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Synchronization in Single-Phase Grid-Connected Photovoltaic Systems under Grid Faults

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***Abstract*—The highly increasing penetration of single-phase photovoltaic (PV) systems pushes the grid requirements related to the integration of PV power systems to be updated. These upcoming regulations are expected to direct the grid-connected renewable generators to support the grid operation and stability both under grid faulty conditions and under normal operations. Grid synchronization techniques play an important role in the control of single-phase systems in order to fulfill these demands. Thus, it is necessary to evaluate the behaviors of grid synchronization methods in single phase systems under grid faults. The focus of this paper is put on the benchmarking of synchronization techniques, mainly about phase locked loop (PLL) based methods, in single-phase PV power systems operating under grid faults. Some faulty mode cases are studied at the end of this paper in order to compare these methods. It is concluded that the Enhanced PLL (EPLL) and the Second Order Generalized Integrator based PLL (SOGI-OSG PLL) technique are the most promising candidates for future single-phase PV systems due to their fast adaptive-filtering characteristics.**

I. INTRODUCTION

Recently, the matured PV technology and the declined price of PV panels make more and more PV generation systems connected to the medium-voltage or high-voltage networks. However, the grid-connected PV generation units might cause severely negative impacts on the whole systems, because they cannot act like the conventional power plants composed of conventional synchronous generators. Thus, many grid requirements have been released in order to regulate interconnected renewable power generation [1]–[5].

Some basic requirements are defined in the grid regulations, like power quality, frequency stability and voltage stability, and some specific demands for wind power systems have also been issued [3]. Nowadays, the high penetration of grid connected single-phase PV systems really raises the concern about PV integration of low-voltage power systems [6], [7]. Therefore, reasonably technical requirements are in an urgent need to be put forward. Like the grid requirements for wind turbines, it is expected that the future grid-connected single-phase PV systems can not only maintain the stability and quality of the grid, but also have some ancillary functions, such as reactive power support and fault ride through (FRT) capability [8]. In that case, the grid monitoring and synchronization techniques and the control strategies should be ready for single-phase PV applications. Many papers discuss the monitoring and synchronization for three-phase systems. Synchronization in single phase PV systems should also be investigated in details.

The phase locked loop (PLL) based synchronization takes much more attention. Nowadays, there are mainly four different PLL-based synchronization techniques reported in the literature [3], [5], [9]–[13]. Among these PLL methods, the adaptive mechanism based synchronization techniques gain more attention because of their high robustness and fast response. This kind of PLL method may be the best one for single-phase PV systems operating in faulty modes. However, it will also cause undesired influences, like frequency swings as discussed in [14].

The intent of this paper is to benchmark and find the best synchronization candidate for single-phase grid-connected PV systems under grid faults defined by the basic grid codes of wind turbine generations, which are expected to be used in the future. Firstly, an overview of selected grid requirements is presented. Special focus will be moved to the synchronization methods, which are crucial for the single-phase PV systems to ride-through utility faults or operate under abnormal grid conditions in compliance with the existing grid requirements applied for medium and/or high-voltage networks. Finally, fault cases are examined and simulated in MATLAB/Simulink using PLECS toolbox to give a comparison of existing PLL-based synchronization methods.

II. OVERVIEW OF SELECTED GRID CODES

The grid requirements are essential for the design and control of grid-connected PV inverters. It is suggested in some international regulations that PV inverters should disconnect from the utility grid in the presence of abnormal grid conditions in terms of voltage and frequency at the point of common coupling (PCC). For instance, it is recommended in IEEE Standard 1547 that the low-voltage systems should cease to energize when the grid voltage is lower than 0.85 p.u. or higher than 1.1 p.u..

Considering the impacts of large-scale PV systems on the low-, medium- or high-voltage networks to which they are connected, these grid requirements are supposed to be revised or extended, or some combined various standardized features as well as custom requirements should be put forward in the future. Several European countries have done this for distributed energy resources, especially wind turbine power systems, connected to medium- or high-voltage networks. It can be foreseen that these regulations will be recommended extending to large-scale low-voltage PV systems.

The German grid code is taken as an example because of the high percentage of distributed power systems in Germany. One specification in the German grid code is that the distributed power systems connected to and operated in parallel with the medium- or high-voltage networks should have the capability of fault ride through when the grid faults occur in the network [2], [6]. This requirement can be described in detail as the ability of

1) remaining transiently stable and connected to the power grid without tripping under voltage sags or swells in a specified time,
2) supporting the utility grid by injecting reactive current in order to avoid grid collapse, and
3) supplying active power to the system immediately after a fault clearance.

