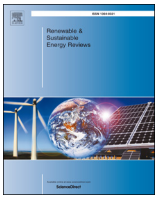
Renewable and Sustainable Energy Reviews 90 (2018) 434–452

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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



Three-phase phase-locked loop synchronization algorithms for grid-connected renewable energy systems: A review

Zunaib Ali[a,*], Nicholas Christofides[a], Lenos Hadjidemetriou[b], Elias Kyriakides[b], Yongheng Yang[c], Frede Blaabjerg[c]

[a] Department of Electrical Engineering, Frederick University, CYTA Building, Kyriakou Matsi Street, 1035 Nicosia, Cyprus
[b] Department of Electrical and Computer Engineering, KIOS Research Center of Excellence, University of Cyprus, P.O. Box 20537, CY-1678 Nicosia, Cyprus
[c] Department of Energy Technology, Aalborg University, 9220 Aalborg Ø, Denmark

ARTICLE INFO

Keywords:
Renewable energy sources (RES)
Grid side converters (GSC)
Synchronization
Phase-locked loop (PLL)
Harmonic distortion
Unbalanced grid conditions
Power converter control
Grid codes

ABSTRACT

The increasing penetration of distributed renewable energy sources (RES) requires appropriate control techniques in order to remain interconnected and contribute in a proper way to the overall grid stability, whenever disturbances occur. In addition, the disconnection of RES due to synchronization problems must be avoided as this may result in penalties and loss of energy generation to RES operators. The control of RES mainly depends on the synchronization algorithm, which should be fast and accurately detect the grid voltage status (e.g., phase, amplitude, and frequency). Typically, phase-locked loop (PLL) synchronization techniques are used for the grid voltage monitoring. The design and performance of PLL directly affect the dynamics of the RES grid side converter (GSC). This paper presents the characteristics, design guidelines and features of advanced state-of-the-art PLL-based synchronization algorithms under normal, abnormal and harmonically-distorted grid conditions. Experimental tests on the selected PLL methods under different grid conditions are presented, followed by a comparative benchmarking and selection guide. Finally, corresponding PLL tuning procedures are discussed.

1. Introduction

Renewable energy sources (RES) require power electronic-based grid side converters (GSC) for efficient and reliable integration with the grid [1–5]. The increasing penetration of renewables [6] requires a continuous revision of the grid codes issued by local/national [7–11] and international authorities [12–16]. This is because GSC are continuously enhanced and diversified with new features and functionalities for supporting the grid and improving the power quality. Grid codes are therefore revised so that such systems support the grid when grid disturbances occur. Furthermore, they can be utilized in the future modeling of power systems, smart grids, and micro grids. Several recent grid regulations are given in Fig. 1, where the RES are required to remain grid-connected, injecting reactive power as long as the voltage level at the point of common coupling (PCC) is above the characteristic line for each case [17–21]. In addition, a RES must also have the Fault Ride Through (FRT) capability (i.e., remain connected under grid faults) even under zero grid voltage conditions for approximately 150 ms (i.e., in Germany [18] and Spain [21]), thereby improving the power system stability [22,23]. Hence, for accurate response and for complying with modern grid regulations, the GSC control algorithms must perform accurately under normal and abnormal grid conditions and be equipped with advanced features and functionalities.

In general, the control of a GSC mainly consists of three modules: the active/reactive power regulation in the outer control loop, the inner current control loop and the synchronization module [24–27]. The power system topology and the corresponding controller diagram for such a three-phase GSC are extensively described in [28–31], and they are also presented in Fig. 2. The *PQ* controller is responsible for generating the current references, which are subsequently tracked by the current controller in order to inject the required active/reactive powers. The synchronization unit performs the function of extracting the grid information that is subsequently used in the control loops. Two main design methodologies are adopted for such control algorithms. One design methodology is implemented in the stationary $\alpha\beta$-reference frame with Proportional Resonant (PR) controllers [32] or other periodic controllers [33]. The other design methodology employs Proportional Integral (PI) controllers in the synchronous *dq*-reference frame (SFR) [34–36]. For both cases, the grid voltage information, that is, the phase angle and frequency, is required for the implementation. In general, a PLL is most commonly used to extract the phase angle of the grid voltage at the PCC and hence the frequency. Many PLL algorithms

---

[*] Corresponding author.
E-mail address: zunaib.ali@stud.frederick.ac.cy (Z. Ali).

https://doi.org/10.1016/j.rser.2018.03.086
Received 19 August 2017; Received in revised form 26 February 2018; Accepted 26 March 2018
1364-0321/ © 2018 Elsevier Ltd. All rights reserved.

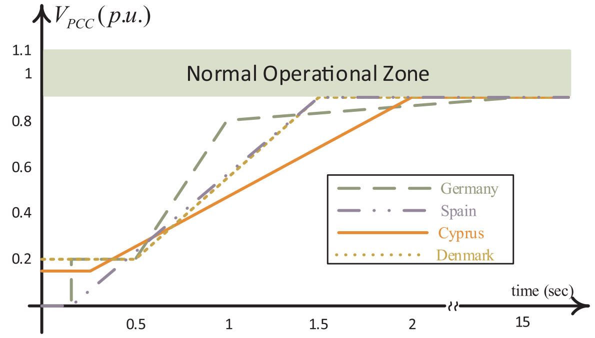


Fig. 1. Fault ride through (FRT) requirement for RES systems under grid faults [44,45], where V_{PCC} is the voltage at the point of common coupling (PCC).

have been proposed and exist in the literature and they are the center of attention in this work. The performance of the PLL under normal and distorted grid conditions directly affects the dynamics of the *PQ* and current controllers. Therefore, the design of PLL systems is critical for the accurate operation of the grid-connected RES.

