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# Effects of post-filtering in grid-synchronization algorithms under grid faults

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ABSTRACT

The spread of distributed generation systems has reinforced concerns and requirements on grid-tied power converters. The synchronization with the utility voltage vector is a major concern. In the literature, algorithms based on Phase Locked Loops are extensively presented. In spite of adequate performances under ideal and balanced grid conditions, under grid faults great inaccuracies arise. Shortcomings are overcome by advanced algorithms at the expenses of the complexity and computational cost. In this paper, grid synchronization algorithms are addressed. A solution is proposed by introducing a new post-filter stage in a Decoupled Double Synchronous Reference Frame not affecting, at the same time, the complexity of implementation, the detection time and damping of the conventional DDSRF solution. The post-filtering stage design criteria are described based on a mathematical derivation of the phase error in a conventional DDSRF algorithm under distorted grid utility. A comparison of system performances with the conventional DDSRF algorithm is carried out under distorted, balanced and unbalanced utility conditions, validating the benefits brought by the proposed solution.



## 1. Introduction

Nowadays, the increasing spread of renewable energy sources and other distributed generation systems has reinforced the already existing concern of grid stability. Grid code requirements actually provide specific constraints for wind or photovoltaic power plants and restrictive constraints are continuously introduced [1–3]. The continuous grid code revisions pose new and great challenges in the design of grid-connected power converters.

In the literature, effects of grid faults on the performances, damages and aging of renewable sources are widely investigated, especially for solid oxide fuel cells (SOFCs), photovoltaic generators and wind turbines [4–6]. Consequently, advanced control schemes in the front-end grid-tied power converter are highly investigated and adopted to provide an efficient protection of renewable energy sources. Power controllability, power quality, fault ride-through capability are only a few examples of addressed issues [7,8]. A distributed generation power system is conventionally expected to be disconnected from the power grid in case of voltage sags and to be reconnected whenever the fault is recovered. In order to avoid this equipment disconnection, advanced research focuses on power quality compensators to enhance immunity to grid faults [9–11]. Grid fault conditions include harmonic distortion and voltage events. If voltage is affected by distortion, effects of high-order harmonics on the output should be canceled providing for fast recovery and grid support. For this purpose, the design of the diagnostic system is often oriented to high-order harmonics rejection, accurate and fast identification of the sequence components of the voltage vector. Voltage events, which are counted among grid fault conditions in actual standards, are caused by remote grid faults in the power system and are considered as short time events characterized by a temporary decrease in the rms voltage. Both balanced and unbalanced voltage events are accounted for, even if balanced voltage events seldom happen. On the basis of the magnitude and the total duration, which is usually limited from a few milliseconds to a few minutes, existing standards differently classify voltage events. Voltage sags or dips are characterized by a change in magnitude from 10% to 90% and the total duration lies within the range from 0.5 cycles to 1 min.

The major concern to be solved is the synchronization with the utility voltage vector. The utility voltage vector should be accurately tracked for a proper control of active and reactive power.

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Control algorithms of grid-tied inverters are usually affected by distorted information. Accurate and fast detection of the phase angle, amplitude and frequency of the grid voltage vector is fundamental for a proper generation of the current reference. Furthermore, the phase angle information is required for coordinate transformation of several control variables. Consequently, if the information on the phase angle is not immune to grid distortion, the power quality requirements will be fulfilled anymore. Grid synchronization algorithms are usually based on Phase Locked Loops (PLLs) providing high accuracy and adequate transient response. In the literature, PLL algorithms for grid synchronization are widely investigated [12–27]. Phase angle and frequency are properly tracked during normal and balanced utility conditions. Yet, during grid faults as distorted, balanced and unbalanced voltage events, conventional PLLs algorithms exhibit great inaccuracies or even lead to a synchronization failure [28]. Shortcomings could be easily overcame by advanced algorithms, as Double Synchronous Reference Frame (DSRF) PLL [29,30] and PLL based on Second Order Generalized Integrator (SOGI) [6,31], at the expenses of the algorithm complexity. Performances of grid synchronization algorithms are usually evaluated in terms of accuracy in the detection of the phase angle of the utility voltage vector, capability to smooth phase and frequency variations and rejection of disturbances and harmonics on the converter output. In Ref. [13] a comprehensive overview of grid synchronization algorithms, which focuses on SRF and Decoupled Double Synchronous Reference Frame (DDSRF) PLL algorithms, is given. A comparison between SRF and DDSRF PLL algorithms is carried out on a grid-connected inverter by simulation results under ideal, unbalanced and distorted grid utility conditions.

