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Performance study of a synchronization algorithm for a 3-phase photovoltaic grid-connected system under harmonic distortions and unbalances

N.F. Guerrero-Rodríguez [a,*], L.C. Herrero-de Lucas [b,1], S. de Pablo-Gómez [c,2], Alexis. B. Rey-Boué [a,3]

[a] Department of Electronics, Computers Technology and Projects, Universidad Politécnica de Cartagena, c/ Dr. Fleming s/n 30202, Cartagena, Murcia, Spain
[b] Department of Electronics Technology, Universidad de Valladolid, c/ Fco. Mendizabal 1, 47014 Valladolid, Spain
[c] Department of Electronics Technology, Universidad de Valladolid, c/ Paseo del Cauce 59, 47011 Valladolid, Spain

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ABSTRACT

In a distributed generation (DG) system, several renewable agents are connected to the low-voltage 3-phase utility grid through an inverter which is used as power condition and must guarantee the higher efficiency of the renewable agent. To attain this level of efficiency, a unitary power factor (FP) between the inverter currents and the utility grid voltages is necessary, and a synchronization algorithm is needed for the perfect synchronization between the renewable agent and the 3-phase utility grid. Within this context, this paper gives a performance study of the Positive Sequence Detector plus a Synchronous Reference Frame Phase-Locked Loop (PSD + dqPLL) as the synchronization algorithm, evaluating its accuracy under different conditions and studying their advantages and drawbacks. A grid-connected photovoltaic system with a nominal power of 6 kW is used so as to evaluate the behavior of the synchronization algorithm when the 3-phase utility grid is affected by some disturbances such as voltage unbalances, frequency variations and harmonic distortions. Firstly, several simulations with a disturbed 3-phase utility grid using MATLAB/SIMULINK from *The MathWorks, Inc.* are shown, and secondly, the previous tests are run in a Real-Time Digital Simulation (RTDS) platform in order to validate the obtained results with simulations.

1. Introduction

Throughout decades, the electric power demand has been rising due to the growth of the industrial sector and transportation, and the development of new technologies that require more energy together with the increase of the global population have led to a higher fuel demand needed for the electric energy generation. The global energy consumption in 2012 was 148,934 TWh [1] and it expected that by 2020 it will increased to 184,600 TWh [2] and the majority of this energy is provided by fossil fuels [2], as well as the electric power generation, although the future of these trend is uncertain [3]. Besides, greenhouse effect is causing environmental changes that concern mankind and provided the creation of new energetic policies is a fact. An alternative for reducing the fossil fuel dependence and the reduction of the greenhouse gas emission is the use of clean and infinite renewable energy sources such as photovoltaic, wind, as well as fuel cells for energy storage, which have been installed in the energy mix. In this context, new photovoltaic agents are connected to the 3-phase utility grid and must be properly controlled according to power electrical legislations [4]. The power factor connection and the harmonic contamination are the main control objectives for allowing high power quality.

Voltage Source Inverters (VSI) are commonly used as the power conditioner units to interface renewable resources to the utility grid in a Distributed Generation (DG) framework [5,6], and are built with semiconductor devices operating in switch-mode. A review of several topologies for interfacing renewable resources to the utility grid can be found in [7].

In order to obtain the higher efficiency of the renewable system, these units are usually controlled in a digital manner with

* Corresponding author. Tel.: +34 968 326514; fax: +34 968 326400.
E-mail addresses: nestor.guerrero@upct.es, nestorguerrero00@gmail.com (N.F. Guerrero-Rodríguez), lcherrer@tele.uva.es (L.C. Herrero-de Lucas), sanpab@eii.uva.es (S. de Pablo-Gómez), alexis.rey@upct.es (Alexis.B. Rey-Boué).
[1] Tel.: +34 983 423521; fax: +34 983 423490.
[2] Tel.: +34 983 423345; fax: +34 983 423310.
[3] Tel.: +34 968 325928; fax: +34 968 326400.

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Nomenclature

v_p	output voltage of the PV generator
i_p	output current of the PV generator
P_{PV}	power in the PV generator
v_{CC}	dc bus voltage
v_{CC_ref}	dc bus voltage reference
i_{CC}	current that will be injected into the inverter
C_{link}	dc-link capacitor
i_{link}	current through the dc-link capacitor
θ	Phase of the 3-phase utility grid voltages
ω	fundamental angular frequency
i_u, i_v, i_w	3-phase inverter line currents
i_r, i_s, i_t	3-phase utility grid currents
v_r, v_s, v_t	3-phase utility grid voltages
S_u, S_v, S_w	states of the power-poles
$\mathbf{u}$	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
i_d, i_q	d–q components of space vector $\mathbf{i}$
u_{ACd}, u_{ACq}	d–q components of space vector $\mathbf{u_{AC}}$
p	instantaneous active power
q	instantaneous reactive power
i_{d_ref}, i_{q_ref}	d–q reference components of vector $\mathbf{i}^*$
q_{-ref}	Instantaneous reactive power reference
$PI_{VCC}, PI_{id}, PI_{iq}$	voltage and current PI regulators
F_{sw}	switching frequency

up-to-date powerful microcontrollers and/or programmable logic devices such as FPGAs, allowing the automation of the power flow control with adaptive control algorithms, the reduction of the time response to grid perturbations and faults, and the monitoring of the main grid variables.

