Analysis and Design of Advanced PLL Techniques Using FOPID Controller under Grid Fault Conditions
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Abstract:
The actual grid code requirements becomes very essential part of distributed generation system especially wind and photovoltaic (PV) systems. The Low–voltage-ride-through requirements are utmost concern for the Transmission system operators (TSOs). In order to achieve better satisfactory results than the STATCOMs and DVR, it is required to count an accurate and fast grid voltage synchronization algorithms which are suitable to work under unbalanced and distorted conditions. The existing PLL methods analyzes synchronization ability of synchronization systems: the decoupled double synchronous reference frame phase-locked loop (PLL), the dual second order generalized integrator PLL, and the three-phase enhanced PLL, designed to work under distorted conditions. Frequency locked loop based systems is also being developed. But PLL is chosen due to their link to controllability, and role in transient response, or the grid fault patterns. In this work, above mentioned PLLs will be explored for different abnormal grid conditions and analysis will be carried out in MATLAB/SIMULINK environment.

I. INTRODUCTION
By 2030 the distributed power generation system is expected to be around 20% share in power generation, whereas integration of renewable energy such as wind and photovoltaic play a dominant role in the electrical network.

The increased chance of integration of this electrical network enhanced certain restrictions within the transmission system operators (TSOs) as leverage in grid stability; as a result, the grid standards for interconnection becoming to reformed more limitation for distributed power generation systems. [2]–[6].

The Real grid code requirements (GCRs), the performance of plants under affected voltage fault conditions has utmost importance for the Transmission system operator. In order for defining the fault restraints for which a grid- interconnected generation system to be connected , determines some definite voltage values that shows depth and clearance time of the voltage sag for cope up the requirements. These requirements are well-defined as Low voltage ride through (LVRT).

The different standards of the LVRT requirements are distinct as demonstrated [8], the major problem of the generation systems is to be connected under voltage sag with in the restriction of their transient response in order to abstain protective disconnection in the network. It is found in the case, for example squirrel cage induction generators of fixed speed wind turbines generally over speed tripping of the generator occurs due to the voltage drop in the stator windings shown in [9]. Similarly, variable speed wind power systems face controllability problems results of tripping rotor side converter take places under such condition while in the practices of injection of active/reactive power [10], [11].

In certain standards, the major role of TSOs is to supply the active and reactive power into the network under a voltage sag conditions ; this is the instance for the German E-on [2] and the Spanish Red Eléctrica Española (REE) [3]. This tendency monitored by others TSOs; likewise, these process requirements is assumed to be prolonged, and explicit demands for balanced and unbalanced sags will rise in the subsequent varieties of the grid codes globally [19].

Similarly, problems such as current controllability persists in PV systems.

The auxiliary solution based systems like STATCOMs and dynamic voltage regulators (DVRs), took a major significant role in augmenting the fault ride through (FRT) ability of distributed generation systems, as explained in [12]–[16]. Similarly, power converters based on advanced control functionalities have demonstrated [17], [18]; moreover, these limitation of solutions can be improved by using a fast detection of the fault. Thus, the synchronization algorithms becomes more important.

In the literature, there are different appropriate developments on the operation of the distributed generation systems for balanced and unbalanced fault conditions. These proposed advanced control systems have an absolute information about voltage parameters, but in order of having a better performance solutions of grid synchronization algorithms become crucial. In power systems, for synchronizing the 3-phase systems the synchronous reference frame PLL (SRF PLL) is the utmost suitable technique [20]. However there performance is acceptable for balanced conditions and during unbalanced, faulty, or distorted conditions the performance becomes incompetent[21].

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In this paper, three improved and advanced grid synchronization systems based on fractional order PID controller are described and discretized: the Decoupled Double Synchronous Reference Frame PLL (DDSRF PLL) [22], the Dual Second Order Generalized Integrator PLL (DSOGI PLL), [23] and the three-Phase Enhanced PLL (3Ph-EPLL) [24].

