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Advanced SOGI-FLL Scheme Based on Fuzzy Logic for Single-Phase Grid-Connected Converters

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Abstract

This paper proposes a frequency-locked loop (FLL) scheme for a single-phase grid-connected converter. A second-order generalized integrator (SOGI) based on fuzzy logic (FL) is applied to this converter to achieve precise phase angle detection. The use of this method enables the compensation of the nonlinear characteristic of the frequency error, which is defined in the SOGI scheme as the variation of the central frequency through the self-tuning gain. With the proposed scheme, the performance of the SOGI-FLL is further improved at the grid disturbances, which results in the stable operation of the grid converter under grid voltage sags or frequency variation. The PSIM simulation and experimental results are shown to verify the effectiveness of the proposed method.

Key words: Current control, Frequency-locked loop, Fuzzy logic, Second-order generalized integrator SOGI), Single-phase converter

I. INTRODUCTION

An important control issue in grid-connected power converters is to synchronize the phase angle of the controller with the grid voltage [1], [2]. A phase-locked loop (PLL) system is often used to detect the phase angle of the alternating current (AC) grid voltage in the power quality field, such as the reactive power compensator, uninterruptable power supply and active power filters. In a three-phase system, a quadrature signal generator (QSG) is easily obtained using Park's transformation. However, this transformation is difficult to apply directly to a single-phase system [3]-[5].

A common application of the single-phase grid converter is illustrated in Fig. 1. To estimate the frequency or the phase angle of the single-phase system, several methods have been proposed in the literatures [6], [7]. A method using a recursive discrete Fourier transform (DFT), in which the adaptive band-pass filter is applied to extract the nth-order harmonic components in a time domain, was proposed in [6], [7]. However, errors in the amplitude and phase angle exist when the time window of the DFT does not match the fundamental frequency of the input signal. This problem is solved by performing a deadbeat adjustment to the time window or by compensating for the phase error calculated from the DFT [7].

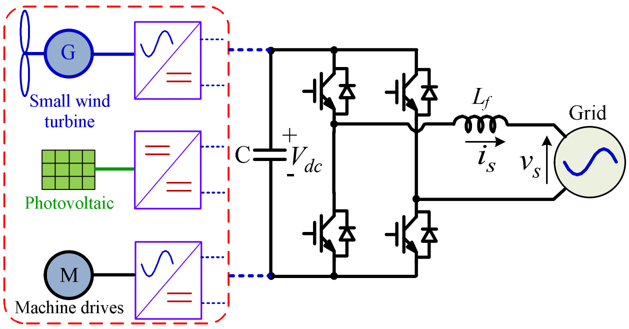

Fig. 1. A typical single-phase grid-connected converter.

Meanwhile, the PLL of the single-phase system has another category, in which the phase detector (PD) consists of a QSG. Different methods can be used to realize the QSG. A simple scheme is to use the all-pass filter or the second-order low-pass filter to generate the quadrature signal [4], though which the PLL performance deteriorates if the grid voltage contains harmonics. In another method, Hilbert transform has been applied [6], [8], causing the signal to be shifted by 90 degrees while the amplitude remains unchanged. Moreover, several methods employs the inverse Park's transform [9] and a full-order state observer [4], the output performance is of

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which is unsatisfactory when the input voltage is distorted.

Another type of PD, which uses the adaptive filter, was suggested to enhance the performance of the PLL [10]. The adaptive notch filter is based on a least-mean-square (LMS) algorithm with two adaptive weights. The LMS algorithm can be understood as a forward discrete integrator that can be transformed into a second-order adaptive filter. A disadvantage of this method is that a complicated computation, including a trigonometric function is required.

The generalized integrator (GI) has recently been widely used to realize PD without the cosine and sine functions [11], [12]. However, the QSG consisting of the GI is susceptible to parameter variations. That is, if the system frequency is disturbed, a phase detection error occurs.

To overcome these drawbacks, several methods have been suggested [13]-[15]. The most popular scheme is to use the second-order generalized integrator [15]. When the input signal of the SOGI is purely sinusoidal at the constant frequency, the output signal delayed by the phase angle of 90° is obtained with the same magnitude. However, if the frequency of the input signal is disturbed or distorted, an additional PLL or FLL is required to obtain a correct output signal. Notably, frequency locking is preferred over phase locking for grid synchronizations since system frequency is less variable than the phase angle. In the SOGI-FLL, an integral controller regulates the frequency error to zero. Designing the integral controller is difficult due to a nonlinear characteristic of the frequency error relative to the variation of the central frequency. Therefore, a gain normalization method has been proposed by using small signal analysis [16]-[18], the response of which was slow in case of an abrupt change in input frequency.

