A comprehensive review of synchronization methods for grid-connected converters of renewable energy source

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ABSTRACT

Recent interest in the integration of renewable energy sources (RES) into the power grid has raised concerns in synchronization of the various RES. Grid variables such as voltage, phase angle and frequency should be continuously monitored to guarantee correct operation and synchronization of power converters connected to the power grid. Numerous synchronization methods have been presented over the years to address issues such as unbalanced condition and frequency variation. This paper presents a review of past studies on synchronization methods for grid-connected converters together with their control and modeling techniques. Various estimation techniques for phase angle, frequency and harmonic are discussed and examined. Key challenges for a smart and efficient synchronization are briefly overviewed and possible future works are also recommended. A consolidated review is the particular focus of this paper, as is the provision of information on the best method for synchronizing grid-connected converters.

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1. Introduction

Distributed generation (DG) systems based on RES such as wind, solar, and hydro are now popular options to reduce the world’s dependence on fossil-based fuels, which are known to deplete sooner or later [1,2]. As reported in [3], 80% of energy generation in this world depends on fossil fuels, which contribute to global warming. Consumption of fossil fuels is estimated to increase by 1.5% annually until 2030, with 2.2% CO2 emission [4]. Therefore, the use of RES must be prioritized because up to today only 15–20% of energy are from RES even though they are abundant [4,5]. However, many issues and technical challenges remain to be considered for successful integration of RES into the utility grid. One of the most important issue is synchronization of the grid-side converter, where output voltage waveform has to be synchronized with the grid voltage to secure continuous and stable operation [6–10]. The situation becomes more critical when the utility grid is subjected to disturbances and unbalanced faults [11]. During such faults, the grid-side converters are exposed to three severe problems: excessive DC link voltage, high AC current, and loss of grid voltage synchronization [12].

Synchronization can be defined as the minimization of the variances in voltage, phase angle, and frequency between the RES generator output and the grid supply [13,14]. Such synchronization must be achieved before connecting the RES generator into the power grid [13,14]. It allows the grid and the synchronized power converter to work together [15]. According to [16], an ideal synchronization approach must:

- Competently track the phase angle of the utility grid.
- Efficiently detect the frequency variations.
- Efficiently eliminate disturbances and high harmonic components.
- Immediately respond to utility grid changes.

The standards of power quality cannot otherwise be achieved. With high penetration of RES into grid, the different small generators connected to the grid cause power quality problems, as does the unpredictable and time-varying nature of RES (especially wind and solar) [17,18]. Correspondingly, the unbalanced relationship between demand and supply might cause nominal frequency deviation in that system. If the total generation exceeds demand due to the surplus internal power exported to the grid by the RES, the frequency will be increased and vice versa. This frequency deviation may destroy the mechanical system of the rotating machines and cause other related problems that can jeopardize the stability of the power system [19]. Hence, to avoid control difficulties and power outages, the power grid frequency should stay within its permissible limits [20]. Several grid codes (e.g., IEEE Std. 1547, IEEE Std. 1588–2008, IEC Std. 1727, IEEE Std. 929–2000) that indicate the limits for frequency, voltage, harmonics, and power rating have been introduced to address this issue [21]. Frequency tracking and estimation are therefore crucial for synchronizing and protecting the power grid and maintaining its power quality and reliability [22,23]. Other than the grid variables stated above, the detection of possible harmonic components produced by the power converter is gaining more attention nowadays as harmonic components can cause control errors and increase loss in equipment [24–28].

Table 1 lists a variety of grid-connected devices that need to be accurately synchronized with the grid voltage and Fig. 1 illustrates the application of grid synchronization in grid-connected power converter control.

Given the multitude of problems concerning grid synchronization, various estimation methods for phase angle, frequency, and harmonic estimation have been proposed for synchronization of grid-connected converters. Published reviews on synchronization methods exist but the behavior and methodologies have not been discussed in detail. This study will bridge that research gap. Its main objective is to provide a comprehensive review of the existing synchronization methods plus their advantages and shortcomings. Detailed analyses on the application of these methods are presented and their dynamic response is quantified. The findings of this paper should help researchers identify the best technique for their product or application. The paper’s organization is as follows: Section 2 presents the various synchronization methods so far proposed for grid integration; Section 3 presents comparisons and analyses of the methods; Section 4 overviews the key challenges to smart synchronization methods and recommends possible future work; and Section 5 concludes the review.