II. GRIDGE CODE REQUIREMENTS (GCR) FOR GRID SYNCHRONIZATION

In the area of grid synchronization there are several works has been published all of them are pointed on their individual responses and without concentrating on time response

Considering the LVRT requirements, it needs to set the common requirements during the entire responses of grid synchronization systems.

The significant feature of advanced grid synchronization systems stands requirements of having exact information of about phase and magnitude of the grid voltage during fault, for injecting required reactive power by means of TSOs.

In view of different demands, the proposed system considers detection of voltage conditions should be around 10-15 ms for accomplishing the requirements for dynamic responses in the Grid codes and same consideration is taken for detecting other disturbance.

III. DESCRIPTION OF THE THREE PLL FOR SYNCHRONIZATION SYSTEMS

Before going to the description of different PLL techniques, the design of FOPID controller based PLL plays a significant role for detection fault during unbalanced, fault or distorted conditions.

There are several positive detection algorithms based on SRF PLL but there is only good response under balanced and looks inadequate responses under balanced conditions (mostly 95% cases) creating problems in frequency stability, which is not in the position of synchronization. so there are so many proposed systems based on advanced models for sustaining the classical PLL.

In these paper there are three advanced FOPID based PLL structures for frequency and amplitude structures under unbalanced, faulty and harmonic polluted grids.

A. DDSRF PLL:

DDSRF PLL is expansion of conventional SRF PLL comprises of two synchronous frames rotating with fundamental frequency rotating clockwise and counter clockwise for identifying positive and negative sequence of voltage afflicts during unbalanced faults in grid, the block diagram of DDSRF PLL is shown in fig.1.

Suppose if there is an unbalanced grid voltage in 3phases, resulting positive sequence voltage vector arise as as dc voltage on the $dq^{-1}$ on SRF axes mean while ac voltage gages as double of the frequency of utility frequency of $dq^{-1}$ axes on negative sequence SRF resulting a.c oscillations of SRF positive sequence. The amplitude of oscillations of positive sequences bouts as dc level of negative sequence SRF and continues like these. Then decoupling network is applied to the systems to cancel out all oscillations present in the system and low pass filter (LPF) is applied to remove all dc components present in decoupled SRF axes, these components accumulate detail information regarding on positive and negative sequence voltage in the grid.

Finally, FOPID controller of DDSRF Pll performs same as SRF PLL working on the decoupled q-axes signal of positive sequence and making the positive sequence voltage detection along the d-axes.

B. DSOGI PLL

For detecting the positive and negative sequence voltage vectors, the working principle is used on DSOGI PLL is based on $\alpha\beta$ stationary reference frame using instantaneous symmetrical component (ISC) method. While these method is established by using the positive-sequence calculation block shown along with DSOGI PLL in fig 2.

In the process of applying ISC method, it is essential to abstain a pair of signals from the input voltage of $\alpha\beta$ stationary reference frame to the another pair of signals $\alpha_1 - \beta_1$ representing in quadrature and lagging with respect to input voltages $\alpha_2 - \beta_2$.

In these method, the signals delivered to the ISC method based on generalized integrator concept (25). Finally the DSOGI output has four signals having filtered signals $\alpha_2$ and $\beta_2$ correspondingly $\alpha_1$ and $\beta_1$ of quadrature signals of $\alpha_2$ and $\beta_2$. 

Finally SRF PLL is applied to the positive sequence voltage vector of ISC method output and then transferred to dq axes of SRF and signal of q-axes is applied to FOPID controller, then the better responses of grid frequency and positive sequence voltage are estimated.

B. 3pEPLL:

In single-phase synchronization system affords a better response in terms of synchronization as demonstrated [26], the EPLL is basically adaptive bandpass filter by adjusting the cutoff frequency as an input and these same structure improved in three phase individually for detecting positive sequence voltage vector of three phases shown in fig 3.

