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Synchronization algorithms for grid-connected renewable systems: Overview, tests and comparative analysis

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A R T I C L E I N F O

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A B S T R A C T

This paper presents five synchronization algorithms that are commonly used in grid-connected renewable systems. The algorithm structures are studied and their corresponding block diagrams are shown and explained in detail. The behaviors of the algorithms are studied according of their response under voltage unbalances, frequency variations and low-order voltage harmonics. The advantages and disadvantages of the algorithms are discussed by analyzing some simulations done with MATLAB/SIMULINK tool from The MathWorks, Inc. Later on, the final validation is done by doing real-time digital tests of the synchronization algorithms with a Real-Time Digital Simulator (RTDS) platform. A grid-connected photovoltaic system with a nominal power of 10 kW is used to evaluate the responses of the synchronization algorithms when the utility grid is affected by disturbances.

1. Introduction

In a Distributed Generation (DG) environment [1–7], where small electrical generators (also known as agents) based mainly on renewable energy sources, are connected to the 3-phase low-voltage utility grid in order to supply the shortage of electrical energy in the energetic mix, it is necessary an appropriated control of the power factor of the inverter-grid connection to obtain the maximum efficiency of the renewable system, and the synchronization algorithm module is used for detecting the phase angle of the 3-phase utility grid voltages. An optimal dynamic response as well as the reliability is mandatory so as to obtain a good synchronization of the controlled 3-phase inverter currents with the 3-phase utility grid voltages in order to ensure the proper behaviour of the inverter control strategy. In addition, this scenario will contribute to decrease the generation of electrical energy from conventional sources [8], such as fossil and nuclear fuels that are not only producing a high level of pollution due to CO_2 emissions [9], the greenhouse effect and the recent climate change, but also are running out.

There are several studies which show different synchronization methods to estimate the phase angel of the 3-phase utility grid voltages [10]. Among them, it can be mentioned the **Synchronous Reference Frame Phase-Locked Loop (dqPLL)** [11], the **Positive Sequence Detector plus a dqPLL (PSD+dqPLL)** [12,13], the **Dual Second Order Generalized Integrator Phase-Locked Loop (DSOGI-PLL)** [14,15], the **Dual Second Order Generalized Integrator Frequency-Locked Loop (DSOGI-FLL)** [16,17], and the **Multiple Second Order Generalized Integrator Frequency-Locked Loop (MSOGI-FLL)** [18]. According to the hardware resources needed for the implementation of these algorithms, the dqPLL is the simplest one, meanwhile the Multiple Second Order Generalized Integrator Frequency-Locked Loop (MSOGI-FLL) technique is the most sophisticated.

It must be pointed out that two up to date papers [19,20] resume several synchronization algorithms, although they lack of a comparison in experimental results applied to a distributed generation (DG) system.

The main goal of this paper is to carry out a detail explanation of the above algorithms, letting know the scientific community and engineers

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Nomenclature

vp	output voltage of the PV system
ip	output current of the PV system
P_{PV}	power of the PV system
v_{CC}	dc bus voltage
v^*_{CC}	dc bus voltage reference
i_{CC}	current that will be injected into the inverter
C_{link}	dc-link capacitor
i_{clink}	current through the dc-link capacitor
θ	phase of the 3-phase utility grid voltages
ω	fundamental angular frequency
d	duty cycle of the DC/DC boost converter
L_{dc} and D	inductance and diode of the DC/DC boost converter
i_{IGBT}	current through the power switch of the DC/DC boost converter
$\mathbf{i}_D$	current through the diode of the DC/DC boost converter
i_u, i_v, i_w	3-phase inverter line currents
i_r, i_s, i_t	3-phase utility grid currents
DQ	in-quadrature signals
ω'	centre angular frequency
ω	angular frequency
k	gain of the SOGI block
v_r, v_s, v_t	3-phase utility grid voltages
s_u, s_v, s_w	states of the power-switches of the inverter
$\mathbf{u}$	inverter voltage space vector
$\mathbf{i}$	inverter line current space vector
$\mathbf{u_{AC}}$	utility grid voltage space vector
L	line inductance
R	resistance of the line inductance
$v\alpha$, $v\beta$	$\alpha\beta$ components of space vector $\mathbf{u}$
$i\alpha$, $i\beta$	$\alpha\beta$ components of space vector $\mathbf{i}$
$uac\alpha$, $uac\beta$	$\alpha\beta$ components of space vector $\mathbf{u_{AC}}$
p	instantaneous active power
q	instantaneous reactive power
i_d, i_q	d-q components of space vector i
$uacd$, $uacq$	d-q components of space vector $\mathbf{u_{AC}}$
i^*_d, i^*_q	d-q reference components of vector $\mathbf{i}^*$
q^*	instantaneous reactive power reference
F_{sw}	switching frequency
ts	settling time
τ	time constant of the first order system
$ts(FLL)$	settling time of the FLL
Γ	gain to set $ts(FLL)$
K_p and K_i	proportional and integral gains