2. Grid synchronization method

Rapid proliferation of DG in power grid has given rise to the proposal of numerous synchronization methods such as zero crossing detection (ZCD) [31–34], Kalman Filter [35,36], discrete Fourier transform (DFT) [37,38], nonlinear least square (NLS) [39], adaptive notch filtering (ANF) [40–45], artificial intelligence (AI) [46,47], delayed signal cancellation (DSC) [48–53], phase locked loop (PLL) [54–78], and frequency locked loop (FLL) [30,79–82]. These methods can be classified as frequency domain or time domain. In this paper, however, the classification is by application, for either single-phase system or three-phase system. Further classification narrows these down into open-loop and closed-loop systems, as seen in Fig. 2. Open-loop systems directly detect the magnitude, phase, and frequency of the input signal, whereas closed-loop systems adaptively update the detected parameters through a loop mechanism. Over the years, three-phase systems are more popular than single-phase systems because in single-phase systems the tasks of grid fundamental and harmonic

Table 1 Grid-connected devices that need to be synchronized with the grid voltage [29].

<table>
<thead>
<tr>
<th>Group of devices</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Renewable Energy Source (RES)</td>
<td>Photovoltaic power plants, wind power plants, nuclear power plants, etc.</td>
</tr>
<tr>
<td>Flexible AC Transmission Systems (FACTS)</td>
<td>Static Var Compensator (SVC), Static Compensator (STATCOM), Static Series Synchronous Compensator (SSSC), etc.</td>
</tr>
<tr>
<td>Custom Power Systems (CUPS)</td>
<td>Active Power Filter (APF), Uninterruptible Power Supply (UPS), Dynamic Voltage Restorer (DVR), D-STATCOM, etc.</td>
</tr>
<tr>
<td>Loads</td>
<td>AC loads with AC/DC converters, DC loads cooperating with grid-connected converters (AC/DC)</td>
</tr>
</tbody>
</table>
detection are more challenging (only one signal is accessible) [83–87]. Nonetheless, to avoid redundancy, this paper will examine the method itself, not the application.

2.1. Zero-crossing detection

One of the simplest ways to obtain grid information such as phase angle is by detecting the zero-crossing point of the utility voltages. This method was reported in [31–34] as being robust to frequency variations and offering stable performance with only a small amount of distortion. However, during voltage variations such as sags, notches, and harmonics (which are regarded as power quality problems), the zero-crossing point is detectable only every half period of the utility voltage/frequency. This is insufficient detection as the dynamic performance will degrade, being sensitive to transient, noise, and grid voltage distortions as it is. Besides, the method proposed in [34] requires additional hardware, which increases costs, so is not preferred.

2.2. Kalman filter

The Kalman filter is one of the signal processing techniques applied in frequency measurement of power system signals, providing an ideal estimation of the state variables of a given dynamic system [35,83]. An extended complex Kalman filter for estimation of power system frequency and grid phase is presented in [35,36]. This method has been found to be stable and accurate even with noise present. Nonetheless, it has quite a complex structure and needs to cope with the burden of computation, and its performance under other disturbances is not well presented. The drawbacks render this method not very popular among the others.

2.3. Discrete Fourier transform

Another grid synchronization method is DFT, which actually is one of the first approaches to detecting harmonic and frequency [83]. A recursive DFT was used in [37] for power converter line synchronization, to filter the incoming grid voltage. This method offers a high degree of invulnerability to noise, but when the time window of the DFT does not match with the grid period, a phase shift occurs between the incoming grid voltage and the filtered output. A sliding DFT (SDFT) has been proposed in [38] to overcome this limitation. This method which is based on phase detection system has been found to be more efficient than conventional DFT as it requires less operation and simpler implementation to extract a single frequency component. As a result, computational complexity is reduced.
2.4. Nonlinear least-square