IV. DISCRETE IMPLEMENTATION

The performance test of three PLL structures in MATLAB/SIMULINK depend upon the discretization method based on continuous equations. there should utmost detailed study as direct application obstruct the responses of three PLLs. There are several methods which are used in the Process of discretization as like forward Euler, backward Euler, Trapezoidal integration as demonstrated in [27].

Hence, depending upon the requirements of different PLLs in the segment each PLL is discretized individually as shown in fig 1-3 and values of each parameter is shown in appendix A.

A. DDSRF-PLL Discretization

The continuous equations of DDSRF PLL of more parameters look same as discrete approach some of notations of transformation blocks $T_{a\beta}$, $T_{dq+1}$, and $T_{dq-1}$ seen in literature.

1) Decoupling Networks of sequence:

The utmost concern of the synchronization are decoupling networks representing in discrete domain looks same as continuous equation. it is required consider a delay $\theta^\beta$, $v_d-1$, $v_q-1$, $v_d+1$, and $v_q+1$ for protection from unwanted loops.

2) Phase and Magnitude Estimator Discretization:

The decoupling network looks like it is enclosed in classic SRF PLL (fig.4) even though without any disturbance phase and magnitude discretization only illustrates the input of this block as $v^*_{d+1}$ and $v^*_{q+1}$.

$$
\begin{bmatrix}
v^*_{d+1}[n+1] \\
v^*_{q+1}[n+1]
\end{bmatrix}
= \begin{bmatrix}
1 & 0 \\
0 & 1
\end{bmatrix}
\begin{bmatrix}
v^*_d[n] \\
v^*_q[n]
\end{bmatrix} + \begin{bmatrix}
-\cos(2\theta'[n]) & -\sin(2\theta'[n]) \\
\sin(2\theta'[n]) & -\cos(2\theta'[n])
\end{bmatrix}
\begin{bmatrix}
v_{d-1}[n] \\
v_{q-1}[n]
\end{bmatrix} 
\begin{bmatrix}
1 & 0 \\
0 & 1
\end{bmatrix}
\begin{bmatrix}
v_{d-1}[n+1] \\
v_{q-1}[n+1]
\end{bmatrix} 
\begin{bmatrix}
-\cos(-2\theta'[n]) & -\sin(-2\theta'[n]) \\
\sin(-2\theta'[n]) & -\cos(-2\theta'[n])
\end{bmatrix}
\begin{bmatrix}
v^*_d[n] \\
v^*_q[n]
\end{bmatrix}
\begin{bmatrix}
1 & 0 \\
0 & 1
\end{bmatrix}
\begin{bmatrix}
v^*_d[n+1] \\
v^*_q[n+1]
\end{bmatrix} 
\ldots 
(1)

The can be erected based by using a backward numerical approximation. The frequency and phase are produced considering as the error to be minimized. In this equation, a feedforward of the nominal frequency is specified by the use of $w_{ff}$.

By using numerical approximations the discrete controller and the integrator were designed, phase and frequency characterized in the form of z-domain (2). assuming...
As error is reduced.

\[ W'(z) = \frac{(k_p + k_i T_s) z - k_p}{z - 1}. V_{q^*+1}(z) + \omega{f} \]

\[ \theta^{+'} = \frac{T_s}{z-1}. W'(z) \tag{2} \]

At the end the sample based equation give rise to (3) equation as

\[ w'[n+1] = w'[n] - k_p + v_{q^*+1}[n] + (k_p + k_i T_s)v_{q^*+1}[n+1] \]

\[ \theta^{+'}[n+1] = \theta^{+'}[n] + T_s w'[n+1] \]

In the above equations, frequency feedforward been presented by initial settings to \( w' \)