This paper is an extended version of the work [19], in which a SOGI-FLL with a self-tuning gain based on the fuzzy logic is proposed for single-phase grid-connected converters. Under grid voltage sag or the frequency variation conditions, the integral gain for the FLL scheme is simultaneously updated by applying the fuzzy logic controller, through which the frequency error and its variation are used as control input variables for the fuzzy logic. The frequency error and variation of the central frequency are then compensated by the adjustable integral gain. With the proposed scheme, the performance of the SOGI-FLL is further improved within the system frequency change. The validity of the proposed method is verified by the simulation and experimental results.

II. Conventional Grid Synchronization Method of Single-Phase Converter

A. Basics of the Phase-Locked Loop

Fig. 2(a) illustrates the basic structure of a PLL system, which consists of three components: PD, loop filter (LF), and voltage control oscillator (VCO). Fig. 2(b) shows the block

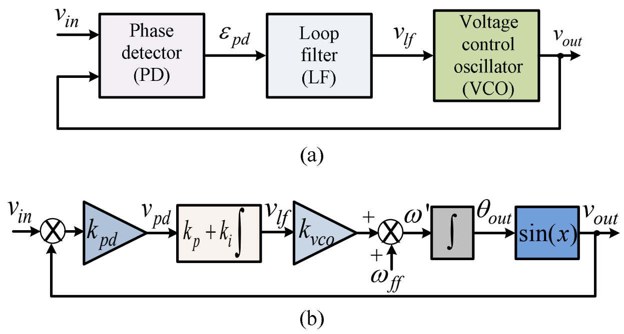


Fig. 2. Principle of PLL. (a) Basic structure of PLL. (b) Block diagram of the PLL system.

diagram of the PLL system in detail. The PD generates the output signal, which is proportional to the phase difference between the input signal v_{in} and the output of the VCO block v_{out}. Depending on the type of PD, the high-frequency components or DC signal may appear in the output of the PD. The high-frequency components are eliminated by the LF or proportional integral (PI) controller. The DC component of the v_{pd} causes the frequency of the output signal to coincide with that of the input signal. The VCO block then generates the output signal, the frequency of which is the same as the input frequency [6].

B. Existing SOGI-FLL Method

A conventional SOGI-FLL scheme based on the adaptive filter has been suggested [17]. In this scheme, an integral gain for the FLL is adjusted by the gain normalization. Fig. 3 shows the block diagram of the SOGI-FLL with a gain normalization, the space-state equations of which are expressed as [16]

$$\dot{x} = \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} -k\omega' & -\omega'^2 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} k\omega' \\ 0 \end{bmatrix} v \tag{1}$$

$$y = \begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & \omega' \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \tag{2}$$

$$\dot{\omega}' = -\gamma x_2 \omega'(v - x_1) \tag{3}$$

where $x = \left[x_1, x_2\right]^T$ and $y = \left[v_d, v_q\right]^T$ are the SOGI-QSG state and output vectors, respectively; v is the input signal; v_d and v_q are the in-phase and in-quadrature signals of the input, respectively; ω' is the estimated grid frequency; k is the SOGI gain; and γ is the integral gain of the FLL.

From Fig. 3, the dynamic of the FLL can be described as

$$\dot{\omega}' = -\gamma \bar{\varepsilon}_f \quad . \tag{4}$$

By considering $\omega' \approx \omega$, $(\omega'^2 - \omega^2)$ can be approximated as $2(\omega' - \omega)\omega'$ for the small signal analysis, (4) can be

