Synchronization signal extraction method based on enhanced DSSOGI-FLL in power grid distortion

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ABSTRACT

With the development of new energy, three-phase grid connected converter has been widely applied. In order to meet the requirement of synchronous signals extraction under the condition of asymmetry, dc components and harmonic distortion, the positive and negative sequence components, amplitude and fundamental frequency of the voltage signal need to be extracted accurately. Based on dual second order generalized integrator frequency locked loop (DSOGI-FLL), the synchronization signal can be extracted under voltage asymmetry and distortion. But when the three-phase voltage is asymmetrical, dc components and multiple harmonics are influenced by the DSOGI-FLL method, the synchronous signal cannot be extracted accurately. In this paper, the structure of second order generalized integrator (SOGI) is improved, and the difference node and adaptive filter are added on the basis of SOGI, and the method of synchronous signal extraction based on improved dual self-turning second order generalized integrator frequency locked loop (DSSOGI-FLL) is proposed. This method can eliminate the effect of asymmetrical, dc components and multiple harmonics, and can extract the positive and negative sequence components, phase and frequency information accurately and quickly. The accuracy and effectiveness of the improved DSSOGI-FLL method are verified by simulation analysis.

KEYWORDS

Synchronous signal; positive sequence component; fundamental frequency; second order generalized integrator; frequency locked loop

1. Introduction

The accurate and rapid extraction of synchronous signal plays an important role in the power grid. A common method of synchronous signal extraction is a phase-locked loop (PLL) technology (Chung et al., 2006; Wusong et al., 2016). The PLL technology can detect the positive and negative sequence components and phase information of the voltage signal in the case of asymmetrical, harmonic and frequency hopping, to realize the advantages of the frequency adaptation and the convenience of implementation.

At present, many methods have been proposed for accurate extraction of synchronous signals. The Extended Kalman Filter (EKF) (Ke et al., 2014; Li, Wang, Bao, & Zhang, 2014; Sun & Sahinoglu, 2011) method can extract the positive and negative sequence components. But when the frequency mutates, the information in the input signals cannot be traced accurately. The Strong Tracking Filter (STF) (Ghoshal & John, 2015; Rende et al., 2013; Sun et al., 2017) can track the change of frequency in real time by reset error covariance quickly. However, the huge amount of algorithm operation will limit the use in some cases. The Synchronous Reference Frame Phase-locked Loop (SRF-PLL) (Hongda, 2013; Luo & Wu, 2017; Xie et al., 2015) can extract the positive and negative sequence of the fundamental under steady-state conditions. But when the three-phase voltage is asymmetrical, the SRF-PLL method will generate 100 Hz waveform fluctuations during the detection of the fundamental negative sequence. The Enhanced Phase-Locked Loop (EPLL) (Gong, 2013; Karimi-Ghartemani, 2014; Wu, Zhang, & Duan, 2015) can separate the positive and negative sequence components, but symmetrical components will increase the computation of the algorithm. The dual second order generalized integrator PLL (DSOGI-PLL) (Hu, Li, & Ai, 2017; Juan & Ningping, 2016; Su et al., 2015) can obtain the fundamental and orthogonal components of the voltage in $\alpha\beta$ coordinate system by using the characteristics of the output orthogonal of SOGI. However, the existence of harmonics and dc components has a great influence on the performance of the SOGI, which makes the traced waveform fluctuate. A phase-locked loop based on adaptive notch filter (ANF) (Xiong et al., 2013; Yin, Guo, & Li, 2013) can eliminate the 100 Hz signal and the positive and negative sequence components of the signal can be detected by the orthogonal output characteristics of the ANF. This
method is simple in structure and similar to the SOGI, but the dc components have a greater influence on it, which leads to larger waveform fluctuations.

In this paper, a new synchronization signal extraction method based on enhanced dual self-turning second order generalized integrator FLL (DSSOGI-FLL) is proposed by adding differential nodes and adaptive filters on SOGI. This method not only inherits the advantages of DSSOGI-FLL, but also improves the system performance under the condition of grid distortion. In order to make FLL unaffected by amplitude, frequency and positive and negative sequence components, the structure of FLL is improved. Finally, the simulation analysis shows that the algorithm can extract the frequency, amplitude and positive and negative sequence components accurately and rapidly.

2. Enhanced SOGI-FLL

2.1. SOGI-FLL

The FLL is an effective mechanism for adapting the centre frequency of the SOGI-QSG. The structure of SOGI-FLL is shown in Figure 1.

