Electric Power Systems Research 144 (2017) 23–31

Contents lists available at ScienceDirect

Electric Power Systems Research

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

Variable, fixed, and hybrid sampling period approach for grid synchronization

Ignacio Carugati [a,b,c,*], Carlos M. Orallo [a,b,c], Sebastian Maestri [a,b,c], Patricio G. Donato [a,b,c], Daniel Carrica [a,b,c]

[a] Instituto de Investigaciones Científicas y Tecnológicas en Electrónica (ICYTE), Argentina
[b] Universidad Nacional de Mar del Plata (UNMdP), Juan B. Justo 4302, Mar del Plata, Argentina
[c] Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Av. Rivadavia 1917, Buenos Aires, Argentina

ARTICLE INFO

Article history:
Received 26 August 2016
Received in revised form 20 October 2016
Accepted 21 October 2016
Available online 22 November 2016

Keywords:
Phase locked loop
Grid disturbances
Sampling period

ABSTRACT

Almost all synchronization methods that can be found in the literature are based on a fixed sampling period approach and implemented by the addition of filter stages to the conventional Synchronous Reference Frame Phase Locked Loop (SRF-PLL) structure. A less common approach is the variable sampling period (VSP), used in methods like VSP-PLL. These methods allow implementing a synchronous sampling period which automatically adapts the monitoring and control systems to the grid voltage and current, improving their processing performance. Notwithstanding the advantages of the synchronous sampling period approach, this operation principle is not commonly adopted in the literature since a proper design is required to avoid implementation problems and possible conflicts with other modules. This manuscript reviews the advantages of VSP approach, unveils similarities between VSP-PLL and SRF-PLL that allow improving the understanding of the former by comparing it to the latter, and provides guidelines for a proper implementation of a synchronous sampling method. In addition, a Hybrid Sampling Period (HSP) approach that combines the advantages of SRF-PLL and VSP-PLL is proposed. The three approaches are compared, the advantages of hybrid methods are discussed and the methodology for adopting the VSP and HSP approach in most fixed sampling period method is presented. Finally, the proposal is verified by experimental implementation.

1. Introduction

Synchronizing certain devices to the power-grid network is critical to ensure appropriate performance. The desynchronization resulting from the different types of disturbances can lead to different issues in these devices, and also end up in power outage. Traditionally, synchronization was achieved with the classical Phase Locked Loops (PLLs), based on the detection of the zero crossing of the voltage grid. However, the current trend in this field is to develop methods based on digital techniques that update the phase information many times by each period of the grid voltage. Among these trends, the most relevant method is the Synchronous Reference Frame PLL (SRF-PLL), proposed by Kaura and Blasko in 1997 [1]. This well-known method has been implemented by many authors. Since the SRF-PLL presents some limitations when the grid voltages do not correspond to an ideal balanced three-phase signal, many authors have enhanced the original method by adding different filter techniques, resulting in the proliferation of diverse improved PLLs (iPLLs) [2–10].

A sharp increase in research papers dealing with synchronism methods has been noted in the last decade. However, in general, no significant breakthrough has been attained in this topic, and most of these works are incremental contributions. An alternative to the basic principles operation of conventional SRF-PLL approach is the variable sampling period (VSP) synchronous methods which, unlike the conventional SRF-PLL, adapts the sampling frequency to be an integer multiple of the grid frequency. VSP approach allows, among other things, to automatically adapt the systems to the input signals (power quality measurement, digital filters, controllers, etc.) [11–16] and reduces the phase jitter effects on power converters associated to the inherent discrete nature of the controller [17]. Some proposals rooted in the VSP technique are based on Sliding Discrete Fourier Transform (SDFT) [18,19] and digital PLLs for static-power converters [20]. In particular, the so-called VSP-PLL method [21,22] stands out for adapting on a sample by sample

* Corresponding author at: Instituto de Investigaciones Científicas y Tecnológicas en Electrónica (ICYTE), Argentina. Tel.: +54 223 481 6600 - 254.
E-mail address: icarugati@fi.mdp.edu.ar (I. Carugati).

http://dx.doi.org/10.1016/j.epsr.2016.10.053

basis, its simple structure, and good dynamic response. This method works as a digital PLL where the input signal is considered as a sequence of values without reference to the sampling period.

Notwithstanding the advantages of VSP methods for signal processing and control, this operation principle is not commonly implemented because of two major reasons: implementation problems and possible conflicts with other control routines. Implementation issues can be solved by most of the commercial microcontrollers or processors currently available, which can update the period of their modules (PWM and timers) in real time during the execution of the routine. Given the fact that conflicts may arise with other control routines, the adaptive sampling period could be properly limited. For instance, the European standard EN50160 [23] for voltage characteristics of electricity supplied specifies that the maximum variations of the frequency grid should range from ±1% in 99.5% of the time in a year, and between +4%/−6% in 100% of the time. Other standards, such as the engineering recommendation G83/2 for small-scale embedded generators [24], restrict the maximum frequency variation to 4% of nominal frequency in order to maintain a power system connected to the grid. As a result, the limitation in the sampling period variation reduces notoriously the potential problems with other modules, since the critical execution times can be accurately calculated, with the downside of affecting the natural dynamic response.