This paper proposes a new solution, based on the introduction of a post-filtering stage on a conventional DDSRF PLL algorithm. The post-filtering stage enhances system performances under grid faults, not requiring complex schemes as for the SOGI algorithm. As it will be shown by simulations results, thanks to the proposed solutions, frequency deviations and fluctuations under ideal conditions, distorted regime, phase jump events and voltage sags are heavily reduced, affecting neither the complexity nor the computational cost of the PLL implementation.

The paper is structured as follows. Section 2 describes the state of art of PLL-based synchronization algorithms. Section 3 provides a detailed description of the designed grid-tied inverter model. Section 4 provides a description of the DDSRF algorithm and implementation. Simulation results with the conventional DDSRF implementation under grid faults are presented in Section 5. Section 6 describes the proposed post-filtering solution and investigates effects of post-filtering stage on system performances by simulation results under grid faults. The post-filtering stage is described based on a mathematical derivation of the phase error in a conventional DDSRF solution. The post-filtering stage features low-complexity and improved performances under distorted grid utility not affecting the complexity, detection time and damping of the conventional DDSRF implementation. A comparison of system performances with the conventional DDSRF algorithm is carried out, validating benefits brought by the proposed solution. In Section 7, conclusions are drawn.

## 2. State of art of grid synchronization algorithms

In the literature, several solutions and architectures are widely proposed and investigated to track the phase angle of the utility voltage vector [15–18,20]. Classification is conventionally based on the coordinates reference frame: natural ($abc$), stationary ($\alpha b$) and rotating (dq). By using stationary or rotating reference frame, disturbance immunity is enhanced. In the past decades, phase tracking algorithms were commonly based on zero crossing detection (ZCD) schemes, which are based on natural coordinates reference frame. Yet, during distorted and unbalanced grid conditions, ZCD algorithms exhibit unacceptable inaccuracies [12]. System performances are now usually enhanced by adopting Phase Locked Loop (PLL) schemes [15–17]. Yet, the enhancement of accuracy is counterbalanced by an increasing complexity of the control scheme. The Synchronous Reference Frame (SRF) PLL is the most commonly adopted. High accuracy and adequate bandwidth are achieved under normal utility conditions. Under harmonic distortion or voltage events, SRF algorithm tracking fails [14,28]. Under distorted grid conditions, high accuracy can be still achieved by reducing the bandwidth at the expenses of the transient response. By reducing the bandwidth, harmonics rejection is further improved. Yet, by reducing the bandwidth, during unbalanced utility conditions performances are worsened. By applying a SRF PLL scheme, a trade-off arises thus limiting the chance of an effective performance enhancement under both distorted and unbalanced grid conditions.

In Refs. [21–23], pre-filtering option is introduced to enhance the detection of the positive and negative sequence components. The DDSRF PLL algorithm is based on two synchronous reference frames, which rotate at the fundamental utility frequency. A decoupling network for positive and negative sequence voltage components is introduced. DDSRF PLL achieves an accurate detection of the positive and negative sequence components of the grid voltage vector even under unbalanced grid conditions [6,29,30]. In Ref. [13], a grid-tied inverter is designed and a detailed comparison between SRF-PLL and DDSRF-PLL algorithms is carried out by simulation under ideal, unbalanced and distorted conditions to highlight advantages brought by the DDSRF algorithm. During distorted grid conditions, harmonic rejection is further improved by the Dual Second Order Generalized Integrator (DSOGI), which implements the instantaneous symmetrical components method by adaptive filters, based on the second-order generalized integrator [6]. In the literature, advanced PLL structures are presented [32–35] and tested under fault conditions. In Refs. [33,34], a modify of the SOGI architecture is presented. The modified structure features a high — pass filtering property. Thanks to the proposed structure, a fast response is obtained canceling the DC offset and limiting the unit vector Total Harmonic Distortion (THD) to 1%.

In Ref. [32] a filter quadrature signal generator and PLL structure forms the Adaptive Vector Grid Synchronization System (AVGS), which allows fast and accurate detection of symmetrical components meeting the transient requirements imposed by the grid codes.

In Ref. [35], a comparison of DDSRF, dual order SOGI and three-phase enhanced PLL are compared under unbalanced and distorted conditions. The comparison has been carried out by experimental results to test the accuracy and implementation features. The SOGI and DDSRF PLLs show a lower computational cost and higher robustness in estimating the voltage parameters.

## 3. The converter model

A two-level full bridge inverter has been simulated. The converter model has been implemented in Matlab/Simulink environment by using the SimPower Systems toolbox, which is available in Simulink library. A three-phase voltage block is introduced in the Simulink schematics to simulate the utility network during grid faults. The nominal grid voltage amplitude is fixed at 400 V and the nominal frequency is set at 50 Hz. A schematic block diagram is shown in Fig. 1.

The inverter is connected to a measurement subsystem and to the grid utility by an LCL filter. A switch subsystem is provided to disconnect the equipment from the power grid according to actual standards. The control subsystem includes the PLL subsystem, the