According to Figure 1, SOGI-FLL is mainly composed of SOGI and FLL. The transfer function of SOGI can be expressed as

\[ D(s) = \frac{v'}{v}(s) = \frac{k\omega's}{s^2 + k\omega's + \omega'^2} \quad (1) \]

\[ Q(s) = \frac{qv'}{v}(s) = \frac{k\omega'^2}{s^2 + k\omega's + \omega'^2} \quad (2) \]

The Bode diagram of (1), (2) is shown in Figure 2.

In Figure 2, D(s) and Q(s) represent the structure of band-pass and low-pass filter respectively and its bandwidth is only affected by the gain coefficient k, which is independent of the resonant frequency \( \omega' \). According to the phase-frequency characteristics, \( qv' \) always lags behind the input signal \( v' \) 90 degrees, so \( qv' \) and \( v' \) are always orthogonal to each other.

The frequency information of the voltage signal is detected by the error signal \( \epsilon_v \) and the orthogonal output signal \( qv' \) in the SOGI-FLL structure. The transfer function of \( \epsilon_v \) can be calculated as

\[ G_{\epsilon_v}(s) = \frac{\epsilon_v}{v}(s) = \frac{s^2 + \omega'^2}{s^2 + k\omega's + \omega'^2} \quad (3) \]

Figure 2. Bode diagram of SOGI-QSG considering different values of k.
in counter phase when

\( v(t) \)

the structure of enhanced SOGI is shown in Figure 4.

When the input signal contains dc components, SOGI-FLL cannot lock the frequency accurately. The difference node is introduced to overcome the lack of SOGI-FLL, and the structure of enhanced SOGI is shown in Figure 4.

The enhanced SOGI is mainly described in the time domain and frequency domain. When the input signal

\( v(t) \)

contains dc component \( A_0 \), that is:

\( v(t) = A_0 + A_1 \sin(ωt) \)

it can be expressed in the frequency domain as

\[
V(s) = A_1 \frac{ω}{s^2 + ω^2} + \frac{A_0}{s}
\] (4)

According to (1) and (4), the output signal \( v'(t) \) can be expressed in the frequency domain as

\[
V'(s) = \frac{kωs}{s^2 + kωs + ω^2} \left( A_1 \frac{ω}{s^2 + ω^2} + \frac{A_0}{s} \right)
\]

\[
= A_1 \frac{ω}{s^2 + ω^2} + \frac{(kA_0 - A_1)ω}{s^2 + kωs + ω^2}
\] (5)

The output signal \( v'(t) \) can be expressed in the time domain as

\[
v'(t) = A_1 \sin(ωt) + \frac{(kA_0 - A)}{1 - (k/2)^2} e^{\frac{−kωt}{2}} \sin(ω\sqrt{1 - (k/2)^2}t + \cos^{-1}(k/2))
\]

According to (6), the output signal \( v'(t) \) is the same as the input signal in the steady state and not has dc offset. Similarly, the quadrature output signal \( qv_1(t) \) can be expressed as

\[
qv_1(t) = A_1 \cos(ωt) - \frac{(kA_0 - A)}{1 - (k/2)^2} e^{\frac{−kωt}{2}} \sin(ω\sqrt{1 - (k/2)^2}t + \cos^{-1}(k/2))
\] (7)

The quadrature output signal \( qv_1(t) \) is orthogonal to the output signal \( v' \) as well. However, the quadrature output signal contains a dc component with a value of \( kA_0 \). The quadrature output signal \( qv'(t) \) of the enhanced SOGI-FLL method is calculated from the error signal \( ε_v \) and the quadrature output signal \( qv_1(t) \) of the conventional SOGI-FLL method. According to (2) and (4), the orthogonal output \( qv'(t) \) of enhanced SOGI-FLL can be expressed as

\[
QV'(s) = \frac{kωs}{s^2 + kωs + ω^2} \left( A_1 \frac{ω}{s^2 + ω^2} + \frac{A_0}{s} \right)
\] (9)

It can be expressed in the time domain as

\[
qv'(t) = A_1 \cos(ωt) - \frac{(kA_0 - A)}{1 - (k/2)^2} e^{\frac{−kωt}{2}} \sin(ω\sqrt{1 - (k/2)^2}t + \cos^{-1}(k/2))
\] (10)

At the steady state, the orthogonal output signal \( qv'(t) \) in (10) does not contain dc components, and the orthogonal output signal and output signal \( v'(t) \) are orthogonal.
completely. So the enhanced SOGI-FLL can eliminate the dc components and lock the frequency and extract the amplitude, phase and other information.