The typical low voltage ride-through curves of a defined stay-connected time are presented in Fig. 1. The required reactive current to support the voltage in case of grid faults in the German grid regulation is shown in Fig. 2. As it is noticed in these figures, the generation systems defined in the German grid code should be capable of riding through 0.15 seconds when the grid voltage amplitude presents a drop to 0 and reject some amount of reactive current into the grid.

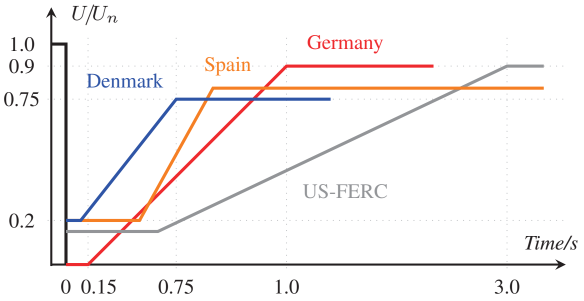

Fig. 1. Low voltage ride-through requirements of wind power systems of different countries [1].

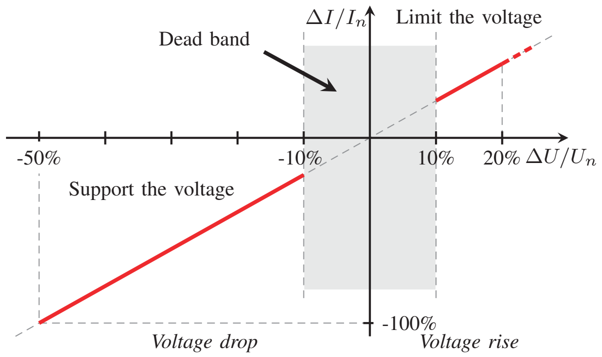

Fig. 2. Voltage support requirements in the event of grid faults [2].

Like wind turbine power generations connected to the medium- and high voltage levels, single-phase PV generation systems supplying low-voltage networks in the future will have to make a contribution to network support due to the much higher penetration of PV generation systems connected to low-voltage grids. In order to fulfill these stringent goals, it is necessary to evaluate the grid synchronization techniques which play an essential role in single-phase PV systems operating under grid faults.

III. GRID SYNCHRONIZATION TECHNIQUES

As aforementioned, the grid synchronization is very important in single-phase PV systems. Fig. 3 presents a typical control structure of such a system, including maximum power point tracking (MPPT), grid condition detection and synchronization system, which is highlighted in light red.

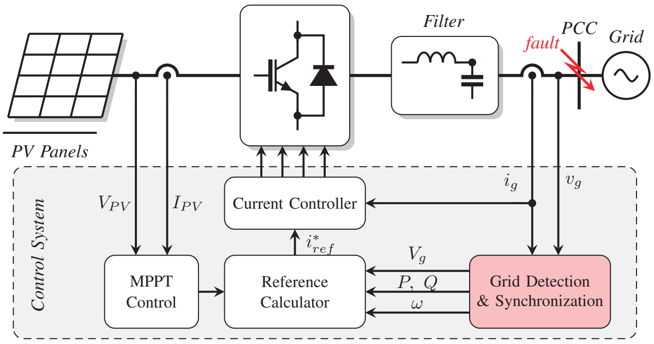

Fig. 3. Overall control structure of a single-phase grid-connected photovoltaic system.

If a phase-to-ground fault occurs at PCC, as shown in Fig. 3, there will be a voltage drop at that point and the detection and synchronization system should respond to this abnormal condition immediately for safety. Thus, there must be a fast and accurate synchronization mechanism incorporated in the control systems in order to generate correct reference signals to ride through the voltage drop within a defined time shown in Fig. 1.

There are many synchronization methods reported in recent literature [3], [5], [9]–[13]. Typically, the synchronization methods can be divided into two category- mathematical analysis methods (synchronization based on Fourier analysis) and PLL-based methods. Among them, the adaptive filtering based PLL techniques gain much more attractiveness.