An alternative technique for frequency estimation is the least-square-error method where the target is to minimize the square error between the modeled and the measured signal. However, the width of the observation window, the Taylor series truncation, and the choice of sampling frequency influence the performance of this algorithm [83]. For the NLS algorithm, the common problem occurs during the estimation of the harmonic content of the periodic signals. Therefore, a tuned resonator-based filter bank was used in [39] to solve the NLS problem for periodic signal estimation. It is a model-based recursive calculation method that guarantees smaller computational demand, less memory space as compared with matrix-based algorithms, and easy implementation. [88] proposes a new method of estimating grid frequency; it is based on multi-harmonic least-square fitting. This method expands a Taylor’s series derivation to avoid the matrix inversion and recursive version in conventional approach. It estimates frequency well and computes well.

2.5. Adaptive notch filter

A synchronization method of ANF-based algorithm is gaining more attention for its simplicity. A second-order notch filter is used in [40] to update the frequency and two extra integrators replaced the voltage-controlled oscillator (VCO). Instead of a simple structure (no VCO), the modified technique in [40] offers higher immunity to noise compared with other conventional methods. The transient response is also faster than the PLL-based method, but some responses are not so accurate in some conditions. A new adaptive notch filtering approach has been introduced by [41], which is composed of a master ANF and a multiplicity of slave ANF. This approach is not only able to detect phase angle, frequency, and amplitude in frequency variations but also current harmonic, and extract reactive components for power quality purposes.

A modified lattice-based discrete-time ANF is proposed in [42] for a three-phase system. The proposed ANF is composed of simple adders, integrators, and multipliers, making it simple to implement and frequency adaptive. This method is able to track frequency and a voltage variation, extract harmonics, and is also insensitive to grid disturbances, harmonics, and other types of pollution that may exist in the power grid. A frequency estimation technique based on ANF concept for three-phase power signals has been proposed in [43]. It comprises a frequency estimation loop with three parallel subfilters. The performance of the proposed technique has been confirmed by Matlab/Simulink software. This technique can precisely estimate the frequency not only in unbalanced condition but also under frequency and amplitude variation. Other features are its simple structure and lower sensitivity to harmonics.

Whereas [43] applied ANF, [44] modified ANF equation to produce amplitude ANF (AANF). Besides its simple structure, AANF method performs better than ANF method in the former’s filtering characteristics, with its allowance for a wide range of frequency deviations. AANF can also be used to detect symmetrical components, harmonics, active power, and reactive power. The estimation scheme was compared by analysis of four adaptive frequency trackers: ANF, adaptive estimation scheme, multiple frequency tracker, and hyper stable adaptive line enhancer [45]. In some cases, the study shows the convergence of ANF to be a bit slower than the other methods. However, some issues of filtering characteristics and transient response had not been considered for a wide range of frequency deviations.

2.6. Artificial intelligence

Over the past decade, AI tools such as artificial neural network (ANN) and fuzzy logic became more significant and more broadly applied in agriculture, identification, process control, military science, medical diagnostics, automation, etc. Bose in [89] equalized AI to imitating human thinking and leading a new, future era in machine drive, power electronics, and motion control. According to [45], ANN, which tends to mimic the nervous system of a human brain, is very powerful in control applications, owing to its learning aptitude. The use of ANN to observe harmonics in a power system is not a new concept [46,47].

In [46], ANN was applied together with least-square technique to identify the deviations of phase, amplitude, frequency, and harmonics in power systems. Simulation results show that this method has very fast response, high convergence rate, and the capability to handle situations that present incomplete information. A radial-basis-function neural network (RBFNN) which represents a function of interest using family members of locally supported basis function was applied to the performance curve [47]. This feature makes RBFNN more suitable for learning functions with local variations and less sampled data. Instead of a simple structure, this method is reported as needing only half a cycle to detect all the harmonic components without sacrificing its computational efficiency.

2.7. Delayed signal cancellation

DSC is a technique initially used in an unbalanced grid voltage scenario [48]. The components of positive and negative sequences of the grid voltage are separated according to the voltage vector in a stationary (αβ) reference frame and the voltage vector is delayed by a quarter of a cycle [48,49]. Wang and Li suggest a novel grid fundamental and harmonic component estimation technique for a single-phase application in [50]. The technique is based on anti-conjugate decomposition of single-phase signals and cascaded delayed signal cancellation (CDSC) which uses a constant zero as the quadrature signal. Use of this technique enables efficient detection of the grid fundamental and harmonic components with zero steady-state error and very short transients. It is also immune to small variations in frequency.