3. DSSOGI-FLL

3.1. SSOGI

The structure of Self-turning SOGI (SSOGI) is shown in Figure 5, which consists of a traditional SOGI, pre-adaptive filter and difference node. The input signal $v$ passes through the self-turning filter to eliminate the harmonic components. Then two orthogonal estimation signals $v'$ and $qv'$ are obtained by means of the SOGI structure containing the differential node. When the input signal contains dc components, SSOGI-FLL can suppress the influence of it through the difference node.

The relationship between $V_1(s)$, $V(s)$, $V'''(s)$ and $QV'''(s)$ can be calculated as:

$$G_{V_1}(s) = \frac{k_a(V(s) - V'''(s))}{s} = \frac{k_a(V(s) - V'''(s)) - (\omega^2 - s^2)V'''(s)/2s}{2ks}$$

According to the transfer function of $V(s)$, $V'''(s)$ and $QV'''(s)$ can be expressed as:

$$G'''(s) = \frac{v'''}{v}(s)$$

$$Q'''(s) = \frac{qv'''}{q}(s)$$

where $k_a$ and $k_1$ is the filter adjustment coefficient, $v$ is the input signal of filter, $v'''$ is the estimation of input signal, $qv'''$ is the orthogonal components of SSOGI's estimation.

According to Figure 5, SSOGI structure has an adaptive filter in front of the traditional SOGI, which can filter the harmonics better. And the dc components are also suppressed by introducing the difference node. To better know the performance of the SSOGI structure, Figure 6 compares the Bode diagram of both SOGI and SSOGI.

According to Figure 6, $D(s)$ $Q(s)$ and $D''(s)$, $Q''(s)$ represent the transfer functions of SOGI and SSOGI structure respectively. The transfer function of SSOGI structure has a narrower bandwidth at the resonant frequency through the amplitude–frequency characteristics, so that the filtering performance will be more advantageous. Similarly, according to the phase-frequency characteristics, the phase difference between $D''(s)$ and $Q''(s)$ is also 90 degrees, so the two estimated signals are orthogonal to each other. The frequency domain characteristics of the SSOGI structure are as follows:

(1) The phase of $qv'''$ lags behind $v'''$ 90 degrees and they are orthogonal to each other.
(2) Compared with SOGI, the SSOGI structure has better filtering and frequency-locking performance in the presence of dc components and harmonics.
(3) The structure enhances the system’s harmonic control and reduces the amplitude distortion of the output signal.

3.2. DSSOGI-FLL

When the voltage signal contains harmonics and dc components, the extraction performance of dual second order generalized integrator FLL(DSSOGI-FLL) will be seriously affected, so a DSSOGI-FLL method based on SSOGI is proposed. The method can eliminate the influence of harmonics and dc components to ensure that the information such as frequency and amplitude can be extracted.
accurately and quickly. The DSOGI-FLL structure diagram is shown in Figure 7 and the internal structure of SOGI-QSG is shown in Figure 1.

For a single-frequency sinusoidal signal \( v = V \sin(\omega t + \phi) \), the stable output of SOGI in Figure 7 is:

\[
y = \begin{bmatrix} v' \\ qv' \end{bmatrix} = V \begin{bmatrix} \sin(\omega t + \phi) \\ \cos(\omega t + \phi) \end{bmatrix}
\]  

(14)

According to (14), Figures 1 and 7, it can be concluded that:

\[
\dot{x}_1 = -\omega^2 x_2
\]

(15)

Then the expression of signal error \( \varepsilon_v \) is:

\[
\varepsilon_v = (v - x_1) = \frac{1}{k} (\omega^2 - \omega^2) x_2
\]

(16)

And the sum of the signal errors \( \varepsilon_f \) is

\[
\varepsilon_f = \bar{\omega} x_{2a} \varepsilon_{v_{\alpha}} + \omega x_{2b} \varepsilon_{v_{\beta}} = \frac{x_{2a}^2 + x_{2b}^2}{k} (\omega^2 - \omega^2)
\]

(17)

where \( \dot{x}_1 \) and \( \dot{x}_2 \) represent the state vector of SOGI; \( \bar{\omega} \) stands for resonant frequency; \( \omega \) stands for the frequency of the input signal; \( \varepsilon_{v_{\alpha}} \) and \( \varepsilon_{v_{\beta}} \) represent the error signals of SSOGI-QSG1 and SSOGI-QSG2 respectively.