As a result of the statements above, this paper describes the advantages of VSP methods in processing and control systems and presents some applications where this approach has been successfully used. The differences and similarities between synchronization methods based on fixed and variable sampling periods are discussed by comparing SRF-PLL to VSP-PLL. The aim is to demonstrate that both methods are equivalent, filling the information gap between them and putting forward a hybrid sampling period (HSP) technique that combines the advantages of both approaches. It is also demonstrated this new approach is possible to be adopted to most iPLLs. The way in which other iPLLs can be adapted by means of the HSP approach is discussed, and the experimental results obtained by a iPLL based on the use of a MAF (Moving Average Filter) in the control loop are presented.

2. Application of variable sampling period method for grid synchronization

VSP technique is an interesting option for measurement and control applications, because it allows to significantly enhance the performance of signal processing. In the field of power quality measurement, some methods that use synchronous sampling as an operation principle have been proposed [11–13,19]. They use a Discrete Fourier Transform (DFT) implementation as processing core to obtain the power quality indices of interest. In order to mitigate the problems faced by DFT in the presence of non-stationary signals, such as leakage [25], a control loop that synchronizes the sampling period with the input frequency is added. This concept has been extended to applications other than power systems, such as medical signal processing [26].

The synchronization control loop has also been widely used to control power devices connected to the grid, as in the case of the optimization of repetitive control performances [14,15,27]. This type of controllers provides an infinite gain control loop in all integer multiples of the input frequency, allowing a total rejection of periodic disturbances, or tracking non-sinusoidal references. To obtain a good performance, the period of the repetitive control has to be equal to the period of the input signal or reference. Some authors propose to do that by adjusting the data buffer and/or using interpolation techniques to estimate the fractional samples [27]. On the other hand, in [14,15], the repetitive control structure remains unchanged and the optimum operation is achieved by using VSP technique, showing the feasibility of implementing the technique and the advantages of synchronizing the control to the grid voltages. Other controllers that can be improved by using a VSP technique are, to name a few, some tuned controllers, such as the resonant, SOGI (Second Order Generalized Integrator), ROGI (Reduced Order Generalized Integrator), etc., since their optimal performance is obtained when the sampling frequency is an exact integer of the input frequency.

Thyristor control systems for particle acceleration facilities is another specific application where VSP techniques have been successfully used [16]. In this case the converter synchronization with the grid voltages is critical to minimize the phase jitter on the firing pulses. In the cited work, a classical PLL based on the zero crossing detection of the input signal is replaced by a VSP-PLL, obtaining an improved performance. Other VSP techniques proposed for grid synchronization of power converters can be found in [18,20].

Despite the above mentioned advantages, VSP technique is not widely used given the issues reported in Section 1 and the ample use of the conventional fixed sampling period methods, like SRF-PLL. Next section introduces theoretical concepts related to the variable and fixed sampling frequency methods in order to identify the common features that allow improving the understanding of the former by comparing it to the latter.

3. Variable and fixed sampling period methods

This section describes the basic operation principle of the synchronous methods based on variable and fixed sampling period approaches. The objective is to demonstrate that both approaches are similar, and to understand VSP method through the fixed sampling period operation, where the SRF-PLL is adopted as the reference method. The mathematical models of both methods are analyzed and their dynamic responses are compared. In order to make a more general analysis, only conventional methods, with no additional filter, are considered.

3.1. Synchronous reference frame PLL (SRF-PLL)

SRF-PLL is the basis of most three-phase synchronization systems due to its simple structure and easy implementation [1]. In Fig. 1(a) a block diagram of the digital version of the SRF-PLL is shown, where acquisition and processing are implemented with a fixed sampling period (T_S^{fix}). For this digital implementation, the integrator is represented by means of the Backward-Euler method. Considering ideal operation conditions, the grid voltages can be represented as:

$$\begin{bmatrix} v_a(k) \\ v_b(k) \\ v_c(k) \end{bmatrix} = V_{+1} \begin{bmatrix} \cos[\varphi_u(k)] \\ \cos[\varphi_u(k) - 2\pi/3] \\ \cos[\varphi_u(k) - 4\pi/3] \end{bmatrix} \tag{1}$$

where $\varphi_u(k)$ and V_{+1} are the phase angle and amplitude of the three-phase input voltage. These signals can be represented in the stationary reference frame by using the Clarke transform, and then in the synchronous reference frame with the Park transform using an estimated phase ($\varphi_{est}(k)$) as reference, and obtaining:

$$\begin{bmatrix} v_d(k) \\ v_q(k) \end{bmatrix} = V_{+1} \begin{bmatrix} \cos[\varphi_u(k) - \varphi_{est}(k)] \\ \sin[\varphi_u(k) - \varphi_{est}(k)] \end{bmatrix} \tag{2}$$