New control algorithms have been designed focusing on improving the performance of the connection of primary renewable energy agents to the low-voltage 3-phase utility grid. It is necessary an appropriated control of the power factor of the inverter-grid connection to obtain the maximum efficiency in the photovoltaic agent, and the synchronization algorithm will be one of the main modules in detecting the phase angle of the 3-phase utility grid voltages with optimal dynamic response. The dqPLL method, also known as *Synchronous Reference Frame Phase-Locked Loop* is the classical synchronization algorithm, since it is easy to implement, but it is also very sensible to grid voltage unbalances leading to errors when the frequency and phase are detected. For this, a large amount of studies have been carried out in this area in order to find a solution to this fact, as may be found in [8–12], all of them showing a perspective of how to solve this issue when the detection of the frequency is conducted. A performance study of one of these methods is carried out in this paper which is focused on the use of a Positive Sequence Detector (PSD) using the Fortescue theorem [13].

The Positive Sequence Detector plus a dqPLL (PSD + dqPLL) method proposed in [8] will be analyzed and tested using a model of a grid-connected PV system and introducing some disturbances to the 3-phase utility grid such as voltage unbalances, frequency variations and harmonic distortions, avoiding major changes in the existing structure of the dqPLL and the use of more complicated methods based on frequency adaptive filters.

The power and control subsystems of a 6 kW grid-connected PV system used to evaluate the performance of the PSD + dqPLL synchronization algorithm under disturbance conditions are discussed and explained in detail in Section 2, meanwhile its parameters are described in Section 3. Several tests, including unbalances in the 3-phase voltages of the utility grid, harmonic distortions and frequency variations, as well as its influence in the global performance of the PV system, will be studied in Section 4 using simulations with MATLAB/SIMULINK [14]. Section 5 is focused on running the previous tests using a Real-Time Digital Simulation (RTDS) platform. Finally, conclusions are shown in Section 6.

2. Grid-connected photovoltaic system

The main purpose for PV grid-connected systems is to control the power flow between the primary renewable energy source and the utility grid [15], as well as the power factor of the inverter-grid connection with high power quality [16]. The power conditioner must guarantee the maximum efficiency by injecting the maximum available power at the PV module, as well as by controlling the power factor of the inverter-grid connection in a four quadrant operation; the latter makes use of the instantaneous reactive power theory [17] for 3-phase systems which allows the control of the instantaneous active and reactive powers in decoupled d–q axes [18]. The global 3-phase PV grid-connected system can be divided into two subsystems [16], the power and the control subsystems, whose block diagrams are depicted in Fig. 1. In this paper, the power converter of the PV system shown in Fig. 1 works in inverter-mode (3-phase Voltage Source Inverter (VSI)) since it delivers all the incoming power from the PV generator into the 3-phase utility grid, although an opposite power flow is also possible (rectifier-mode), being able to feed local dc loads from the utility grid.

2.1. Power subsystem

The power subsystem is formed by the PV modules, an inverter, the LCL filter, and the EMI filter. Following, a brief description of each block is developed.

2.1.1. Photovoltaic modules

PV modules are the main part of a PV system [19]. There are several kinds of PV module technologies with different levels of efficiencies [20]. The function of a PV module is to supply the necessary power for the renewable grid-connected system, and it will depend of the available solar irradiance [21] and the temperature, meanwhile its size (arrange of parallel-series PV cells) will depend of the required power of the photovoltaic system [22].

2.1.2. The inverter

The mission of the inverter, mainly built with semi-conductor electronic devices [7] (IGBTs and diodes), is to convert the generated dc voltage into suitable ac currents to be fed into the 3-phase low-voltage utility grid [5,7]. Pulse-width modulation (PMW) and space vector modulation (SVM) [23] techniques are used to control the gate signals of power switches according to the averaged voltage and current references.

According to Fig. 1, the dc side of the inverter can be described as follows:

$$
\begin{aligned}
& i_p = i_{clink} + i_{CC} \\
& i_{CC} = S_u \cdot i_u + S_v \cdot i_v + S_w \cdot i_w \\
& i_{clink} = C_{link} \frac{dv_{CC}}{st} \\
& P_{PV} = i_p V_p
\end{aligned}
\tag{1}
$$

where v_p, i_p are the voltage and the output current of the PV generator, respectively, P_{PV} is the available power for a specific irradiance, v_{CC} is the dc bus voltage, i_{clink} is the current through the link capacitor C_{clink}, and i_{CC} is the current delivered to the 3-phase VSI (which