3) LPF Block Discretization:
The outputs of the decoupling networks consists of amplitudes of the dq positive- and negative-sequence components. Though, four infinite impulse response (IIR) LPFs remove the ripples from every sequence estimation to emphasize the response of the PLL under harmonic pollution. So a first-order filter by a cutoff frequency, \( w_f \) equivalent to half of the grid frequency. so the same transfer function is implemented as

\[ y[n] = \frac{1}{T_s \omega_f + 1}. x[n] + \frac{T_s \omega_f}{T_s \omega_f + 1}. u[n] \]

\[ x[n+1] = y[n] \]

B. DSOGI-PLL Discretization

DSOGI-Quadrature signal generator (QSG) Block Discretization:

According to requirements of Section II, the QSG of Fig.2 comprises of two self-regulating DSOGI-based quadrature signal generator and decoupled second-order generalized integrators (SOGI). Subsequently, each SOGI-QSG quadrature signal generator can be independently discretized, thus simplifying its into the mathematical equations. In Fig.5 the block diagram SOGI is shown

The discrete representation of quadrature signal generator (QSG) is obtained steadily if the continuous state space is abstracted before, the SOGI state space equations was demonstrated as in (5). here \( v \) defines as the input whereas \( v' \) and \( qv' \) are the two in-quadrature output signals.

\[ \dot{x}_n = A. x_n + B. v \\
\]
\[ y_n = C. x_n \quad y_n = \begin{bmatrix} y' \\ qv' \end{bmatrix} \]

\[ A = \begin{bmatrix} 0 & 1 \\ -\omega^2 & -k. \omega \end{bmatrix} \quad B = \begin{bmatrix} 0 \\ k. \omega \end{bmatrix} \quad C = \begin{bmatrix} 1 & 0 \end{bmatrix} \tag{5} \]

The discretization of this structure has been accomplished by trapezoidal integrators because of enhanced detection of the phase, where \( T_s \) is the estimated frequency magnitude, which is output of estimation finished at the SRF-PLL block of each individually, and \( k \) is the gain at SOGI [14].

\[ x[n+1] = A'. x[n] + B'. v[n] \]

\[ y[n] = c'. x[n] + D'. v[n] \tag{6} \]

The discretization of above state space equation is acquired through the continuous representation of mathematical formula presented as in (7)

\[ A' = \left( I + \frac{A. T_s}{2} \right)^{-1} \]

\[ B' = \left( I - \frac{A. T_s}{2} \right)^{-1} . B \]

\[ C' = T_s . C . \left( I - \frac{A. T_s}{2} \right)^{-1} \]

\[ D' = C . \left( I - \frac{A. T_s}{2} \right)^{-1} \cdot \frac{B. T_s}{2} \tag{7} \]

2) SRF PLL Discretization:

The phase and frequency detection is acquired by using SRF PLL shown in Fig. 6. The backward numerical approximation is used in discretization of the controller and the integrator where frequency and phase is represented in Z-domain. where \( v_{q^+} \) is the error to be reduced.

Fig.5 quadrature signal generator based on a second order generalized integrator

![Fig.5 quadrature signal generator based on a second order generalized integrator](image-url)

Fig.6. State variable of the SRF-PLL block

![Fig.6. State variable of the SRF-PLL block](image-url)
\[ W'(z) = \frac{(k_p + k_1 T_z) z - k_p}{z - 1} V_{q+1}^*(z) + \omega f \]
\[ \theta'[n+1] = \frac{T_z z}{z - 1} W'(z) \] 

(8)

It can be observed that the earlier equations in (8) are equal to (2), for equally cases, an SRF PLL is implemented. Similarly, sample-based representation of above equation can be written as
\[ w'[n+1] = w'[n] - k_p, \quad v_{q+1}[n] + (k_p + k_1 T_z) v_{q+1}[n + 1] \]
\[ \theta'[n+1] = \theta'[n] + T_z, w'[n+1] \] 

(9)

C. 3phEPLL Discretization

In these system the EPLL as a quadrature signal generator for three-phase grid synchronization systems by handling each phase of voltages by an independent EPLL again the same EPLL structure is used to detect phase magnitude of the positive-sequence voltage component.