A basic PLL structure is given as Fig. 4, which consists of a phase detector (PD), a loop filter (LF) and a voltage-controlled oscillator (VCO). Actually, if a first order low-pass filter is used as the loop filter, the small signal model of a single phase PLL will typically be a second order system, which is described as (1). The details of the PLL modeling can be found in [3].

$$\begin{aligned}\frac{\Theta_o(s)}{\Theta_i(s)} &= \frac{K_1K_2G_{lf}(s)}{s+K_1K_2G_{lf}(s)}\\ &= \frac{K_1K_2K_ps+K_1K_2K_i}{s^2+K_1K_2K_ps+K_1K_2K_i},\end{aligned} \tag{1}$$

where Θ_o, Θ_i are the output and input phase respectively,
K_1, K_2 are the gains of PD and VCO respectively,
$G_{lf}(s) = K_p + K_i/s$, is the LF transfer function,
K_p, K_i are the proportional and integral gains of LF.

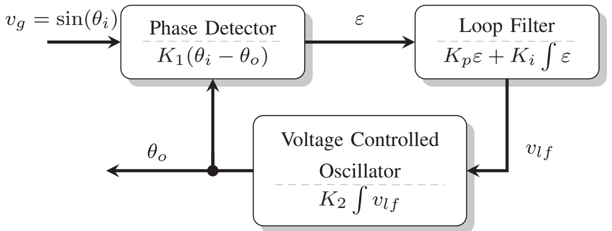

Fig. 4. Basic structure of a phase locked loop.

From (1), the damping ratio and the undamped natural frequency can be given by,

$$\zeta = \frac{1}{2}\frac{K_p}{\sqrt{K_i}}, \ \omega_n = \sqrt{K_i},$$

when $K_1 = K_2 = 1$. The settling time can be obtained subsequently,

$$t_s = \frac{4.6}{\zeta\omega_n}.$$

It should be noted that the main difference among various single-phase PLL techniques is the configuration of the phase detector, and intuitively, a sinusoidal multiplier is adopted to detect the phase error [11], [12]. One solution is to use an Orthogonal Signal Generator (OSG) to create an "$\alpha\beta$" system and then the Park transform can be utilized to extract the phase error. Hence, the task will be shifted to build an OSG system. Another possibility of phase detection is to use adaptive filters which can self-adjust the output according to an error feedback loop.

In the following subsections, four typical single-phase PLL solutions will be described thoroughly, including T/4 Delay PLL, PLL based on Inverse Park Transform (IPT-PLL), Enhanced PLL (EPLL) and the Second Order Generalized Integrator based PLL (SOGI-OSG). The former two methods are trying to build a "dq" system by incorporating an OSG system, while EPLL and SOGI-OSG methods are based on the combinations of adaptive filters with a sinusoidal multiplier and an OSG system, respectively.

A. T/4 Delay PLL

Considering an ideal sinusoidal signal, $v_i = V_m \sin(\theta) = V_m \sin(\omega t + \phi)$, where V_m, θ, ω and ϕ are the amplitude, angle, frequency and phase angle of the input signal, it can be taken as the "α" component of "$\alpha\beta$" system, the "β" component can be obtained simply by introducing a phase shift of $\pi/2$ rad with respect to the fundamental frequency of the input voltage. Thus the Park Transform ($\alpha\beta \to dq$) can be used in this system to detect the phase error, which is expressed as the following,

$$\begin{aligned}\begin{bmatrix} v_d \\ v_q \end{bmatrix} &= \begin{bmatrix} \cos\hat{\theta} & \sin\hat{\theta} \\ -\sin\hat{\theta} & \cos\hat{\theta} \end{bmatrix} \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} \\ &= \begin{bmatrix} V_m \sin(\Delta\theta) \\ -V_m \cos(\Delta\theta) \end{bmatrix}, \end{aligned} \tag{2}$$

where $\Delta\theta = \theta - \hat{\theta}$ is the detected phase error, and $\hat{\theta}$ is the locked phase angle. Actually, the error $\Delta\theta$ is very small in steady state, and then we have the linearized equations,

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} \approx \begin{bmatrix} V_m\Delta\theta \\ -V_m \end{bmatrix}. \tag{3}$$

From (3), it is known that v_d can be controlled to be equal to zero using PI controller, and then the phase of the input signal is locked. This kind of PLL method is called T/4 Delay PLL, where T is the fundamental period of input signal. The structure of T/4 Delay PLL is given in Fig. 5, in which the gains of PD and VCO are equal to 1 ($K_1 = K_2 = 1$).