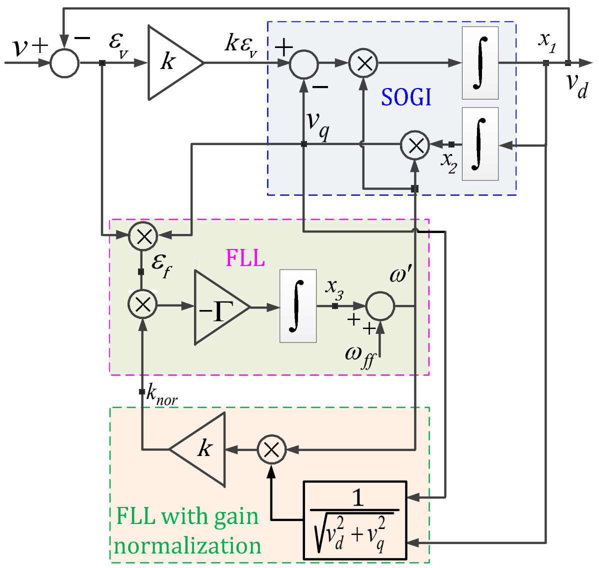
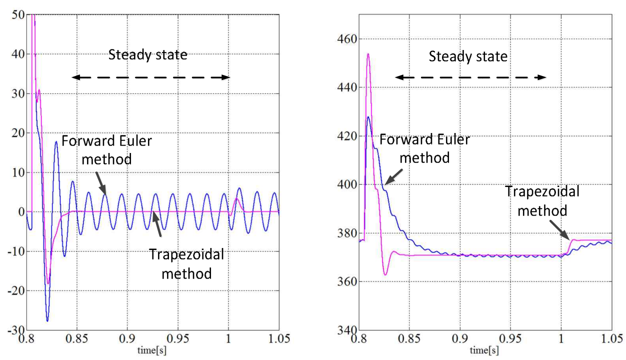


Fig. 3. Block diagram of SOGI-FLL with gain normalization.



(a) (b)

Fig. 4. Effects of integral operation in a time domain. (a) Frequency error. (b) Estimated central frequency.

rewritten as [16], [17]

$$\dot{\omega}' = -\frac{\gamma V^2}{k\omega'}(\omega' - \omega) \tag{5}$$

where V is the magnitude of the input signal.

To achieve the linearized system from the nonlinear dynamics of the FLL, the γ should be normalized. The linearized system then becomes independent of the grid voltage and the SOGI gain. In (5), γ can be normalized as

$$\gamma = \frac{k\omega'}{V^2}\Gamma \tag{6}$$

where Γ represents a new gain, which can adjust the settling time of the frequency estimation loop [17].

From (5) and (6), the transfer function of the frequency estimation loop can be expressed as

$$\frac{\overline{\omega}'}{\omega} = \frac{\Gamma}{s+\Gamma}. \tag{7}$$

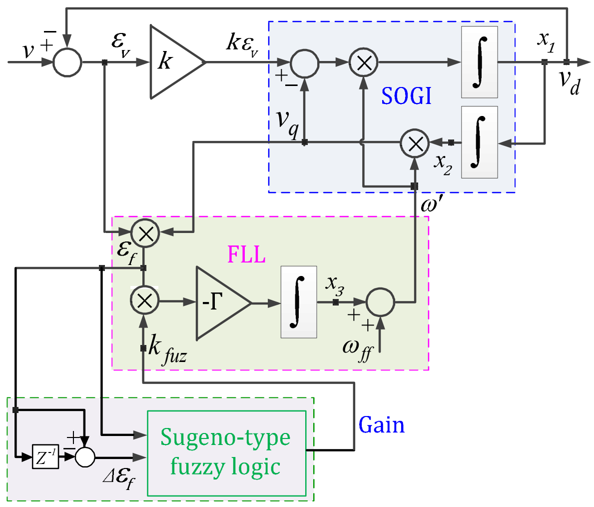


Fig. 5. Block diagram of the proposed SOGI-FLL, based on FL.

In this study, the SOGI parameters are set as $k = 1$ and $\Gamma = 46$ by using a trial-and-error method.

III. Proposed SOGI-FLL Based on Fuzzy Logic Control for Single-Phase Converters

The frequency error $\overline{\varepsilon}_f$ is a nonlinear function of $\dot{\omega}'$ and ω. Accordingly, the linear control technique is unsuitable for use with the SOGI-FLL scheme. When the integrators are implemented in the SOGI scheme in the time domain, the frequency error and the estimated central frequency may have oscillations, depending on the type of digital integrators, the effects of which are shown in Figs. 4(a) and 4(b) [15]. With the forward Euler method, these oscillations are remarkably large, both in the transient and steady states. However, these terms are almost eliminated with the trapezoidal method.

In this research, fuzzy logic is used to determine the value of the FLL gain γ. Fig. 5 shows the block diagram of the proposed SOGI-FLL method, in which the integral gain, γ, is adjusted by the fuzzy logic. For this control, the frequency error and its variation are used as control input variables for the fuzzy logic. The fuzzy rules are described as follows: If the frequency error is high [for example, positive-big (PB) or negative-big (NB)], the fuzzy gain is set to a low value to reduce the integral gain in the FLL. The frequency error is consequently decreased. If the frequency error is low [for example, zero (Z)], the fuzzy gain is set to a high value for rapid estimation. Fig. 6 shows the fuzzification process of the frequency error when the system frequency varies. For instance, we consider that the grid frequency is changed from 60 Hz to 59 Hz without any voltage drop. With the inputs of the frequency error and its rate of change, the membership functions are designed to determine the output, which is the gain shown in Fig. 5.