1) QSG Block—EPLL Discretization: The block diagram of the EPLL applied in this paper is demonstrated in Fig. 7. From these diagram, the continuous state space equation of the EPLL as written as
\[ A'(t) = k_e(t), \cos \theta'(t) \]
\[ \omega'(t) = -k_e(t), \sin \theta'(t) \]
\[ \theta(t) = \omega'(t) + \frac{k_p}{k_1}, \omega'(t) \] 

(10)

The discrete state space variable demonstration by using a forward Euler approximation used in [44] has been executed here to achieve suitable results as shown
\[ e[n+1] = u[n+1] - w'[n] \]
\[ A'[n+1] = A'[n] + T_z, k_e[n], \cos(\theta'[n]) \]
\[ w'[n+1] = w'[n] - T_z, k_1, e[n], \sin(\theta'[n]) \]
\[ \theta'[n+1] = \theta'[n] + T_z, w'[n] - T_z, k_p, e[n], \sin(\theta'[n]) \] 

(11)

After calculating state variables then EPLL output is obtained (12) by means of two quadrature signals.
\[ v'[n+1] = A'[n+1], \cos(\theta'[n+1]) \]
\[ qv'[n+1] = -A'[n+1], \sin(\theta'[n+1]) \] 

(12)

In these discretization technique require an accurate tuning, due to difference of the stable regions of the s-plane and z-plane in [52]. Conversely, it is compared to the Tustin or backward integration, assistances from the speed of computational block.

2) Computational Block Unit: The demonstration of these block is the same for both continuous and discrete equations. However, definite equations used in these paper are detailed as shown in (14).
\[ v_1^* = \frac{1}{3} v_x[n] - \frac{1}{3} (v_y[n] + v_z[n]) \]
\[ + \frac{1}{2\sqrt{3}} (v'_{y'[n]} - jv'_{z'[n]}) \]
\[ v_2^* = \frac{1}{3} v_x[n] - \frac{1}{3} (v_y[n] + v_z[n]) \]
\[ + \frac{1}{2\sqrt{3}} (v'_{y'[n]} - jv'_{z'[n]}) \]
\[ v_3^* = -(v_x[n] + v_y[n]) \] 

(13)

3) Phase and Magnitude Detection Block: These block based on additional EPLL which is used for estimation of phase and the magnitude of the positive-sequence fundamental component then its discretization is same as that of above shown in (11)

\begin{table}[h]
\centering
\begin{tabular}{|c|c|}
\hline
PROPERTY OF TESTING VOLTAGE SAG &  \\
\hline
\hline
\textbf{Parameter} & \textbf{Value} \\
\hline
$V^+$ & 40$^\circ$  \\
$V^-$ & 0$^\circ$  \\
$V^0$ & 0$^\circ$  \\
\hline
\end{tabular}
\caption{Sag parameters}
\end{table}

Positive, negative, zero sequence vectors during the fault Condition for the sag

V. TESTING SIGNALS IN SETUP

From the discrete equations of three PLL structures, the design of MATLAB/Simulink control PLL structures were designed and performance of fast and accurate synchronization was tested in MATLAB/SIMULINK under various fault Scenarios like voltage sag, total harmonic distortions.

The voltage distortions were generated by the use of auxiliary transformer and three phase programmable voltage source. The outline diagram used in the paper as shown in fig 8 there are three faulty and distorted conditions were designated for the three synchronization systems under test.
• Voltage sags: In Table I, the characteristics of voltage sags have been précised. It is a most occurrence sag in wind power systems. During the fault period the symmetrical component of voltage were specified in table by supposing $\psi^a=100$, $\psi^c=0$, $\psi^b=0$

Fig .8. Generation of grid voltage sag in setup diagram

• Harmonic-polluted voltage (8% THD): Depending on the standard of EN50160 standards, the requirements of distorted Voltage waveforms should not exceed than 8% , so, there are different harmonic compositions used in programmable source for the response of grid synchronization under these test under distorted grid voltage.

