Research on Single Phase Frequency Locking Technology Based on Second Order Generalized Integrator

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Abstract. New energy generation has the characteristics of nonlinearity, randomness and fluctuation, which may cause many kinds of power quality problems, such as harmonics, voltage fluctuation, frequency offset and phase jump, so synchronization technology under disturbance becomes one of the key factors. At present, there are many summaries about three-phase phase-locked loop (PLL), three-phase frequency-locked loop (FLL) and single-phase PLL, but few summaries about single-phase FLL. Therefore, single-phase FLL based on second-order generalized integrator (SOGI) is summarized in this paper, including SOGI-FLL, cascaded SOGI-FLL (CSOGI-FLL) and multiple SOGI-FLL (MSOGI-FLL). The simulation models are established in Matlab/Simulink. The performance of FLLs are compared with square error integral index (ISE), maximum frequency deviation and adjusting time in ideal condition, voltage sag condition, frequency offset condition, phase jump condition, the amplitude of fluctuation is used to compare the four PLLs under harmonic condition. The application scopes of different FLLs are summarized to flexible selection in actual working condition.

1. Introduction

New energy generation system has the characteristics of non-linearity, randomness and fluctuation. Many kinds of power quality problems [1], such as harmonic, voltage fluctuation, frequency offset and phase jump, are emerge, so synchronization technology under disturbance becomes one of the key factors for the uninterrupted operation of new energy sources [2]. Among the commonly used synchronization technologies, FLL has better robustness and real-time performance than zero-crossing comparison and PLL [3], so characteristic of FLL needs research. The principle, parameter design and tracking performance of single-phase PLL under perturbation are researched in [4]. Orthogonal methods and enhanced filtering methods are listed in [5] and the influence of SRF-PLL, EPLL, QPLL and DSOGI-PLL on the output current harmonics of inverters is studied in background harmonics. The implementation complexity and synchronization performance of SRF-PLL, EPLL, DSRF-SPLL and DSOGI-FLL under non-fault and fault conditions are compared in [6]. The principles of DSOGI-PLL, CSOGI-FLL and ROR-FLL are analyzed, the transient performance is compared, and the advantages, disadvantages and application scope are given in [7]. SOGI-FLL, LKF-FLL, CBF-FLL and CLO-FLL
are compared and the advantages and disadvantages are pointed out in [8]. The harmonic disturbance performance, transient performance and stability of single-phase SOGI-FLL and CSOG-FLL are compared in [9]. Reference [10] compares SOGI-FLL with MSOGI-FLL, and MSOGI-FLL is sensitive to unknown frequency, super-synchronous inter-harmonics and sub-synchronous inter-harmonics. The single phase PLL, three-phase PLL and three-phase FLL have been summarized and studied, while the single-phase FLL lacks of summary.

This paper describes the principles of SOGI-FLL, CSOGI-FLL and MSOGI-FLL, deduces the mathematical model. Then simulation models are built based on MATLAB/Simulink. The performances of FLLs are compared under ideal condition, voltage sag condition, frequency offset condition, phase jump condition and harmonic condition. Finally, the application scope of different FLLs is summarized.

2. Principle and mathematical model

2.1. SOGI

Figure 1 is the block diagram of SOGI, $u$ is input signal, $v$ and $qv$ are output signals, $\omega$ is the angular frequency of $u$, $\omega'$ is the angular frequency of SOGI. The closed-loop transfer function is

$$
\begin{align*}
D(s) &= \frac{v(s)}{u(s)} = \frac{k\omega's}{s^2 + k\omega's + \omega'^2} \\
Q(s) &= \frac{qv(s)}{u(s)} = \frac{k\omega'^2}{s^2 + k\omega's + \omega'^2} \\
E(s) &= \frac{e(s)}{u(s)} = \frac{s^2 + \omega'^2}{s^2 + k\omega's + \omega'^2}
\end{align*}
$$

(1)

Bode diagram of SOGI is shown in Figure 2.

Figure 1. Block diagram of SOGI.

Figure 2. Bode diagram of SOGI.