A review of various three-phase PLLs is presented in [37], however, many of the important state-of-the-art-PLLs such as, the dαβPLL, FPD dαβPLL, adaptive dαβPLL, MSHDC PLL, DNαβPLL, PMAFPLL, αβEPMAFPLL, EPMAFPLL Type 2, LPNPLL, FFTPLL, EPLL, modified PI based PLLs and the MRF PLL are not considered. The review study in [38] considers three-phase PLLs such as the dqPLL, the αβPLL, the DSRFPLL, the EPLL, the 3EPLL and the DSOGIPLL. Both review studies [37,38] lack experimental benchmarking. The review studies in [39,40] compare only three PLLs and do not consider many of the other important state-of-the-art PLLs, such as the ones discussed in this work. The work presented in [41,42] considers four PLLs from the literature. The selected PLLs are dqPLL, modified dqPLL, DSOGIPLL and Multiple SOGI (MSOGI) PLL, neglecting many important ones. A recent review study [43], includes the dqPLL, the EPLL, the Quadrature PLL and the variable sampling rate PLL. However, the study does not provide experimental results comparison and in addition, several advanced PLLs are not considered.

This PLL review study is thorough from all aspects and considers the most important categories and the latest state-of-the-art PLLs that have not been considered in previous review studies. These include filtering based approaches, decoupling network based PLLs, modified loop filter PLLs and other important PLL approaches. Every PLL has been discussed in detail along with its operating principle, mathematical analysis and schematic diagram. In addition, their performance capabilities together with their advantages and disadvantages are provided. Another main contribution of this paper is the experimental benchmarking of the selected three-phase PLLs for the first time in the literature. The work summarizes the benchmarking of the PLLs in a tabular form (Table 7), obtained from experimental analysis. This can be used as a selection guide by engineers and new researchers who want to contribute to the area. Furthermore, it can help engineers to select the appropriate PLL algorithm according to specific application requirements and grid operating conditions. The benchmarking considers various aspects: such as performance accuracy of PLLs under normal and abnormal grid operating conditions, the dynamic response of the PLLs, the computational complexity and frequency/phase overshoot of the PLLs.

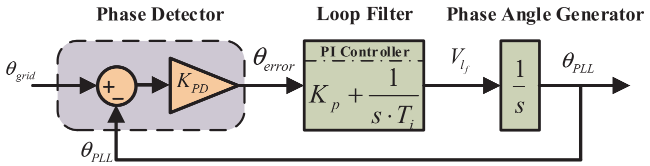


Fig. 3. Block diagram of the fundamental phase-locked loop (PLL) system.

The paper is organized as follows: Section 2 presents the basic and conventional types of PLLs. Advanced PLL algorithms considering unbalanced and distorted grid conditions are discussed in Section 3. Section 4 presents the experimental verification and comparative study for the selected PLLs, providing a selection guide for choosing the most appropriate PLL algorithm for specific application and under specific grid conditions. Finally, the tuning methods of the PLLs are presented, followed by the conclusion.

2. Review of conventional three-phase PLL algorithms

The block diagram of the fundamental PLL consisting of a Phase Detector (PD), a Loop Filter (LF) and a frequency/phase generator (FPG), also called a Voltage-Controlled Oscillator (VCO), is presented in Fig. 3. The simplest PLL algorithms are the conventional dqPLL and the αβPLL.

2.1. The dqPLL

The dqPLL [46,47] is designed according to the Clarke and Park transformation, shown in (1), which converts the natural *abc* reference frame into the synchronous *dq*-reference frame. To acquire the phase of the input voltages, the *q*-component of the positive sequence voltage in (3) tracks a zero reference through a PI controller, the loop filter in Fig. 3. As a result, under ideal voltage conditions, θ_{dqPLL} becomes equal to the phase angle of the three-phase voltage and component v_d perfectly tracks the magnitude of the positive sequence voltage $\mathbf{v}^{+}$. Since the synchronous frame is rotating with the positive angular speed, the dqPLL works accurately for balanced grid faults. It fails to track the phase angle when an unbalanced fault occurs. This is because of the presence of double-line frequency oscillations induced by the negative sequence components $\mathbf{v}^{-}$ that disturb the *dq*-components resulting in the mismatch of v_d from the positive sequence magnitude $|\mathbf{v}^{+}|$ [34]. In addition, the *dqPLL* cannot work for harmonically distorted three-phase voltages. The structure of the dqPLL is presented in Fig. 4.

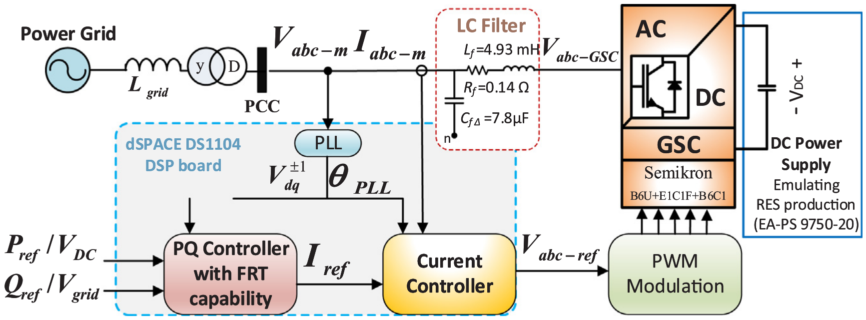


Fig. 2. General structure of a grid-connected renewable energy system.

Download English Version:

https://daneshyari.com/en/article/8111315

Download Persian Version:

https://daneshyari.com/article/8111315

Daneshyari.com