<table>
<thead>
<tr>
<th>Order of harmonic</th>
<th>THD (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2\textsuperscript{nd}</td>
<td>2%</td>
</tr>
<tr>
<td>4\textsuperscript{th}</td>
<td>1%</td>
</tr>
<tr>
<td>5\textsuperscript{th}</td>
<td>5%</td>
</tr>
<tr>
<td>7\textsuperscript{th}</td>
<td>4%</td>
</tr>
<tr>
<td>11\textsuperscript{th}</td>
<td>3%</td>
</tr>
<tr>
<td>13\textsuperscript{th}</td>
<td>3%</td>
</tr>
</tbody>
</table>

VI. SIMULINK PERFORMANCES OF THE PLLS UNDER TEST

A. Behavior Voltage Sag test:
This voltage sag look as three phase fault resulting high short circuit currents so, it is required to balance voltage drop in the system. From the figure 9(b) and (c) shows good response of DDSRF PLL and the DSOGI PLL as both as fast detecting the positive sequence (10ms), but the response of 3phEPLL shows transient in the estimation of positive sequence.

B. Polluted Grids (THD = 8%): The 3ph EPLL shows better response as filtering the input signal like as band pass filter by proper filtering among the other PLLs under the test by achieving good responses without having distorted phase and magnitude while on the estimation .Although DSOGI PLL also performs as like bandpass filter, the tuning parameters results faster stabilization shown in Fig. 10(c) resulting small oscillations in the estimation of positive-sequence compared to the DDSRF PLL.
Fig. 10. Amplitude and Phase estimation of three PLL in polluted grid (a) Input signal (b), (c) and (d) amplitude (v) and phase (rad) of DDSRF, DSOGI, 3phEPLL respectively.
VIII. CONCLUSION

These paper evaluated the performance of three advanced grid synchronization systems. From these three over three PLL performance have been tested in MATLAB/Simulink and synchronization capability of three PLL under test shown as fast and accurate under faulty scenarios allowing detection of the positive sequence voltage in 10-15 ms in all cases. Meanwhile 3ph EPLL and DDSRF PLL has better immunity under polluted network due to great band pass and low filtering compared to DSOGI PLL. But the simple structure of DSOGI PLL and DDSRF PLL affords easier tuning of their control parameters and therefore more accurate control of their transient response.

APPENDIX

The parameters used for tuning advanced PLL techniques are shown in Table 3.

<table>
<thead>
<tr>
<th>DDSRF-PLL</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_s</td>
<td>100 µs</td>
</tr>
<tr>
<td>k_r</td>
<td>2.22</td>
</tr>
<tr>
<td>k_q</td>
<td>246.74</td>
</tr>
<tr>
<td>( \omega_f )</td>
<td>314.1592 rad/s</td>
</tr>
<tr>
<td>( \omega_r )</td>
<td>157.0796 rad/s</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>DSOGI-PLL</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_s</td>
<td>100 µs</td>
</tr>
<tr>
<td>k_r</td>
<td>2.22</td>
</tr>
<tr>
<td>k_q</td>
<td>61.7</td>
</tr>
<tr>
<td>k</td>
<td>( \sqrt{2} )</td>
</tr>
<tr>
<td>( \omega_f )</td>
<td>314.1592 rad/s</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3ph EPLL</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_s</td>
<td>100 µs</td>
</tr>
<tr>
<td>k_r</td>
<td>5</td>
</tr>
<tr>
<td>k_q</td>
<td>450</td>
</tr>
<tr>
<td>k_s</td>
<td>500</td>
</tr>
<tr>
<td>( \omega_f )</td>
<td>314.1592 rad/s</td>
</tr>
</tbody>
</table>

References:


