PLL and Self-synchronized Synchronverter: An Overview of Grid-inverter Synchronization Techniques

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Abstract — In this paper, a brief summary of synchronization approaches is discussed sequentially from older techniques to latest technology. There are many techniques that have been developed which focusing of synchronization, from basic grid evaluating technique, phase-locked-loop (PLL) and later to synchronous reference-frame phase-locked-loop where is established on basis of phase estimation and determination where it can give fast synchronization time. Recently, due to the advancement of inverter control strategy which is based on the mathematical formulas derivation, a synchronous generator characteristic can be integrated in the inverter controller design. As a result, the inverter will behave like the synchronous generator whereas known it has fast synchronization time and known as synchronverter. At the end of this paper, a comparison table among the existing PLLs with synchronverter in terms of efficiency will be addressed.

Keywords - Distributed energy; grid-inverter; synchronization; PLL; amplitude; phase angle; synchronverter.

I. INTRODUCTION

The locally introduced distributed energy resources (DERs) are connected with conventional grid for sharing loads by means of inverters. For injecting quality power into the grid, there are many power electronic devices and control mechanisms are employed between the conventional grid and DERs. The synchronization between grid and inverter is one of most important issue to deliver high class of power to the grid. The advanced control strategy of synchronization is required for preserving as well as improving the stability of the power system [1-3]. There are many studies have been done on the field of power system control strategies for sending the power from DERs to the conventional ac grid. Most of DERs offer dc output and the dc-storage battery bank is connected with existing alternating current grid network through an efficient inverter [4]. Usually, current-source inverter (CSI) and in case of standalone operation voltage-source inverter (VSI) are used to supply energy to the grid or utility. Amusingly, the VSI does not need external reference to keep synchronized [5], even it works with other systems with regard to frequency and voltage droops that caused outlining microgrid [6]. During operation of VSI at grid connected mode, it acts like current source instead of voltage source. By maintaining inverter in synchronized condition, the inverter could inject good quality power into the grid at reasonable change in terms of voltage, frequency and phase angle [7]. However, the synchronization unit often needs to provide the value of frequency and the amplitude, with an addition the phase of the fundamental component of the grid voltage for the references for the power controller [8]. In case of synchronous generator (SG) is connected with infinity bus, the power (torque) angle control method is another control method. The phase difference between phase of the grid voltage and of the SG is often called power angle. The control of power angle as well as torque angle control and current vector control for VSI are mostly studied methods. The real power flowing to the grid is controlled by the phase difference, called the power angle or torque angle, between the generated voltage and the grid voltage. The reactive power is controlled by regulating the amplitude of the generated voltage and grid voltage [9]. As shown in figure 1, this conventional synchronization structure consists of synchronization unit to synchronize with the grid in terms of voltage and frequency.

Figure 1. Typical grid-inverter connection structure

In the operation point of view of synchronous generator, several mathematical models and algorithms behave alike synchronous generator that can be called virtual synchronous machine, commonly the synchronverter has been suggested in [10] that give good synchronization between the inverter and grid. At the same time, the power flow between them can be controlled. It can be run in the mode of grid-connected in addition or stand-alone since it has ability to control voltage and frequency. Moreover, by maintaining proper control topology and algorithm it is capable to share real power and reactive power depends on controlling facilities.

In case of three phase applications, there are further demands such as estimations of the fundamental positive or...
negative sequences [11], whose characteristic applications are the flexible power control [7] of grid-interfaced converters for distributed power generation from distributed energy resources [12] and active power filters [13] under the distorted and unbalanced circumstances. In addition, fast and precise synchronization are forthright requirement having wide range of reactive and real power controlling options [11]. In this paper, various synchronizing techniques of converter have been discussed in the synchronization means with grid and converter and the details on the synchronverter also been discussed.

II. CONNECTIONS AND SYNCHRONIZATION TECHNIQUES

The most important and basic conditions for such applications are to possess inverter synchronized with the grid before and after the inverter being connected to the grid. So that, 1) an inverter can be connected to the grid, and 2) the inverter can feed the right amount of power to the grid even when the grid voltage changes its frequency, phase, and amplitude [14]. Moreover, the concept of “plug and play” distributed microsources is the key to microgrids. To accomplish this goal, the ideas of active-power/frequency and reactive-power/voltage droop controls will be used. Its allow microsources to share power and maintain stability without the need for fast communications [14]. However, it has been a norm to adopt a synchronization unit, e.g. PLL to make sure that the inverter is synchronized with the grid. This practically adds an outer-loop controller (the synchronization unit) to the inverter controller [15] such as shown in Figure 1.

III. PLL AND SYNCHRONIZATION

The most extensively acknowledged for synchronization procedure in time domain is shown in figure 2. It shows, the difference between input phase angle \( V_{in} \) and the output signal \( \theta \) are measured by the Phase Detection (PD) and passed through the Loop Filter (LF). The output signal of LF triggers the Voltage-Controlled Oscillator (VCO) to generate the output signal, which would monitor the input signal from the inverter voltage.

As known, Synchronous-Frame PLL (SF-PLL) in three-phase systems is effectively synchronized grid-inverter connection due to keep reference voltage locked to utility voltage vector phase angle. In the event of utility voltage is distorted which having high-order harmonics, PLL bandwidth reduction is not satisfactory in the presence of the unbalanced utility voltage [16]. It should be noted that, Synchronous Reference Frame PLL (SRF-PLL) does not provide individual values of the amplitude, phase and frequency rather than average information. On the other hand, this scheme cannot be applied to single phase systems in an up-front manner [17]. Conversely, it affords a beneficial structure for single-phase PLLs as long as the 90 degree shifted orthogonal component of the single phase input signal is created [18]. The instantaneous real and imaginary power theory (PQ-PLL) has the alike arrangement to the conventional SF-PLL [18]. Figure 3 shows the PQ-PLL block diagram.

This PQ-PLL can be easily understood from as a instantaneous power theory concept. The fundamental positive-sequence component is obtained as a by-product. Sometimes, PLL fails in tracking the system voltage during initialization under some opposing conditions, and oscillations is caused by the existence of subharmonics pulls the stable point of operation synchronized to the subharmonic frequency. In order to settle these problems, a robust PQ-PLL is presented to maintain synchronization in presence of subharmonics, harmonics, and negative sequence unbalances [19].

Moreover, Double Synchronous Frame PLL (DSF-PLL) is constructed based on both transformation on the positive and negative sequence components of the utility voltage into the double synchronous frame, which can entirely disregard the detection errors of the conventional SF-PLL [20-21]. On the other hand, Sinusoidal Signal Integrator PLL (SSI-PLL) tracks the utility voltage by extracting the fundamental positive sequence to the SF-PLL [22-23]. Consequently, it operates under voltage distortions as well as imbalances condition. The block diagram of SSI -PLL is shown in figure 4, whereas the constant K regulates the bandwidth and the speed-response of the SSI-PLL.

A sequence detector chooses the sign of \( V\alpha+ \) and \( V\beta+ \). When the voltage sequence at the PCC is recognized in advance, the sequence detector can be abolished. The main advantages of SSI-PLL are invulnerability to the voltage

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**Figure 2. Typical synchronization structure**

**Figure 3. Block diagram of PQ-PLL**

**Figure 4. SSI-PLL block diagram**
distortion and unbalance conditions. In addition, it can be extended into the single-phase system applications with a few modifications successfully. Similar, Double second order generalized integrator (DSOGI-PLL) extracts the fundamental positive sequence to the SF-PLL whereas it operates a double second order generalized integrator to implement the quadrature-signals generator [24]. Therefore, the precise sequence component extraction here requires 90° phase shift for $V_a^+$ and $V_b^+$. There are two solutions for this purpose, the transport delay buffer method and the all pass filter method. Proper mixing Band Pass Filter (BPF) and Low Pass Filter (LPF) remove the harmonics and 90 phase shift by recognizing the angular frequency $\omega$. Figure 5 shows the DSOGI-PLL block diagram. On the other hand, Enhanced PLL (EPLL) is a frequency-adaptive nonlinear synchronization approach [25]. The main progress over the conventional PLL lies in the PD mechanism it permits more flexibility and provides more facts such as amplitude and phase angle.

![Figure 5. DSOGI-PLL block diagram](image)

EPLL also provides higher degree of resistance and insensitivity to noise, harmonics and unbalance of the input signal. Whereas, Three Phase Multi-PLL (3MPLL) adaptively tracks and estimates the magnitude, phase angle, and frequency of the input signal [26]. The operation principle of Quadrature PLL (QPLL) is stated in [27] where this method is based on estimating in-phase and quadrature-phase amplitudes of the fundamental component of the input signal. In advantage, it is applicable for both in distributed generation and communication system applications. In case of wide-range of synchronization, the Predictive PLL (PPLL) comprises of a predictor, oscillator, and phase-shifter and data acquisition blocks [28]. It has phase locking mechanism similar to the conventional PLL while PPLL locks to the phase of input signals, however, it works the systematic expressions for computing the frequency, amplitude and phase difference in a predicted manner [29]. In addition, the synchronize information can be determined within two cycles of the input signal period in the poor condition for example perturbations in frequency, amplitude and phase angle. There are some other PLL have been developed on linear and non-linearity basis as well as adaptability in Adaptive Linear Combiner (ALC) [30], Multi-rate-PLL (MR-PLL) [31], Adaptive PLL (APLL) [32] and more basic zero-crossing detector (ZCD) method for stable and sinusoidal input signal [32].

IV. SYNCHRONVERTER

A synchronverter is an inverter that mimics a conventional synchronous generator. Synchronverters are grid-friendly inverters that mimic synchronous generators (SG) [10]. Mathematically, a synchronverter is a model, which behaves as in same as synchronous machine to deliver a voltage supply. Since, PLLs are characteristically nonlinear, difficult and time-consuming to tune the PLL parameters to reach satisfactory performance while controlling the inverter in power system. It affects not only control performance and degrade system stability but also a complex synchronization unit is often computationally intensive. The controlling principle of a power controller is combined capability of controlling the voltage and frequency parameter. So it is able to achieve real power control, reactive power control, frequency regulation, and voltage regulation. Consider a round rotor machine has stator inductances are constant. The mathematical equations for the generator can be written by assuming there is no damper windings in the rotor, that there is one pair of poles per phase without having any magnetic-saturation effects in the iron core as well as no eddy currents. The phase voltage $v$ of terminal can be obtained below.

$$v = -R_s i - \frac{d\phi}{dt} = -R_s i - L_s \frac{di}{dt} + e$$  \hspace{1cm} (1)

$$e = M_s i_f \frac{\sin \theta}{<\sin \theta>} <\cos \theta>$$  \hspace{1cm} (2)

$$\dot{\theta} = \frac{1}{J} (T_m - T_e - D_i \dot{\theta})$$  \hspace{1cm} (3)

$$T_e = M_s i_f \sin \theta$$  \hspace{1cm} (4)

$$e = 0 M_s i_f \sin \theta$$  \hspace{1cm} (5)

$$Q = -0 M_s i_f <\sin \theta>$$  \hspace{1cm} (6)

Where $T_m$, $T_e$, $e$, $\theta$, and $Q$ are the mechanical torque applied to the rotor, the electromagnetic torque, the three-phase generated voltage, the rotor angle, and the reactive power. Figure 6 shows that Electronic part of synchronverter with controller. Assume that figure 7 is the per-phase model of a synchronous generator is connected to an infinite bus.

![Figure 6. Synchronverter with control](image)
The generated real power $P$ and reactive power $Q$ are expressed.

$$P = \frac{V_E}{X_S} \sin(\theta - \theta_g)$$  \hspace{1cm} (7)

$$Q = \frac{V_E}{X_S} [\cos(\theta - \theta_g) - V_g]$$  \hspace{1cm} (8)

The real power is controlled by a frequency droop control loop. This loop regulates the (imaginary) speed of the synchronous machine and creates the phase angle for the control signal $e$. The reactive power is controlled by a voltage droop control loop using the voltage droop. This loop regulates the field excitation, which is proportional to the amplitude of the voltage generated. Hence, the frequency control, voltage control, real power control, and reactive power control are all integrated in one compact controller with only four parameters. It is appealed in [11] that regulation of reactive power $Q$ flowing out of the synchronverter can be comprehended to frequency response found in few cycle in experimental synchronverter [10]. This operation is tested in grid frequency lower and higher then nominal 50Hz successfully. The voltage droop modes of proposed synchronverter comprises slight overshoots with smooth transition [11]. Some experimental results from the novel synchronverter well found with a PLL is presented in [32].

V. CONCLUSION

An ample analysis of phase locked loop methods and synchronization techniques have been executed to discover a comprehensive viewpoint on their dissimilar and diverse structures and applications. On the design simplicity, frequency adaptive, timing, distortion insensitivity, unbalanced insensitivity and single-phase points of view, it is proved that synchronverter is most prospective solution for grid-inverter synchronization having extensive range of controlling strategy in distributed energy resources as well as all grid-connected applications. In order to simplify the collection of the given requirement, Table I provides brief comparisons as well as guidelines for the proper choice of PLL and synchronization schemes for specific applications.

ACKNOWLEDGMENT

Authors gratefully acknowledge the support of Universiti Tun Hussein Onn Malaysia (UTHM) for UTHM Scholarship funding and RAGS (R037) to undertake this research activity.

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DOI 10.5013/IJSSST.a.17.41.08 8.4 ISSN: 1473-804x online, 1473-8031 print
Table I. Brief Comparisons of Synchronization Schemes for Specific Applications

<table>
<thead>
<tr>
<th>Type of schemes</th>
<th>Design Simplicity</th>
<th>Frequency adaptive &amp; range</th>
<th>Distortion insensitivity</th>
<th>Unbalance insensitivity</th>
<th>Timing</th>
<th>Aptness to Single-phase</th>
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<td>Average</td>
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"TABLE I. BRIEF COMPARISONS OF SYNCHRONIZATION SCHEMES FOR SPECIFIC APPLICATIONS"