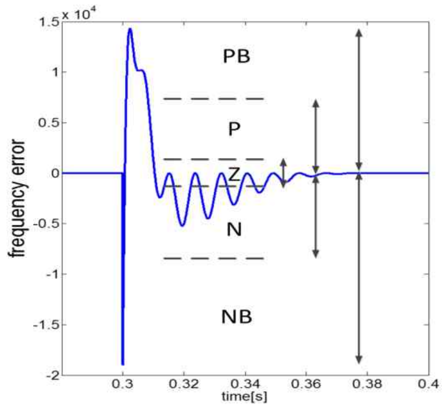


Fig. 6. Fuzzification of the frequency error.

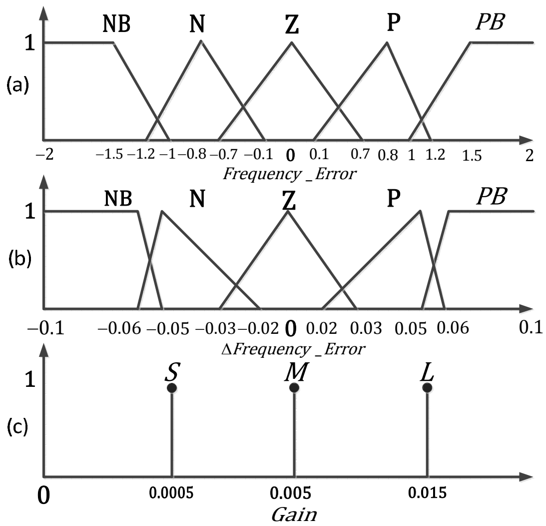


Fig. 7. Membership functions. (a) Frequency error (ε_f). (b) Variation of frequency error ($\Delta\varepsilon_f$). (c) Fuzzy output.

TABLE I

RULES OF FUZZY LOGIC CONTROLLER

		ε_f				
$\Delta\varepsilon_f$		NB	N	Z	P	PB
	NB	S	S	S	S	S
	N	S	L	M	L	S
	Z	S	M	L	M	S
	P	S	L	M	L	S
	PB	S	S	S	S	S

Fig. 7 shows the membership functions for the fuzzy set of inputs and outputs, in which the linguistic variables are represented by PB, Positive (P), Z, Negative (N), NB, Large (L), Medium (M), and Small (S). The grade of the input membership functions is obtained from

$$\mu(x) = 1 - \frac{|x-m|}{0.5w} \tag{8}$$

where w is the width, m is the coordinate of the point at which the grade of the membership is one, and x is the value of the input variable. In this study, the Sugeno-type fuzzy interference is applied [20]. Each rule is weighted by the weighting factor, W_i, which is obtained from the minimum operation as

$$W_i = \min\{\mu_{Fr\_Error}(F), \mu_{Fr\_Error}(\Delta F)\}. \tag{9}$$

The weighted average of all rule outputs that expresses the variation of integral gain, I_{gain}, is calculated as

$$I_{gain} = \sum_{i=1}^{N} W_i C_i \Big/ \sum_{i=1}^{N} W_i \tag{10}$$

where N is the total number of rules, and C_i is the coordinate corresponding to the respective output or consequent membership function.

Next, a fuzzy rule is expressed as follows:

$Rule_i$: *If* $\varepsilon_f(k)$ is A_i and $\Delta\varepsilon_f(k)$ is B_i, then I_{gain} is C_i,

where A_i and B_i comprise the fuzzy subset, and C_i is a fuzzy singleton. All fuzzy rules are listed in Table I. For convenience, the inputs of the FL are normalized by the scaling factor of 10,000 depending on the range of the frequency error.

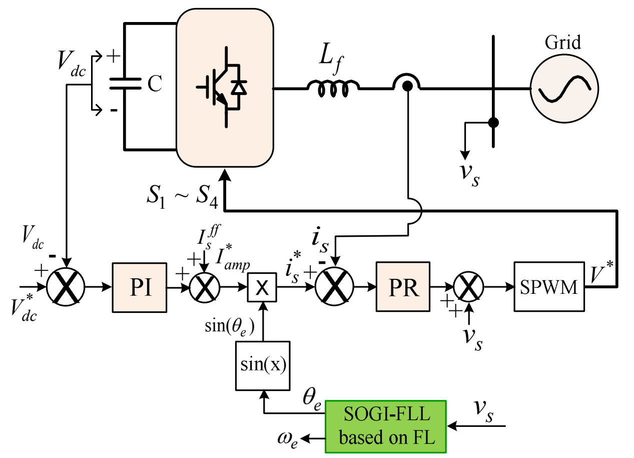


Fig. 8. Control block diagram of the single-phase converter.