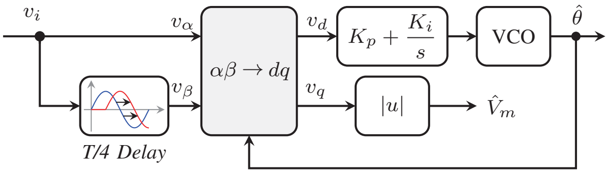

Fig. 5. Structure of T/4 Delay PLL.

The T/4 Delay PLL is the easiest one that can be used to extract the phase angle in single phase applications. However, due to the dependence of the input signal period, this kind of PLL technique is not suitable for single-phase systems subjected to voltage sags or frequency variations. In order words, the frequency variation is a challenge to the robustness of T/4 Delay PLL technique.

B. PLL Based on Inverse Park Transform

The Inverse Park Transform ($dq \to \alpha\beta$) can be used to generate the "β" component in order to build an OSG systems, as it is shown in Fig. 6, where the input voltage is chosen as the "α" component.

According to the IPT-PLL structure (Fig. 6), the OSG mechanism can be described by the following set of equations:

$$\begin{cases} \boldsymbol{v}_{dq}(s) = \begin{bmatrix} v_d(s) \\ v_q(s) \end{bmatrix} = \boldsymbol{T}_p \begin{bmatrix} v_i(s) \\ v'_\beta(s) \end{bmatrix} \\ \boldsymbol{v}'_{\alpha\beta}(s) = \begin{bmatrix} v'_\alpha(s) \\ v'_\beta(s) \end{bmatrix} = \boldsymbol{T}_p^{-1} \begin{bmatrix} v'_d(s) \\ v'_q(s) \end{bmatrix} \\ \begin{bmatrix} v'_d(s) \\ v'_q(s) \end{bmatrix} = G_L(s) \begin{bmatrix} v_d(s) \\ v_q(s) \end{bmatrix} = \dfrac{\omega_L}{s + \omega_L} \begin{bmatrix} v_d(s) \\ v_q(s) \end{bmatrix} \end{cases} \tag{4}$$

where $\boldsymbol{T}_p$ is the Park transformation matrix in *Laplace* domain, $G_L(s)$ is the low pass filter transfer function and ω_L is the cutoff frequency.

It seems that the inverse Park transform based PLL is a good candidate for single-phase applications because it is easy to implement with only two additional low-pass filters compared

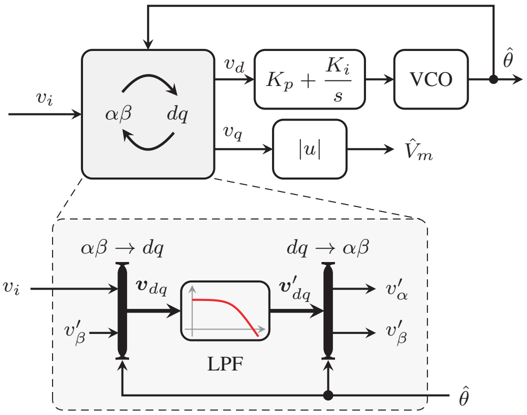

Fig. 6. Inverse Park transform based PLL.

to conventional PLL methods. However, the incorporated LPFs in this PLL solution must be adequately tuned in order to guarantee the performance. For example, the nonlinear inner loop which is used to generate the "β" component must be fast enough to achieve this goal [13], [15].

C. Enhanced PLL

The Enhanced PLL (EPLL) introduced in [14], [16] is a kind of PLL based on a simple adaptive filter (AF), which can refine the transfer function according to a feedback algorithm driven by an error signal. The general configuration of an EPLL is demonstrated in Fig. 7, where v_i is the input voltage as defined previously, $\hat{v}_i$ is the output of adaptive filter or the desired locked signal, and $F(\cdot)$ is the adaptive feedback algorithm. As it can be seen, the EPLL PD system consists of an adaptive filter and a multiplier in such a way that it can enhance the capability with information about the amplitude of the input signal to extract phase error.

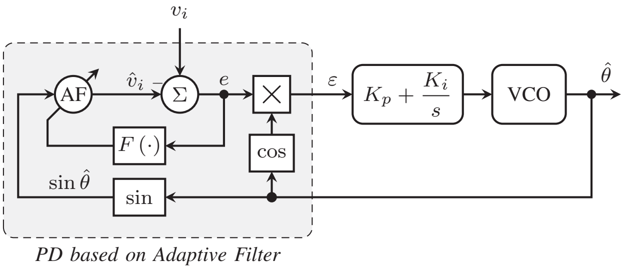

Fig. 7. General structure of an enhanced PLL with an adaptive filter.