their own advantages and disadvantages. However, despite the possibility of using all these algorithms in grid-connected renewable systems, the decision whether to use one or another is not always clear in the scientific literature, and the choice might depend on the requirements and/or regulations to be fulfilled, as well as the type of utility grid to be fed by the renewable energy source. For example, weak grids will demand more sophisticated and expensive algorithms to deal with their common perturbations, such as harmonics, unbalances, frequency variations, faults, etc., meanwhile a stiff grid will demand simple and cheaper synchronization algorithms.

Section 2 is focused on the descriptions and study of the mentioned synchronization algorithms: their structures and design requirements are shown and discussed in order to obtain its major performance. In Section 3, several simulations using MATLAB/SIMULINK tool [21] will be done in order to evaluate its behaviour when the 3-phase utility grid is affected by disturbances, and a 10 kW grid-connected photovoltaic (PV) renewable system will be used for this. In Section 4, real-time digital experiments will be performed using a DS1006 DSPACE platform [22] with several I/O, ADC and DAC blocks in order to reinforce the validity of the previous study. Finally, some conclusions are shown in Section 5 of this paper.

2. Synchronization algorithms used in grid-connected inverters

2.1. Synchronous Reference Frame Phase-Locked Loop (dqPLL)

A 3-phase Phase-Locked Loop (PLL) synchronization algorithm structure is shown in Fig. 1, which is made by the Clarke [23] and Park transformations (also known as abc→dq transformation) [24], the PI regulator [25] as the loop filter, and an integrator as the voltage-controlled oscillator (VCO). This PLL structure is also known as Synchronous Reference Frame PLL or dqPLL: the input variables are the 3-phase utility grid voltages (u_r,u_s,u_t), and the output variable is its phase angle (θ_{obs}).

The design of the PLL gain is a critical point within this process. From the point of view of dynamic systems, high gains will imply higher dynamics [26], but stability may become unacceptable. The closed loop transfer function of the dqPLL of Fig. 1 is expressed by (1) [10]:

$$H(S) = \frac{Kp\ s\ +\ Ki}{s^2\ +\ Kp\ s\ +\ Ki} \tag{1}$$

where K_p and K_i are the proportional and integral gains, respectively, of the employed PI regulator. Eq. (1) is a second order transfer function, similar to (2).

$$G(S) = \frac{2\zeta\omega_0\ s +\ \omega_0{}^2}{s^2\ +\ 2\zeta\omega_0\ s +\ \omega_0{}^2} \tag{2}$$

where: ω_0 is the natural angular frequency, and ζ is the damping factor.

Equating (1) and (2):

$$Kp\ =\ \frac{9.2}{ts} \tag{3}$$

$$\omega_0 = \frac{Kp}{2\zeta} \tag{4}$$

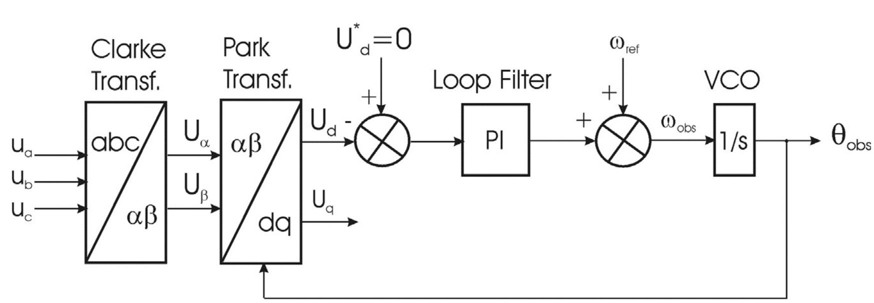

Fig. 1. Block diagram of the dqPLL synchronization algorithm.