$D(s)$ is a second-order bandpass filter, the bandwidth is set by gain $k$ and the center frequency is $\omega'$, the output is the central frequency section of input. $Q(s)$ is a second order lowpass filter, the output can obtain 90 degree information lagging input signal. $E(s)$ is a second order bandstop filter. Therefore, the main functions of SOGI are pre-filtering and constructing orthogonal signals, $v$ has same phase with $u$, and $qv$ is orthogonal to $u$.

2.2. SOGI-FLL

SOGI-FLL is adopted for improving the real-time performance, robustness and simplicity of synchronous signals [11]. Figure 3 is the block diagram of SOGI-FLL, SOGI acts as bandpass filter, $-\gamma$ realizes negative feedback Control, $\omega'$ is fed back to SOGI to realize frequency adaptive adjustment.

Figure 3. Block diagram of SOGI-FLL.
2.3. CSOGI-FLL
There are two kinds of FLL using cascade form, CSOGIv-FLL uses in-phase signal $v_i$ [12] and CSOGIqv-FLL uses orthogonal signal $qv_i$ [13]. Figure 4 and Figure 5 are the block diagram. CSOGI consists of two-stage filters and FLL.

\[
\begin{align*}
\text{SOGI}_1 & : v_1 = \frac{k_1 \omega s \cdot (s^2 + k_1 \omega s + \omega^2)^2}{(s^2 + k_1 \omega s + \omega^2)^2} \\
\text{SOGI}_2 & : v_2 = \frac{k_2 \omega s \cdot (s^2 + \omega^2)^2}{(s^2 + \omega^2)^2}
\end{align*}
\]

Figure 6 is bode diagram of CSOGIv. Figure 7 is bode diagram of CSOGIqv.

From Figure 6 and Figure 7, CSOGIv has sub-synchronous filtering function, and CSOGIqv has better filter function of super-synchronous.

2.4. MSOGI-FLL
Figure 8 is block diagram of MSOGI-FLL, which consists of MSOGI filter and SOGI1-FLL. $D_i$ is the transfer function from $u$ to $v_i$, the transfer function of MSOGI is deduced as

\[
\frac{v_i}{u} = \prod_{i=2}^{n} (1-D_i)
\]

Figure 9 is bode diagram of MSOGI, which shows that specific frequency harmonics (3th, 5th and 7th) are eliminated.
3. Performance comparison

Simulation models are built in MATLAB/Simulink, and parameters are shown in Table 1. To simplify the representation, A stands for SOGI-FLL, B1 stands for CSOGIv-FLL, B2 stands for CSOGIqv-FLL, and C stands for MSOGI-FLL. In order to evaluate the performance of four FLLs, maximum frequency deviation $\Delta f_{\text{max}}$ defines as maximum frequency minus minimum frequency, the moment when frequency error equals 0.01Hz is defined as adjusting time $t_s$, Integral Squared Error (ISE) is defines as $\text{ISE} = \int_0^{\infty} e^2(t)dt$ [14]. If ISE is bounded, which means FLL can lock frequency accurately, the smaller the ISE value is, the better the performances are.

|       | SOGI-FLL | CSOGI-FLL | MSOGI-FLL |
|-------|----------|-----------|-----------|
| $k$   | $\sqrt{2}$, $\gamma=49$ | $k_1=k_2=\sqrt{2}$, $\gamma=23$ | $k_1=\sqrt{2}/i$, $\gamma=49$ |
| $r$   | $348$    | $943$     | $348$     |

3.1. Ideal voltage

Figure 10 is the starting waveform of FLLs under ideal grid voltage. Figure 11 shows the performance indicators. Four FLLs can lock frequency without deviation under ideal grid voltage. SOGI-FLL has the smallest starting frequency deviation, MSOGI-FLL has the shortest adjust time, and SOGI-FLL has the best ISE index.