So the frequency response characteristics of FLL can be expressed as

\[
\dot{\omega} = -\gamma \varepsilon_f \approx -\frac{2\gamma}{k} \left( x_{2a}^2 + x_{2b}^2 \right) (\omega - \omega)
\]

(18)

Through the analysis of the DSSOGI-FLL, the input signal of the FLL in DSSOGI-FLL is the sum of the error of the two SSOGI-QSG output signals. Compared with other methods, it can eliminate 100 Hz signal and track the frequency, amplitude and other information faster and more accurately in the case of frequency mutation, and can improve the response speed of frequency tracking.

4. Positive and negative sequence extraction

4.1. Decomposition of positive and negative sequence

In the three-phase system, three-phase voltage asymmetry occurs frequently in the power grid. So the symmetrical component method is used to decompose the positive sequence, negative sequence and zero sequence, that is \( v_{abc} = v_{abc}^+ + v_{abc}^- + v_{abc}^0 \).

\[
v_{abc}^+ = [T_+] v_{abc}
\]

\[
v_{abc}^- = [T_-] v_{abc}
\]

\[
v_{abc}^0 = [T_0] v_{abc}
\]

(19)

(20)

(21)

where \( a = e^{j\pi/3} \) represents the Fortescue phase shift operator, which applied to instantaneous input signals. The three-phase voltage is transformed to two-phase through the Clarke transform. The positive and negative sequence in \( \alpha \beta \) can be obtained by:

\[
v_{\alpha\beta}^+ = [T_{\alpha\beta}] v_{abc}^+ = [T_{\alpha\beta}][T_+] v_{abc}
\]

\[
= [T_{\alpha\beta}][T_+] [T_{\alpha\beta}^T] v_{\alpha\beta}^+ = -\frac{1}{2} \begin{bmatrix} 1 - q \\ q \end{bmatrix}
\]

(22)

\[
v_{\alpha\beta}^- = [T_{\alpha\beta}] v_{abc}^- = [T_{\alpha\beta}][T_-] v_{abc}
\]

\[
= [T_{\alpha\beta}][T_-] [T_{\alpha\beta}^T] v_{\alpha\beta}^- = -\frac{1}{2} \begin{bmatrix} 1 q \\ -q \end{bmatrix}
\]

(23)

where \( q = e^{-j\pi/3} \) is a phase-shift calculation with 90 degrees delay, which applied to the time domain to obtain the quadrature component of the input signal.

4.2. Positive and negative sequence extraction based on enhanced DSSOGI-FLL

By combining DSSOGI-FLL with positive/negative sequence calculation block (PNSC), a positive and negative sequence extraction method based on DSSOGI-FLL is proposed. The block diagram of this method is shown in Figure 8.

**Figure 7.** Block diagram of DSSOGI-FLL.
According to Figure 8, the equation of the frequency response can be expressed as

$$\dot{\omega} = -\frac{\gamma \dot{\omega}}{v^2 + qv'^2} e_v$$

(24)

From Figure 8 and (23), we can get the following

$$v'^2 + qv'^2 = (V'^{+\alpha})^2 + (V'^{+\beta})^2 \approx V^2$$

(25)

The frequency response equation of FLL can be obtained as

$$\dot{\omega} = -\frac{2\gamma}{k}(\omega - \omega)$$

(26)

It can be clearly seen in (26) that the time constant in FLL changes to $\tau = k/2\gamma$, and there is no relationship between the tracking of the frequency and the amplitude and frequency in the voltage. So the DSSOGI-FLL method with amplitude and frequency adaptive can extract the frequency, amplitude and positive and negative sequence rapidly and accurately when the voltage is mutated.

When the voltage asymmetry is large, the excessive negative sequence amplitude component will affect the extraction performance of the DSSOGI-FLL with amplitude and frequency adaptive, which leads to the serious distortion of the information traced to the fundamental frequency and amplitude of the positive and negative sequence components. So this paper enhanced the FLL to make it possible to extract the positive and negative sequence, frequency and other information accurately under the condition of large voltage asymmetry. The structure of FLL is shown in Figure 9.

