$) to obtain a, where n is the number of harmonics to be compensated. TPW also performs a multiplication ($a|_{\mathrm{TPW}} = 0.5 \cdot \sin(\omega_o T_S)$) and FOH performs a subtraction and a division ($a|_{FOH} = (1 - \cos(\omega_o T_S))/\omega_o T_S$), which leads to a slightly higher computational burden. Obviously, this type of implementation results in a quite large consumption of resources, but can be addressed by most of today's digital processors. Note that $\omega_o T_S$ requires the multiplications of two terms only, $\hat{f}$ and $2\pi h T_S$. The latter is stored in the processor's memory as a single value.

2.2. Resonant controller based on Second Order Generalized Integrator with lead-lag network (Res-SOGI-LLN)

Some modifications should be made to the original SOGI in order to control the phase shift, as presented in [2,3] in the context of the output voltage control of a VSC. In this article, this type of controller is adapted to the current control of a shunt-connected through an L-filter VSC applied to the grid.

The transfer function of the SOGI-LLN is given by (3), where the lead-lag network controls the phase shift nearby the resonant frequency by means of parameters f and α_c.

$$C(s) = \frac{1 + \frac{\alpha_c}{\omega_o}s}{1 + f\frac{\alpha_c}{\omega_o}s} \cdot \frac{k_{ih}\omega_o s}{s^2 + \omega_o^2} = C_a(s) \cdot C_b(s) \tag{3}$$