



Analysis of Grid Synchronization Techniques for Distributed Generation System During Grid Abnormalities

KEYWORDS

Distributed Generation (DG) system, Grid synchronization, Dual Synchronous Reference Frame (DSRF) PLL, Second Order Generalized Integrator (SOGI) based PLL, Quadrature Signal Generation.

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ABSTRACT Distributed Generation (DG) System based on renewable energy sources provides a good substitute to the centralized power generation systems which consumes fossil fuels and has imposed several problems on the environment. The safe operation of DG systems requires proper synchronization with power grids by using power electronics converters. The use of Phase Locked Loop (PLL) is an important technique for grid synchronization along with control optimization. This paper presents a comparative study between Dual Synchronous Reference Frame (DSRF) PLL based on synthesis circuit and Second Order Generalized Integrator (SOGI) based PLL. The comparative study has been made on the basis of how they track the phase angle during different abnormal grid conditions like voltage sag, line to ground fault and frequency deviations. The results are obtained from MATLAB/SIMULINK environment and are analyzed for feasibility of the study.

I. INTRODUCTION

The Distributed Generation (DG) systems based on renewable energy systems which include solar power, wind power, small hydro power etc. present a good prospect for the future power demands. The most important aspect of DG systems is their proper control so as to ensure sinusoidal current injection into the grid. For this their proper synchronization with the grid (utility voltage vector) is very essential [1]. The information about phase angle of utility voltage vector is very important especially to control the flow of active and reactive power and to turn on and off power devices [2]. Hence it should be tracked properly.

Phase Locked Loops (PLLs) are used as an important technique for grid synchronization and to track the phase angle. For single phase synchronization Linear PLL is used, whereas for three phase grid synchronization, PLLs based on

Synchronous Reference Frame (SRF) are used. But SRF PLL fails to detect the phase angle for unbalanced conditions [3-4]. To detect the phase angle in abnormal grid conditions various advanced PLL algorithms have been proposed like Double Synchronous Reference Frame (DSRF) PLL based on synthesis circuit proposed in [4], Decoupled Double Synchronous Reference Frame (DDSRF) PLL proposed in [5], etc. Enhanced PLL (EPLL) was proposed that synchronizes the three phases separately and does not use the Synchronous Reference Frame [6]. The PLLs based on Synchronous Reference Frame uses Park's Transformation which takes two orthogonal signals as inputs and generates constant voltages. To generate orthogonal components Clarke's transformation is employed [3-4]. The use of Second Order Generalized Integrator (SOGI) was proposed as an alternative of Clarke's transformation to generate orthogonal signals and then to use it for grid synchronization. Dual Second Order Generalized Integrator – Frequency Locked Loop (FLL) was proposed as an advanced method for grid synchronization [7-8]. Other than orthogonal signal generation SOGIs can be used as current controller, to eliminate harmonics [9] and to detect multiple grid frequencies. Multiple Second Order Generalized Integrator – Frequency Locked Loop (MSOGI FLL) was proposed in [10] which estimate not only the positive and negative sequence components at fundamental frequency but also other sequence components at multiple frequencies.

In this paper, a comparative study is made between DSRF PLL (based on synthesis circuit) and SRF PLL for phase angle detection under grid disturbances. Both the PLLs can accurately detect the phase irrespective of the grid conditions along with decoupling of positive and negative sequence components. But the steady state and dynamic response of the DSRF PLL is better than SRF PLL. Further, it demonstrates how the two PLLs can track the phase angle during some of the major abnormal grid conditions like voltage unbalance, line to ground fault and voltage sag etc. The difference in response of the two PLLs is studied in MATLAB/SIMULINK environment.

The organization of the paper is as follows: The paper begins with the description and mathematical analysis of SRF PLL (based on synthesis circuit) in section II. In section III, a detailed description and mathematical analysis of DSRF PLL is given. The general conclusion followed by references is revealed in section IV.

II. ANALYSIS OF SRF PLL

A synchronous Reference Frame PLL (SRF PLL) is mainly used for tracking the phase angle in case of 3-phase signals which works in a similar way as a linear PLL with only difference in the Phase Detector (PD) block. It uses Park's Transformation of a 3-phase signal as the PD. Figure 3.3 shows the block diagram of a SRF PLL in which v_a , v_b , v_c are the components of a 3-phase signal. First block in the figure is Clarke's Transformation which translates a 3-phase voltage vector from the abc natural reference frame to the $\alpha\beta$ stationary reference frame. The second block is the Park's Transformation which translates the $\alpha\beta$ stationary reference frame to rotating frame. A Proportional Integrator (PI) controller is used as loop filter [5].

Under unbalance utility conditions, the voltage vector can be expressed as:

$$v = v_+ + v_- + v_0$$

where subscripts +, - and 0 define the vector for the positive, negative and zero sequence components.

Using Clarke's transformation, the voltage vector in the $\alpha\beta$ plane is given by :-

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \begin{bmatrix} U_+ \cos \theta_+ + U_- \cos \theta_- \\ U_+ \sin \theta_+ + U_- \sin \theta_- \end{bmatrix}$$

By Park's Transformation

$$\begin{aligned} \begin{bmatrix} v_d \\ v_q \end{bmatrix} &= \begin{bmatrix} \cos \hat{\theta} & \sin \hat{\theta} \\ -\sin \hat{\theta} & \cos \hat{\theta} \end{bmatrix} \begin{bmatrix} U_+ \cos \theta_+ + U_- \cos \theta_- \\ U_+ \sin \theta_+ + U_- \sin \theta_- \end{bmatrix} \\ &= \begin{bmatrix} U_+ \cos(\theta_+ - \hat{\theta}) + U_- \cos(\theta_- - \hat{\theta}) \\ U_+ \sin(\theta_+ - \hat{\theta}) + U_- \sin(\theta_- - \hat{\theta}) \end{bmatrix} \\ &= \begin{bmatrix} U_+ + U_- \cos(2\omega t) \\ U_+ - U_- \sin(2\omega t) \end{bmatrix} \end{aligned}$$

where ω is the angular frequency of voltage vector and =

$$\hat{\theta} = \theta_+ = -\theta_- = \omega t \text{ in the steady state.}$$

So if the conventional SRF PLL is used during unbalanced grid conditions the second harmonic ripples are so high that makes it difficult to get the information of phase angle and amplitude.

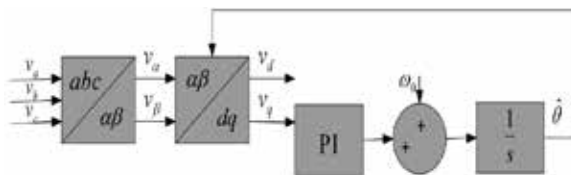


Figure 1 Block diagram of SRF PLL

II. ANALYSIS OF DSRF PLL

In a DSRF PLL, as shown in figure 4, the d-axis component from the Park's transformation is fed to the synthesis circuit. This signal is actually the voltage amplitude in steady state. The synthesis circuit consists of a Low Pass Filter (L.P.F.), two multipliers, and two orthogonal trigonometric functions as shown in figure 2. The main objective of the orthogonal functions is to create orthogonal and in-phase signals with respect to the input signal, multiplying them with the amplitude.

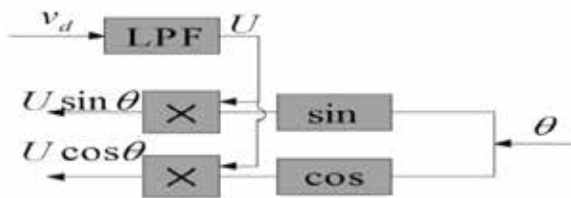


Figure 2 Synthesis Circuit used in DSRF PLL-

These signals are used as decoupling signals as shown in the figure. The two PLLs are required to detect the positive and negative sequence at the same time. The signals generated by the synthesis circuit are used as feedback for the unbalanced input signal. The input to the Park's transformation v_α and v_β is the difference of actual v_α and v_β and the generated signals from the other PLL. As the process goes on the input to the PLL cleans up and the distortion at the output is cancelled. The positive sequence

is detected by the PLL with ω_{0+} as the initial angular frequency and the negative sequence is detected by the one with ω_{0-} as the initial angular frequency. The detailed mathematical analysis is given below

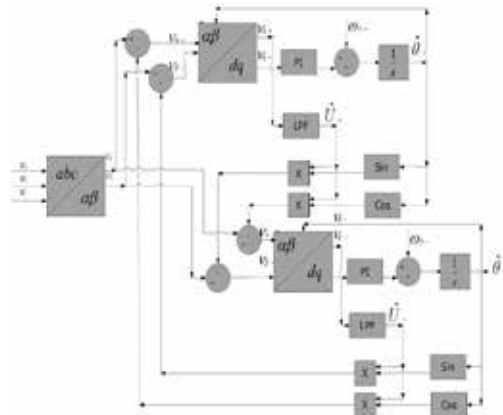


Figure 4 Block Diagram of DSRF PLL

At initial state $v_d = 0$, $\hat{\theta} = \omega_0 t$. Hence the output of the synthesis circuit is zero and decoupling circuit has no effect. Each PLL contains both positive and negative sequence information. In rotating reference frame, rotating with positive direction, the Park's transformation output is,

$$\begin{bmatrix} v_{d+} \\ v_{q+} \end{bmatrix} = U_+ \begin{bmatrix} \cos(\theta_+ - \hat{\theta}_+) \\ \sin(\theta_+ - \hat{\theta}_+) \end{bmatrix} + U_- \begin{bmatrix} \cos(\theta_- - \hat{\theta}_+) \\ \sin(\theta_- - \hat{\theta}_+) \end{bmatrix}$$

$\hat{\theta}_+ = \omega_{0+} t$ at initial state, which is the approximate center angular frequency of positive sequence component. Then above equation becomes

$$\begin{bmatrix} v_{d+} \\ v_{q+} \end{bmatrix} = \begin{bmatrix} U_+ + U_- \cos(-2\omega_0 t) \\ U_- \sin(-2\omega_0 t) \end{bmatrix}$$

As it can be seen, there are some 2ω ripples in the d-axis component which is attenuated using a low pass filter. This makes the PLL more stable. The LPF is defined as

$$LPF(s) = \frac{\omega_c}{s + \omega_c}$$

Where ω_c is the cut off frequency of the LPF.

The PLL behaviour is analysed by using state variable model. The state equations can be derived as (taking 2 state variables, x_1 and x_2 as the state vectors):-

$$\dot{x}_1 = \omega_c (U_+ - x_1 + (U_- - x_2) \cos(\theta_+ - \theta_-))$$

$$\dot{x}_2 = \omega_c (U_- - x_2 + (U_+ - x_1) \cos(\theta_+ - \theta_-))$$

where $\hat{\theta}_+$

$$x_1 = U_+$$

$$x_2 = U_-$$

At steady state $x_1 = U_+$ and $x_2 = U_-$. This implies that the d-axis component will converge to input voltage vector amplitude after sometime, and the decoupling of signals by the synthesis circuit begins.

So each PLL input will be:

$$v_{\alpha+} = v_{\alpha} - U_{-} \cos \theta_{-} = U_{+} \cos \theta_{+}$$

$$v_{\beta+} = v_{\beta} - U_{-} \sin \theta_{-} = U_{+} \sin \theta_{+}$$

And

$$v_{\alpha-} = v_{\alpha} - U_{+} \cos \theta_{+} = U_{-} \cos \theta_{-}$$

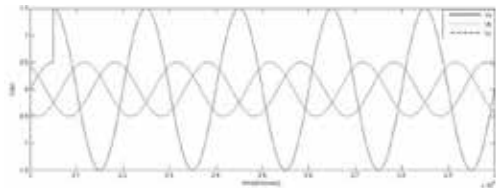
$$v_{\beta-} = v_{\beta} - U_{+} \sin \theta_{+} = U_{-} \sin \theta_{-}$$

Thus it can be seen that at steady state the two sequence components are perfectly decoupled and hence the PLL can perfectly track the phase angle for both the sequence components even in unbalanced grid conditions.

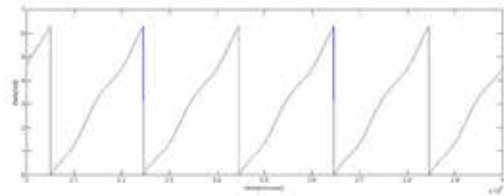
IV. RESULTS AND DISCUSSION

Response of SRF PLL and DSRF PLL Under Unbalanced grid voltage

The results obtained from simulation for DSRF PLL and SOGI PLL under line to ground fault are shown in Fig. 6. For this study, the gain of PI controller was taken as $K_p=67.5$ and $K_i=100$.

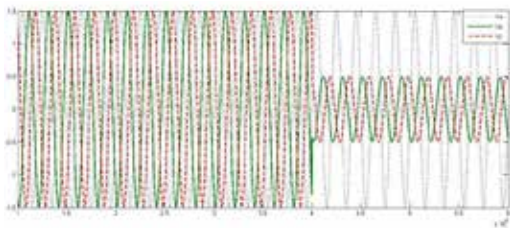


(a)

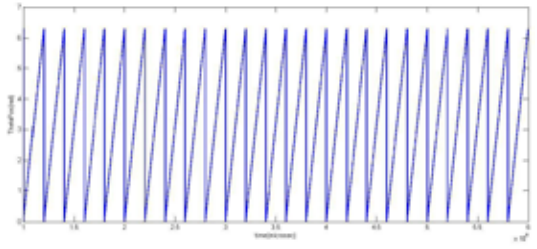


(c)

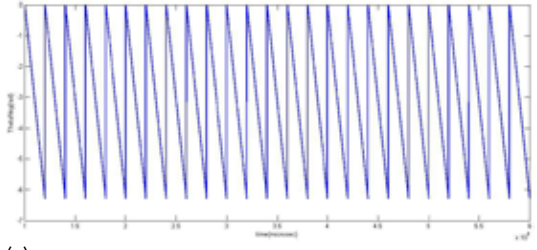
Figure 5: simulation results during unbalanced condition (a) Grid voltage waveform (c) detected phase angle.



(b)



(d)



(e)

Figure 6: simulation results of DSRF PLL during unbalanced condition (a) Grid Voltage Waveforms (d) Detected Phase Angle of Positive Sequence Component (e) Detected Phase Angle of Negative Sequence Component.

V. CONCLUSIONS

The paper presents the comparative analysis of Synchronous Reference Frame (SRF) PLL with Dual Synchronous Reference Frame (DSRF)PLL with synthesis circuit for detecting the phase during major grid abnormalities like unbalanced grid condition. From this study, it can be seen that, DSRF PLL detects the phase angle by decoupling the positive and negative sequence components and tracking the corresponding phase angles components. Further, the transients response of DSRF PLL during grid abnormalities is better than SRF PLL, even though both the PLLs can detect the phase angles accurately.

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