3.2. Voltage sag

Figure 12 is the waveform of FLLs when voltage sags 0.1pu at 0.02s. Figure 13 shows the performance indicators. Four FLLs can lock frequency without deviation under voltage sags. CSOGIv-FLL has the smallest frequency deviation, MSOGI-FLL has the shortest adjust time, and the ISE index of CSOGIv-FLL is the best.
3.3. Frequency offset
Figure 14 is the waveform of FLLs when the frequency of grid voltage changes from 50Hz to 49Hz at 0.02s. Figure 15 is the main performance indicator. Four FLLs can lock frequency without deviation under frequency offset. SOGI-FLL has the smallest frequency offset, MSOGI-FLL has the shortest adjust time, and MSOGI-FLL ISE index is the best.

3.4. Phase jump
Figure 16 is the waveforms of FLLs when the phase jumps 30° at 0.02s. Figure 17 is the main performance indicator. Four FLLs can lock frequency without deviation under phase jump. CSOGIv-FLL has the smallest frequency deviation, SOGI-FLL has the shortest adjust time, and the ISE index of SOGI-FLL is the best.

3.5. Harmonic
DC is regarded as 0th harmonic by using the concept of generalized harmonic, so harmonics can be divided into DC offset, sub-synchronous inter-harmonic, low-order harmonic, low-order inter-harmonic and high-order harmonic. Under harmonic condition, the waveform of FLL fluctuates and ISE is not a finite value, so the amplitude of fluctuation is used to compare the four PLLs.
3.5.1. DC offset
Figure 18 shows the waveform of FLLs when 0.1pu DC is injected into the grid voltage at 0.02s. Four FLLs have frequency fluctuations with DC offset, and CSOGIv-FLL has smallest frequency fluctuation.

3.5.2. Sub-synchronous inter-harmonics
Figure 19 shows the waveforms of FLLs when 0.5th 0.1pu harmonic is injected into the grid voltage at 0.02s. Four FLLs have frequency fluctuations with Sub-synchronous inter-harmonics, and CSOGIv-FLL has the smallest fluctuation, because pre-filters of four FLLs have different slope at the sub-synchronous frequency.

3.5.3. Low-order harmonics
Figure 20 shows the waveform of FLLs when 3th 0.1pu harmonic is injected into the grid voltage at 0.02s. Four FLLs have frequency fluctuations with low-order harmonics, and the fluctuation amplitudes are different. MSOGI-FLL has the smallest fluctuation, because MSOGI-FLL has cross-cancellation to suppress low-order harmonics.

3.5.4. Low-order inter harmonic and high-order harmonic
Figure 21 and Figure 22 show the waveforms of FLLs when 3.5th 0.1pu and 13th, 0.1pu harmonic are injected into the grid voltage separately at 0.02s. Four FLLs have frequency fluctuations, and CSOGIvq-FLL has smallest frequency fluctuation.
4. Summary
The results of section 3 are summarized, and table 2 is application scope of four FLLs. FLL can be selected according to the actual working conditions of single phase power grid.

Table 2. Application scope of FLL.

| SOGI-FL | CSOGIv-FL | CSOGqv-FL | MSOGI-FL |
|---------|-----------|-----------|----------|
| Ideal voltage | Voltage sag | High-order harmonic | Frequency offset |
| Phase jump | DC offset | Super-synchronous inter-harmonics | Low order harmonics |

5. Conclusion
This paper introduces the basic principles of SOGI-FLL, CSOGIv-FLL, CSOGqv-FLL and MSOGI-FLL. Simulation models are built in MATLAB/Simulink. ISE index is used to comparing the frequency locking performance under ideal conditions, voltage sag conditions, frequency offset conditions and phase jump conditions. Fluctuation amplitude is used to comparing the frequency locking performance under harmonic condition. The simulation results show that:

1. SOGI-FL is suitable for ideal condition and phase jump condition.
2. CSOGIv-FL is suitable for voltage sag condition and DC bias condition.
3. CSOGqv-FL is suitable for high-order harmonics and super-synchronous inter-harmonics condition.
4. MSOGI-FL is suitable for frequency offset condition and low-order harmonics condition.
5. Four kinds of FLLs are not suitable for large sub-synchronous inter-harmonics.
6. FLL can be selected according to the actual working conditions of single-phase power grid.

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