Here, the objective of enhanced PLL is to track the input voltage in terms of amplitude V_m and phase angle θ. Using conventional PLL method to regulate phase error ε, the phase angle θ can be locked easily. Thus, the task of adaptive filter is to estimate the amplitude according to the error signal e and the locked phase $\hat{\theta}$ as shown in Fig. 7, which means that the adaptive algorithm $F(\cdot)$ is a function of the error signal and the locked phase.

Assuming the PI controller is tuned well and the phase angle is locked, in this case, the adaptive process is to modify the filter parameters in order to minimize a so-called objective function in this way that the amplitude is estimated. Define the objective function as,

$$E(\hat{V}_m, \hat{\theta}) = \frac{1}{2}e^2 = \frac{1}{2}(v_i - \hat{v}_i)^2, \tag{5}$$

where $\hat{V}_m$ is the estimated amplitude of input voltage. Then, the desired output of the filter can be expressed as $\hat{v}_i = \hat{V}_m \sin\hat{\theta}$, and the filter parameters are updated by iterating,

$$\hat{V}_m(k+1) = \hat{V}_m(k) + \Delta\hat{V}_m(k), \tag{6}$$

in which k is the iterating number and the correction term $\Delta\hat{V}_m(k)$ is supposed to minimize the quadratic approximation of the objective function [17].

Several optimization methods can be adopted to minimize the objective function [17]. Here, the popular least-mean-square (LMS) adaptive algorithm is used. Then the correction term $\Delta\hat{V}_m(k)$ can be expressed as,

$$\Delta\hat{V}_m(k) = -\mu\frac{\partial E}{\partial\hat{V}_m} = \mu e(k)\sin(\hat{\theta}(k)), \tag{7}$$

where μ is the control parameter.

Based on (6) and (7), the following differential equation is obtained [14],

$$\dot{\hat{V}}_m = \frac{\mu}{T_s}e\sin\hat{\theta} = k_a e\sin\hat{\theta}. \tag{8}$$

in which T_s is the sampling period and k_a is defined as μ/T_s. Subsequently, the continuous-time implementation of Enhanced PLL can be given as it is shown in Fig. 8.

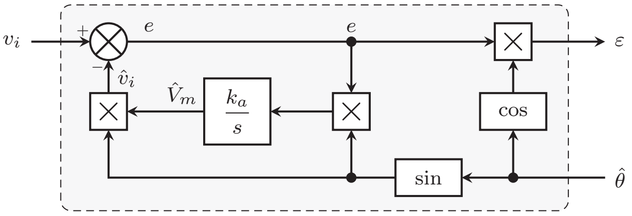

Fig. 8. Adaptive filter based PD structure of an enhanced PLL.

One important feature of EPLL concluded from the above discussion is that the output signal $\hat{v}_i$ is locked both in phase and in amplitude compared to the conventional PLL methods [16]. However,it should be noted that the performance, such as the stability and the speed of the estimation process, is exclusively dependent on the control parameter k_a. By linearizing (8), this relationship can be described as [16],

$$\frac{\hat{V}_m(s)}{V_m(s)} = \frac{1}{\tau s + 1}, \tag{9}$$

where $\tau = 2/k_a$ is the time constant. The response of such an adaptive filter in the EPLL system with different time constants is shown in Fig. 9.

It is noticed in Fig. 9 that a large value of k will make the estimated output signal coming to steady-state quickly.

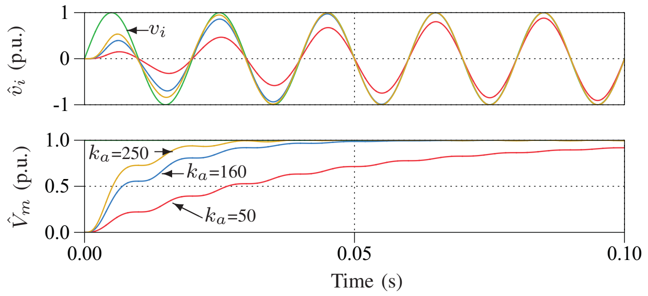

Fig. 9. Response of the adaptive filter of an EPLL with different k_a (different time constants, τ).

Approximately, the settling time of this system can be calculated as: $4\tau = 8/k_a$. For instance, if $k_a = 160$, the estimated amplitude will be settled to 98% of the input voltage in 50 ms.

D. Second Order Generalized Integrator based PLL

Another adaptive filtering based PLL solution is using second order generalized integrator (SOGI) to create the OSG system, commonly known as SOGI-OSG PLL [3], [18], [19]. The general structure of SOGI-OSG PLL is depicted in Fig. 10, in which ω_0 is the nominal frequency of input voltage and k_e is the control parameter.

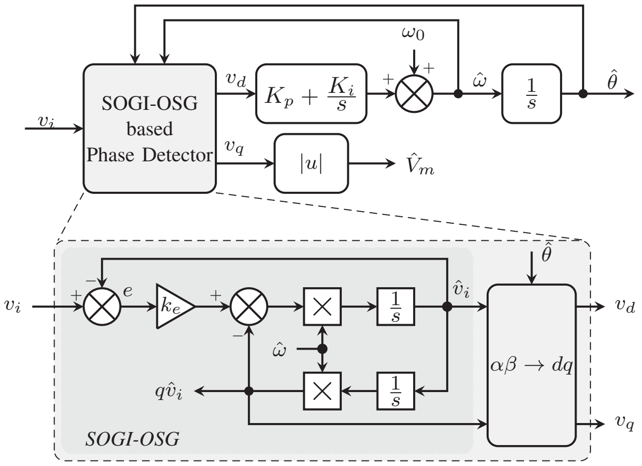

Fig. 10. Second order generalized integrator based PLL.

Actually, the EPLL discussed above is using only one-weight adaptive filter, which is the simplest one. If two-weight adaptive filters are adopted in single-phase applications, it will present a better performance and it behaves like a “sinusoidal integrator” [3], [18], [20]. The transfer function of such a kind of adaptive filter can be expressed as,

$$G_{AF}(s) = \frac{s}{s^2 + \hat{\omega}^2}. \tag{10}$$

Multiplied by $\hat{\omega}$, it shares the transfer function of a second-order generalized integrator in common [18], [21].

Thus, referring to Fig. 10, the closed loop transfer functions of the SOGI-OSG PLL can be obtained as,

$$\begin{cases} \dfrac{\hat{v}_i(s)}{v_i(s)} = \dfrac{k_e\hat{\omega}s}{s^2 + k_e\hat{\omega}s + \hat{\omega}^2}, \\ \dfrac{q\hat{v}_i(s)}{v_i(s)} = \dfrac{k_e\hat{\omega}^2}{s^2 + k_e\hat{\omega}s + \hat{\omega}^2}. \end{cases} \tag{11}$$

In order to evaluate the performance of SOGI-OSG PLL, approximately, the settling time can be given as,

$$t_s = \frac{9.2}{k_e\hat{\omega}}.$$

In the above definitions, $\hat{\omega}$ is the locked angular frequency of input voltage. The detailed derivation of these transfer functions can be found in [3] and [18].

IV. COMPARISON OF THE PLLS

For the comparison of above synchronization solutions, a faulty grid case of 0.85 p.u. voltage sag is studied and simulated in PLECS with the parameters shown in TABLE I. The results are shown in Fig. 11.

TABLE I
SIMULATION PARAMETERS

Nominal Voltage Amplitude	$V_m = 220\sqrt{2}\ V$
Nominal Voltage Frequency	$\omega_0 = 100\pi\ rad/s$
PI Controller for all PPLs	$K_p = 0.3,\ K_i = 13.6$
Cutoff Frequency	$\omega_L = 100\sqrt{2}\pi\ rad/s$
Control Parameters	$k_a = 160,\ k_e = \sqrt{2}$

As it can be seen in Fig. 11, the performances of these PLL methods are not good enough in the presence of a voltage sag. The T/4 Delay method has a better performance and can follow the amplitude change quickly. However, as aforementioned, this method can not be a good monitoring and synchronization technique used in single-phase systems because its performance is dependent on the fundamental frequency.

As for EPLL, the attractiveness is that it can estimate both the amplitude and the frequency of the input voltage without double the input frequency oscillations when it is compared to the conventional PLL using multiplier as the phase detector. Nevertheless, this kind of PLL method presents a slow transient variation, which demonstrates how the adaptive filter minimizes the objective function.

The inverse Park transform based PLL and SOGI-OSG PLL can track the input voltage with better performance compared to T/4 Delay PLL and EPLL. It is concluded that the IPT-PLL method and the SOGI-OSG method could be the best candidates for single-phase applications. An interesting conclusion which is also evidenced in Fig. 11(c) is that the transient behavior of the IPT-PLL method is very similar to that of the PLL based on SOGI-OSG. In fact, if a first-order low-pass filter is used in the IPT-PLL structure to attenuate the oscillations in v_d (and v_q) component resulting from the

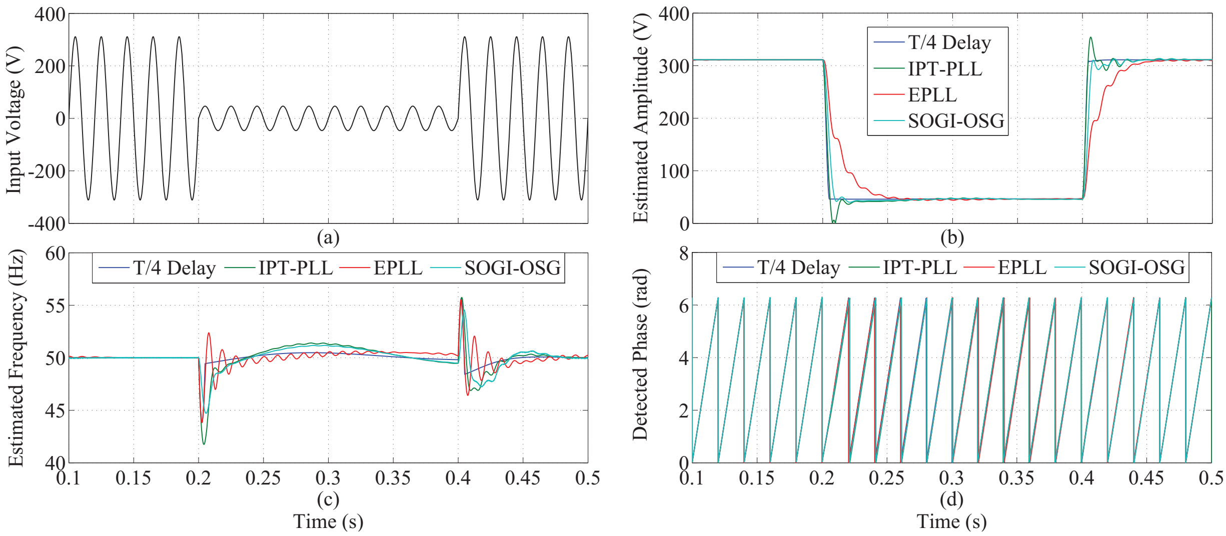

Fig. 11. Comparisons of selected PLL methods in case of a voltage sag (0.85 p.u.): (a) input voltage; (b) estimated amplitude of input signal; (c) estimated frequency of input signal; (d) detected phase of input voltage.

direct Park transform, this kind of PLL structure performs like an adaptive filter [3].

V. SYSTEM RIDE-THROUGH OPERATION

A simple case study of single-phase system is examined by simulation under a voltage sag. This system consists of a DC voltage source, a boost DC-DC converter and a single-phase full bridge inverter. This simulation is designed for further analysis and control of single-phase applications under grid faults in compliance with some grid codes. A repetitive controller is used and the SOGI-OSG PLL is adopted in this case. The simulation results of this case are shown in Fig. 12.

In this examination, a phase to ground fault is evaluated with a voltage profile shown in Fig. 12(a). It is seen that at t=0.7s, the system is controlled to limit the active power output, and thus the current drops, as shown in Fig. 12(d). In the meantime, the single-phase system starts to provide reactive power in order to support the grid, which is shown in Fig. 12(f). When the voltage recovers to 0.8 p.u. at t=1.15s, the system increases the active power output to 80% capacity of its rated power. Still, reactive power is injected into the utility grid until the grid voltage recovers to 0.9 p.u. at t=1.3s or the fault is completely cleared, and the current and active power output goes back to normal values, as depicted in Fig. 12(d) and (e).

This simulation is intended to give a basic demonstration about single-phase systems in faulty mode operations. Practically, a single-phase PV systems can operate under voltage sags, and the active power could be controlled by regulating the maximum power point. Moreover, the basic concept of the frequency and voltage droop control through active and reactive powers, respectively, could be adopted to adjust the active and reactive powers as reported in [22].

Anyway, regarding single-phase PV systems with LVRT functionalities, the control methods, together with detection and synchronization units, should be capable to provide appropriate references without exceeding DC nominal voltage, tripping the current protection due to low voltage with constant active power operation and failing to synchronize in compliance with the upcoming grid codes.

VI. CONCLUSION

This paper presents the future requirements for single-phase grid-connected PV systems under grid faults. It can be concluded that the future grid-connected PV systems will be more active and more “smart”, which means the future grid-connected PV systems should have some ancillary functionalities as the conventional power plants do in presence of an abnormal grid condition. Thus this paper discussed one essential part of the control of such a “smart” PV system-monitoring and synchronization.

Selected monitoring and synchronization techniques are compared in MATLAB using PLECS toolbox in case of grid faulty conditions. The comparison demonstrates that the SOGI-OSG based PLL technique might be the promising candidate for single-phase systems under grid faults. Furthermore, another adaptive filtering based PLL (EPLL) also presented a good performance under a voltage sag, but the parameters should be tuned well to avoid transient variations. A simple simulation case is studied at the end of this paper in order to give a better understanding of the overall system performance under grid faulty conditions.

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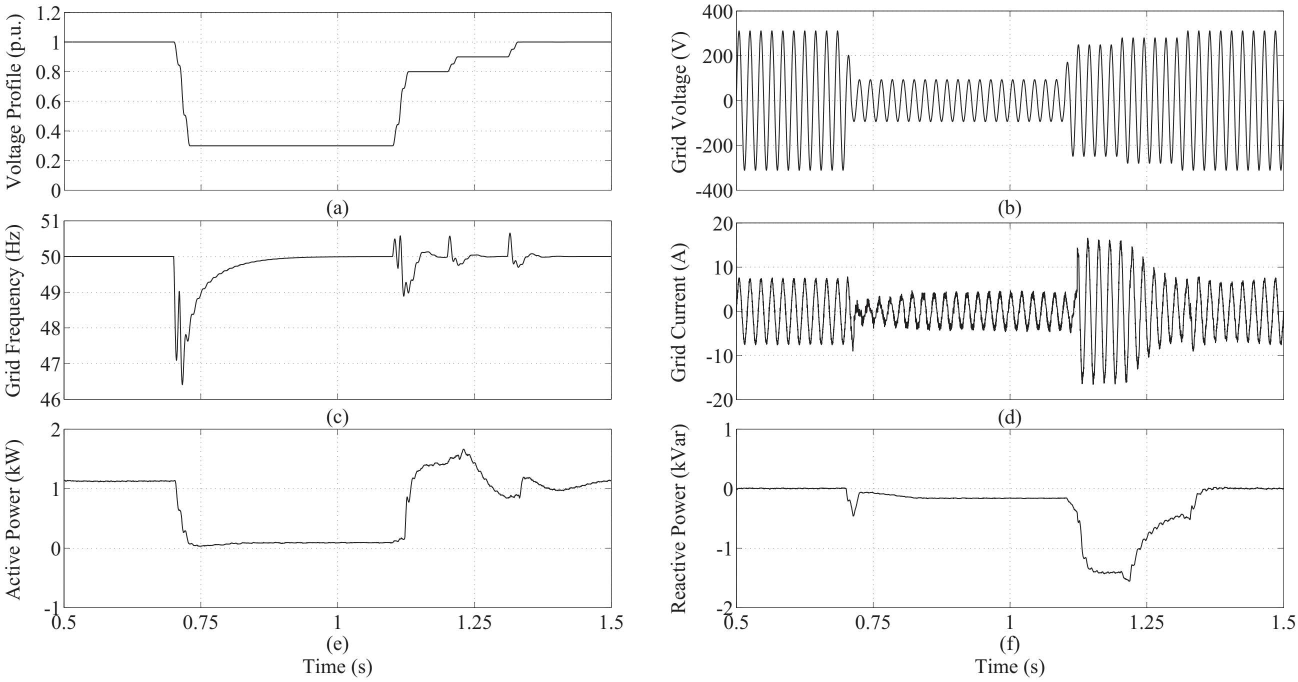

Fig. 12. Simulation results for a single-phase PV system under voltage dip using repetitive controller and SOGI-OSG PLL synchronization method: (a) voltage profile; (b) grid voltage; (c) PLL response to voltage sag; (d) grid current; (e) active power; (f) reactive power.

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