When the voltage is asymmetric, $V_a$ and $V_\beta$ can be expressed as $V_a = V_1 \sin(\omega_1 t + \phi_1)$, $V_\beta = V_2 \cos(\omega_1 t + \phi_2)$. The frequency response characteristics of FLL under voltage asymmetry is:

$$\dot{\omega} = -\frac{\gamma(V^2_1 + V^2_2)}{k[(V'^{+\alpha})^2 + (V'^{+\beta})^2 + (V'^{-\alpha})^2 + (V'^{-\beta})^2]}(\omega - \omega)$$

(27)

Figure 10. Dynamic response of less voltage asymmetry. (a) Less symmetric of three-phase voltage. (b) Estimation of fundamental frequency. (c) Waveform of positive sequence component. (d) Waveform of negative sequence component.
The dynamic response of the input voltage containing DC components. (a) Three-phase voltage with DC components. (b) Variation of frequency before and after the difference node is added. (c) Variation of voltage before and after the difference node is added.

The values of the molecules in (27) is relevant to \( V_\alpha \) and \( V_\beta \), and the positive sequence values cannot cancel out the \((V_1^2 + V_2^2)\) in the molecule. From Figure 9 it can be obtained that

\[
(v_\alpha^{+r})^2 + (v_\beta^{+r})^2 + (v_\alpha^{-r})^2 + (v_\beta^{-r})^2 = \frac{V_1^2 + V_2^2}{2}
\]  

\[\hat{\omega} = -\frac{\nu}{k}(\hat{\omega} - \omega)\]  

The FLL in the enhanced DSSOGI-FLL will have better performance in the process of tracking the frequency and can extract it accurately. Compared with DSSOGI-FLL, the enhanced DSSOGI-FLL can extract the information of frequency, amplitude and positive and negative sequence quickly and accurately when the voltage asymmetrical and harmonics exist.

5. Simulation results

5.1. Less asymmetry of three-phase voltage

In order to better analyse and improve the performance of the DSSOGI-FLL method under the condition of voltage asymmetry, three-phase voltage drops 10%, 20% and 30% respectively when \( t = 0.3 \) s, the result is shown in Figure 10.

5.2. DC components

In order to better analyse the extraction performance of frequency, amplitude and positive and negative sequence components under the condition of dc components, the enhanced DSSOGI-FLL method is adopted. When \( t = 0.3 \) s, the three-phase voltage is added to \( D_a = 5 \) V, \( D_b = -3 \) V, \( D_c = 6 \) V, the result is shown in Figure 11.

According to Figure 11, the enhanced DSSOGI-FLL with difference node can suppress the influence of dc components, and can also extract the frequency and amplitude accurately and quickly.

5.3. Harmonics and frequency hopping

In order to better analyse the performance of the enhanced DSSOGI-FLL method under frequency mutation and harmonic conditions, the fundamental frequency is changed from 50 to 60 Hz at \( t = 0.3 \) s, and the 3rd harmonic of 20 V, the 5th harmonic of 15 V, and the 7th harmonic of 10 V are added to the voltage, the result is shown in Figure 12.
When the input voltage contains harmonics and the frequency is abruptly changed, the enhanced DSSOGI-FLL adaptive filter can eliminate the effects of various harmonics. Compared with DSOGI-FLL, this method can be extracted the frequency and amplitude accurately and quickly.

5.4. Large asymmetry of three-phase voltage

In order to better analyse the performance of FLL in the DSSOGI-FLL method under the condition of large asymmetry of three-phase voltage, the three-phase voltage drops 70%, 80%, and 90% respectively at $t = 0.3$ s, and the frequency is changed from 50 to 60 Hz, the result is shown in Figure 13.

When the voltage is asymmetrical and the degree of drop is large, the FLL in the enhanced DSSOGI-FLL can track the frequency accurately. Compared with DSSOGI-FLL, this method can extract the frequency and amplitude component accurately and quickly.

6. Conclusion

(1) This paper proposes a structure of SSOGI by introducing difference nodes and adding adaptive filters on the basis of SOGI, which can eliminate the effect of harmonics and dc components effectively.

(2) By combining DSSOGI-FLL with PNSC, a positive and negative sequence extraction method based on DSSOGI is proposed, which can extract the frequency, positive and negative sequence components and other information accurately and rapidly under the condition of voltage asymmetry.

(3) When the frequency and amplitude mutates, a positive and negative sequence extraction method based on amplitude–frequency adaptive DSSOGI-FLL is proposed. When the asymmetry of the three-phase voltage is large, the negative sequence component will affect the extraction performance of the DSSOGI-FLL with adaptive amplitude frequency. So the enhanced DSSOGI-FLL method is proposed to suppress the oversize effect of the negative sequence component and to achieve accurate and rapid extraction of the positive and negative sequence components of the fundamental wave.

Disclosure statement

No potential conflict of interest was reported by the authors.

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