Several works have tried synchronizing RES in abnormal utility voltage conditions. Some of the weaknesses can be avoided without much effect on power quality. A three-phase CDSC phase-locked loop (CDSC-PLL) proposed in [51] can detect power system harmonic selectively and disregards small grid-frequency deviations. Another useful feature of CDSC-PLL is the capability to eliminate undesired harmonics completely with zero steady-state error and very short transient. Synchronization of RES through variable sampling frequency has been analyzed in [52,53], to investigate the influence of DSC in harmonic estimation and to examine the use of DSC in discrete time domain. Validation by experiment found that both non-ideal sampling frequency and time-varying grid frequency influence DSC performance. Besides, the use of weighted mean average value can reduce the estimated error and the error due to grid frequency variation, which appears the same as the error caused by non-ideal discretization.

![Fig. 3. Basic structure of PLL.](image-url)
2.8. Phase-locked loop

Among the methods presented here, PLL is the most acknowledged, owing to its simplicity, effectiveness, and robustness in various grid conditions. In fact, PLL is an old technology since its concept was published in 1932. It has been used in a vast range of applications such as control systems, communications, instrumentation, and many more [54,55]. It is a nonlinear closed-loop feedback control system which synchronizes its output signal with the reference input signal in frequency and phase [56–59].

As shown in Fig. 3, a basic PLL structure comprises three main blocks, which are phase detector (PD), loop filter (LF) and VCO. First, the PD will compare the two input signals and the error signal will be filtered by LF which is then used to drive the VCO to generate output phase \( \theta_0 \). This process will continue until the phase error \( \Delta \theta \) between the output and the reference phase \( \theta^* \) as defined in (1) reduces to minimum value. Once the error is zero, the output phase will be locked.

\[
\Delta \theta = \theta^* - \theta
\]

Various modifications and enhancements have been made to improve PLL performance in various grid conditions such as synchronous reference frame PLL (SRF-PLL), enhanced PLL (EPLL), fixed-reference frame PLL (FRF-PLL), and variable sampling period filter PLL (VSPF-PLL). The difference among these usually lies in how the PD block is implemented.

2.8.1. Synchronous reference frame PLL

Several studies [58–64] have shown that SRF-PLL is widely used in three-phase grid-connected power converters for its simple implementation and fast and accurate estimation of the phase/frequency in ideal grid conditions (the basic structure of SRF-PLL is illustrated in Fig. 4). However, the three-phase voltage vector in abc natural reference frame need to be transformed to dq rotating reference frame first through Park's transformation [1,58,65] as shown in (2) and (3). Proportional Integrator (PI) is then used to control the q variables and the output of this PI is the grid frequency. The utility phase angle is obtained by integrating this grid frequency which is then fed back into the PD (\( a\beta \rightarrow dq \) transformation).

\[
\begin{bmatrix}
V_a \\
V_b \\
V_c
\end{bmatrix} = \frac{1}{2} \begin{bmatrix}
1 & -1 & -1 \\
-\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} & 0
\end{bmatrix} \begin{bmatrix}
V_a \\
V_b \\
V_c
\end{bmatrix}, \text{where } 
\begin{bmatrix}
V_a = V \sin(\theta) \\
V_b = V \sin(\theta - 120^\circ) \\
V_c = V \sin(\theta + 120^\circ)
\end{bmatrix}
\]

(2)

\[
\begin{bmatrix}
V_d \\
V_q
\end{bmatrix} = \begin{bmatrix}
\cos \theta & \sin \theta \\
-\sin \theta & \cos \theta
\end{bmatrix} \begin{bmatrix}
V_a \\
V_b
\end{bmatrix}
\]

(3)

As mentioned earlier, conventional SRF-PLL allows fast and accurate estimation of phase angle and grid-voltage frequency in ideal condition. Unfortunately, during unbalanced grid voltage, frequency deviation, and in the presence of harmonic, the performance is highly degraded as it is very sensitive to immediate changes of phase angle (it has double frequency errors caused by negative sequence component) [58,60,63,64,79]. Therefore, a decoupled double SRF-PLL (DDSRF-PLL) method is proposed in [66,67], which transforms both the positive and the negative sequence components of the utility voltage into double SRF and develops a decoupling network to extract and separate the components. As can be seen in Fig. 5, the voltage vector is divided into two components: positive \((m)\) and negative \((n)\), rotating in opposite directions. The components then simultaneously filter out \(V^m d\), \(V^m q\), \(V^n d\), \(V^n q\) by using a decoupling cell (DC). Low-pass filters (LPFs) are used to filter the DC component. Even though this method can completely eliminate estimation errors in conventional SRF-PLL, and is precise and robust in unbalanced and...
distorted grid conditions, the estimation process is quite complex and sensitive to the phase-angle jump of the grid voltage. The theoretical basis of DDSRF-PLL with its decoupling network model (Fig. 5) is explained below.

For DDSRF-PLL, an unbalanced input voltage vector can be expressed as:

$$\mathbf{V}_{abc} = \mathbf{V}_{abc}^+ + \mathbf{V}_{abc}^- = \mathbf{V}^+ \begin{bmatrix} \cos(\theta) \\ \cos(\theta - \frac{2\pi}{3}) \\ \cos(\theta + \frac{2\pi}{3}) \end{bmatrix} + \mathbf{V}^- \begin{bmatrix} \cos(\theta) \\ \cos(\theta + \frac{2\pi}{3}) \\ \cos(\theta - \frac{2\pi}{3}) \end{bmatrix}$$

(4)

On aβ stationary reference frame, the voltage vector can be obtained by:

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \begin{bmatrix} 1 & -\frac{1}{2} & \frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \mathbf{V}_{abc}$$

(5)

$$\mathbf{V}_{a\beta} = \mathbf{V}_{a\beta}^+ + \mathbf{V}_{a\beta}^- = \mathbf{V}^+ \begin{bmatrix} \cos \theta \\ \sin \theta \end{bmatrix} + \mathbf{V}^- \begin{bmatrix} \cos \theta \sin \theta \end{bmatrix}$$

(6)

On the dq reference frame, the voltage is found by,

$$\begin{align*}
V_{dq}^+ &= \begin{bmatrix} \cos \theta' & \sin \theta' \\ -\sin \theta' & \cos \theta' \end{bmatrix} \cdot \mathbf{V}_{a\beta} \\
V_{dq}^- &= \begin{bmatrix} \cos \theta' & -\sin \theta' \\ \sin \theta' & \cos \theta' \end{bmatrix} \cdot \mathbf{V}_{a\beta}
\end{align*}$$

(7)

(8)

A modified SRF-PLL (MSRF-PLL) is proposed in [68] where the PLL is replaced with 4th order elliptic filter. Even though it is an application for three-phase systems, this method actually is based on a single-phase SRF-PLL concept derived from Coulou oscillator. The MSRF-PLL is applied to a shunt active power filter PLL which verified its excellent performance in steady-state and transient conditions. For harmonic selectivity, a new phase-estimator known as adaptive lattice SRF-PLL (ALSRF-PLL) is presented in [63]. The development of ALSRF-PLL is based on grid-voltage adaptive filtering. A set of infinite-impulse-response (IIR) notch filters along with gradient-adaptive lattice algorithm is used to remove harmonics selectively. The advantages of this scheme include its capability to reject grid-voltage imbalance and harmonic distortion despite frequency variation. It is also very stable during adaptation process, but its computational burden is larger than conventional SRF-PLL’s. Owing to these drawbacks and other issues, several advanced SRF-PLLs including multiple reference frame PLL (MRF-PLL), dual second-order generalized integrator PLL (DSOGI-PLL), and multiple complex coefficient filter PLL (MCFC-PLL) have been projected by Golestan et al. [58]. A comprehensive design-oriented study of these advanced schemes reveals that all of them give almost identical results in frequency deviation and phase jump. Karimi-Ghartemani [69] analyzed several single-phase SRF-PLLs to understand the connection between them. It shows single-phase SRF-PLL as equivalent to enhanced PLL (EPLL).

2.8.2. Enhanced PLL

EPLL was introduced in [70,71] to track the frequency, magnitude, and phase angle of three-phase-input systems. Its working principle is based on the extraction of the positive sequence component of an input signal through a band-pass filter. This technique provides accurate and smooth detection of the fundamental parameters, with no steady-state error and good transient response. It is also frequency adaptive and robust to harmonics and noise. EPLL is also applied with unified power quality conditioner (UPQC) to control its voltage source converters (VSCs) [72]. When tested in the presence of voltage sag and harmonic on an Electromagnetic Transients DC analysis program, the UPQC was able to extract the reference signals quickly and directly for the supply voltage and the load current.

2.8.3. Quadrature-based PLL

As the name implies, the quadrature-based PLL (QPLL) is based on estimating in-phase and quadrature-phase amplitudes of the input signal [73]. Nonetheless, amplitude and phase angle are not estimated directly but obtained through mathematical calculations. The PD block of conventional PLL is replaced by an alternative mechanism (see Fig. 6) [74] which enables online estimation of the phase-locked fundamental component, the input signal frequency, and the rate of change. Implementation of low-pass filters permits QPLL to operate with acceptable speed and accuracy even in highly polluted conditions while the band-pass filter is used at the input terminal to improve performance. Internal parameters $K_s$ and $K_f$ control its behavior (the speed of convergence of the amplitude and frequency). QPLL offers fast and accurate detection of frequency, performs well in distortions and uncertainties, generates insignificant steady-state error in the estimated frequency, is less sensitive to harmonics, and is insensitive to unbalanced system conditions.

In contrast is the feed-forward action proposed in [75] for conventional QPLL for detection of frequency variation and the phase angle of the positive sequence of a three-phase system. A modified feedback action reduces phase-angle detection error and the low-pass filter attenuates disturbances. All these features guarantee high dynamic performance of this method in tracking frequency variations and locking the desired phase despite the distortions.

2.8.4. Variable sampling period filter PLL

A novel digital synchronization method based on VSPF-PLL and proposed in [7,76] can be used for both single-phase and three-phase systems. The phase information is obtained by sampling the utility voltage and calculating their space vector representation. A sliding-Goertzel-transform filter is applied to this method to
mitigate the disturbances. During amplitude fluctuations and frequency changes, this method is still capable of performing well in locking the phase and frequency (verified by experiment). Unbalanced voltage and harmonics are also eliminated.

2.8.5. Fixed-reference-frame PLL

Most of conventional PLL schemes are based on the assumption of linearization ($\sin x = x$, $x$ is arbitrarily small) where the results are assured only locally and the performance in polluted conditions is poor [77]. A new algorithm to overcome this problem is suggested by Escobar et al. [77]. This method is provided in fixed-reference-frame coordinates while its design and analysis follow the Lyapunov approach, through which the angular frequency is detected for the synchronization process. When tested in unbalanced condition and frequency variation, the approach was observed as able to maintain the correct value of the estimated frequency after a moderately short transient. The estimated phase angle had almost unnoticeable transient and the estimated positive sequence voltage was nearly pure sinusoids. To improve this response, its bandwidth can be reduced but at the cost of degrading the dynamic response of the system.

2.9. Frequency-locked loop

A new grid-synchronization technique for three-phase systems, proposed in [30,81], uses frequency-locked loop (FLL) to estimate the frequency of the input signal (instead of estimating the phase angle as in many classical approaches). A good feature of this technique is that it is not influenced by phase-angle jumps. The method in [30] is based on two adaptive filters implemented by means of a second-order generalized integrator (SOGI) on a stationary $\alpha\beta$ reference frame that can self-tune to the grid frequency. This technique is known as dual SOGI PLL (DSOGI-FLL) and is capable of estimating the phase and magnitude of symmetrical components precisely even in the presence of voltage sag. It is also capable of estimating the phase and magnitude of symmetrical components at harmonic frequencies. This method uses a harmonic decoupling network that consists of multiple SOGI and filters implemented by experiment). Unbalanced condition and frequency variation, the approach was observed as able to maintain the correct value of the estimated frequency after a moderately short transient. The estimated phase angle had almost unnoticeable transient and the estimated positive sequence voltage was nearly pure sinusoids. To improve this response, its bandwidth can be reduced but at the cost of degrading the dynamic response of the system.

On the other hand, the DSOGI-FLL proposed in [79] can be used not only in synchronization but also to control the disconnection, reconnection, and resynchronization of the microgrid. It is implemented in the $\alpha\beta$ stationary reference frame with an intelligent connection agent competent in handling balanced and unbalanced conditions. It also has less influence in the transient condition of the phase jump.

A multiresonant frequency adaptive synchronization method for both single-phase and three-phase system as introduced in [81,82] can also detect the positive-sequence and negative-sequence components at fundamental frequency and other sequence components at harmonic frequencies. This method uses a harmonic decoupling network that consists of multiple SOGI and PLL, hence the name MSOGI-PLL. In extremely polluted conditions, MSOGI-PLL permits accurate, low-computational-burden detection of symmetrical components of harmonics. It can also easily be programmed into low-cost digital signal processing (DSP) platforms.

3. Features comparison of the methods

Three approaches to synchronization have been categorized in [90]: (i) active synchronization, (ii) passive synchronization, and (iii) open-transition transfer. Table 2 summarizes them with their applications. Among them, passive synchronization is the simplest approach; it does not require a special control mechanism or temporary interruptions to the load. However, there is still a lack

<table>
<thead>
<tr>
<th>Synchronization approach</th>
<th>Complexities and power reliability</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active</td>
<td>• Inbuilt control mechanism is used to match the voltage, frequency, and phase angle of the island system to the grid. • Involves complex controlling techniques.</td>
<td>Mostly applied for inverter-based systems, but can be applied in hybrid systems.</td>
</tr>
<tr>
<td>Passive</td>
<td>• Maintain the power reliability.</td>
<td>Depends on the techniques lower capital cost compared to active synchronization methods.</td>
</tr>
<tr>
<td>Open-Transition Transfer</td>
<td>• Do not require special control mechanism or temporary loads interruption.</td>
<td>For synchronous generator based systems having different types of generation.</td>
</tr>
</tbody>
</table>

Table 2: Summary of synchronization category and their applications [90].
<table>
<thead>
<tr>
<th>Grid-connected synchronization method</th>
<th>Single phase</th>
<th>Three phase</th>
<th>Harmonic detection</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
</table>
| Zero crossing detection             | √           | √           | x                  | Simplest implementation [1,31–34]  
Robust under frequency variations [31–34]  
Accurate under frequency variations [91] | Poor performance under grid voltage variation such as harmonics or notches [1]  
Sensitive to transient and noise [21–34]  
Difficulty in covariance selection [91]  
Computational burden [91] |
| Kalman filter                       | √           | √           | x                  | Accurate under frequency variations [91]  
Robust under frequency variations [31–36]  
Sensitive to transient and noise [31–36] | Not able to cope with unbalanced conditions [71]  
Produce phase shift when the DFT sampling is asynchronous with power grid [37–91] |
| Discrete Fourier transform          | x           | √           | √                  | Stable and accurate even in the presence of noise [35,36]  
Suitable for very distorted environments that require good filtering characteristics [91]  
Noise immunity [37] | Long transient time intervals in detecting frequency changes [71]  
The adaptation process is inevitably slow [50] |
| Nonlinear least-square              | √           | x           | x                  | Easy to implement [39]  
Low computational burden [39] | Neural network complexity is proportional with harmonic component [46]  
Insensitive to small frequency variations [50] |
| Adaptive notch filter               | √           | √           | √                  | Simple implementation [40]  
Transient response is faster than PLL-based [40]  
Can also detect symmetrical components, harmonics, active power and reactive power [41,44]  
High computational speed [46]  
High convergence rate [46] | Neural network complexity is proportional with harmonic component [46] |
| Artificial intelligence             | √           | √           | √                  | Stable [50]  
High computational speed [46] | Insensitive to small frequency variations [50] |
| Delayed signal cancellation         | √           | √           | √                  | Simple implementation [86]  
Accurate synchronization [92] | Might have negative impact on the performance of VSC-HVDC in weak ac system [92]  
During unsymmetrical voltage faults, 2nd harmonic produced by negative sequence will propagate through PLL system and will be reflected in the \( \theta^* \) [1]  
Introduce double frequency oscillation to the phase error signal [11] |
| Phase-locked loop                   | √           | √           | √                  | Most sophisticated and reliable under frequency variations, voltage unbalance and harmonics [93] | High computational burden [93] |
| Frequency-locked Loop               | x           | √           | √                  | Better rejection of grid harmonics & notches [1] | Neuro network complexity is proportional with harmonic component [46]  
Insensitive to small frequency variations [50] |
of reports or studies on the limits of this approach in a real microgrid (which may experience poor voltage and frequency control) [90].

In general, grid synchronization methods depend on their performance in unbalanced condition, disturbance invulnerability, phase angle and frequency adaptivity, noise immunity, and detection accuracy. Structural simplicity and computational burden are also important criteria for grid synchronization. For ease of reading, the features of each synchronization method presented in the past section are listed in Table 3 including their advantages and disadvantages.

4. Key challenges and future recommendations

Synchronization is a key issue to grid-connected converters in enhancing their capability during interrupted operation in abnormal utility voltage conditions. In spite of the economics and governmental support for fast integration of RES, there are still several designs and technological challenges to be overcome for a smart synchronization method. Some of the key challenges and problems are summarized below [9,25,85–87,92,94–98].

- In most of the grid synchronization methods discussed in this paper, detection of the phase angle and frequency is done in the same loop in PLL. This causes spurious frequency transients when there is a change in the phase angle. This transient will reflect back on the phase variable and can delay the estimation and synchronization processes. The same is possible during the startup operation of the PLL if the initial phase angle of the input signals is far from the initial phase angle of the PLL integrator. Therefore, efficient methods for detection of phase angle and frequency variation, with good dynamic performance during voltage depression and harmonics, need to be developed.

- Grid frequency variable is known to be firmer than voltage phase angle in the course of transient faults. However, most of the synchronization schemes presented so far is still based on estimating the input signal phase whereas the dynamic response during transients is very sensitive to phase-angle jumps. A synchronization scheme based on estimation of the grid voltage and frequency should therefore be given more attention in future studies.

- In general, there is still a lack of reports or studies on the use of artificial intelligence in the synchronization of grid-connected power converters. Correspondingly, a study can be initiated for a hybrid of this method with other conventional methods and an evaluation of its performance in grid fundamental estimation.

- The methods proposed to date can detect grid variables, tolerate the tradeoff between tracking ability and noise reduction, and identify system disturbance. However, they still lack in triggering the corrective procedures automatically to maintain power quality. A robust method with advanced features such as expert systems has been identified as efficiently injecting power into the grid, with low total harmonic distortion (THD) of the current.

- From the synchronizing methods listed above, the biggest concern is how to achieve uninterrupted operation of the RES in abnormal utility voltage conditions. None of the phase-tracking methods presented so far can meet the grid code requirement regarding THD, especially in low power flows. The upcoming reality of smart grids will require an intelligent technique for fast and effective synchronization of the desired positive/negative sequences, fundamental variables and harmonic voltage components for the controller. With such techniques, total demand distortion (TDD) can also be used in medium-/low-voltage grids to enhance power quality and fulfill the grid code.

5. Conclusion

This paper has comprehensively reviewed state-of-the-art grid-synchronization methods and classified a wide assortment of publications on them. The advantages and disadvantages of the detection techniques for phase angle, frequency, and harmonic component in grid-connected converters have been analyzed and discussed in Section 2. From literatures, some new methods are found to perform better than classical PLL yet PLL is still well-accepted for its simplicity. Therefore, many modifications to PLL have been made to enhance and improve its performance during a weak grid. From the comprehensive review tabulated in Section 3, the synchronization performance of grid-connected converters can be concluded as quantifiable into aspects such as RES penetration, connecting time, converting characteristics, weather conditions, and control and modeling techniques. Hybrid and intelligent techniques for effective and robust grid synchronization especially in adverse grid conditions deserve more attention in possible future works, as summarized in Section 4.

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