Fig. 8 shows the control block diagram of the single-phase grid-connected converter, to which the proposed SOGI-FLL algorithm is applied to detect the phase angle of the grid voltage. The control structure of the converter consists of the DC-link voltage control loop with PI controller and an inner current control loop with a proportional resonant (PR) regulator [21]. The sinusoidal PWM (SPWM) is used to modulate the converter reference voltage.

IV. SIMULATION RESULTS

To verify the effectiveness of the proposed method, the PSIM simulation was carried out for the single-phase AC/DC PWM converter. The specifications of the grid converter are listed in Table II. The parameters of the controllers are listed in Table III. The normal grid voltage is at 220 V and 60 Hz. The DC-link voltage is controlled at 340 V by the single-

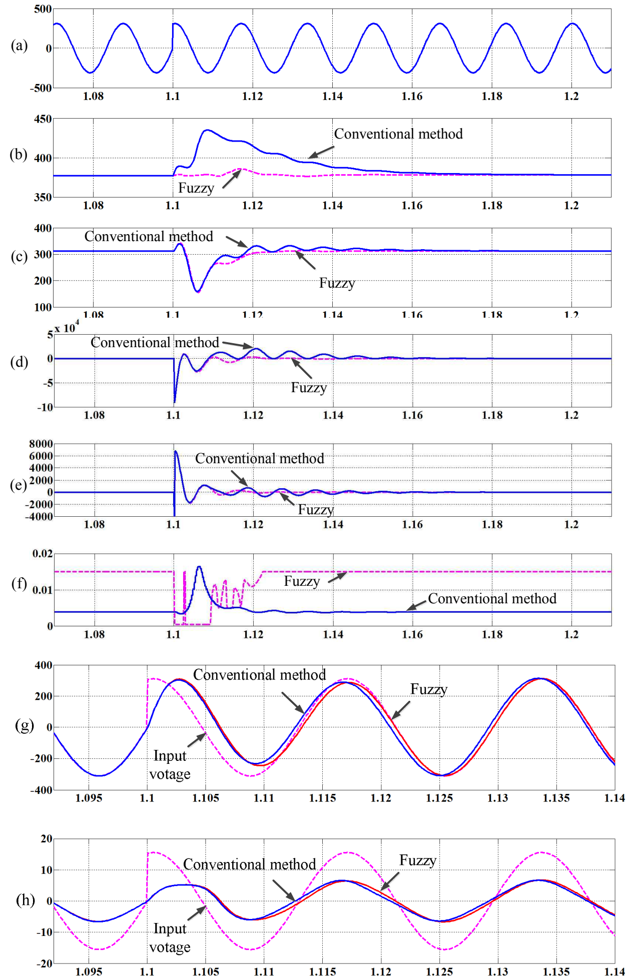


Fig. 9. Performance of conventional and proposed methods. (a) Grid voltage. (b) Estimated angular frequency. (c) Magnitude. (d) Frequency error. (e) Variation of frequency error. (f) Integral gain. (g) SOGI outputs. (h) Grid voltage and current reference.

phase grid converter, the switching frequency of which is 10 kHz.

Fig. 9 shows the performance comparison of the SOGI-FLL scheme after applying the conventional SOGI-FLL with gain normalization and the proposed methods based on the fuzzy control when the angular frequency of the grid voltage is changed from 60 Hz to 60.2 Hz at 1.1 s. Moreover, at 1.1 s, the phase angle of the grid voltage increases from 0° to 90°. The grid voltage is shown in Fig. 9(a). The estimated angular frequency, grid voltage magnitude, frequency error, and the variation of the frequency error are illustrated in Figs. 9(b), (c), (d), and (e), respectively. The gain tuning method using fuzzy logic outperforms the conventional approach. As the grid frequency varies, the estimation error of the frequency with the gain normalization method becomes large, which requires a long time to reach the steady state value, as shown in Fig. 9(b). Fig. 9(f) shows the variation of the integral gain for a large frequency error. The value of integral gain with the fuzzy logic is tuned more finely and thus adapted well

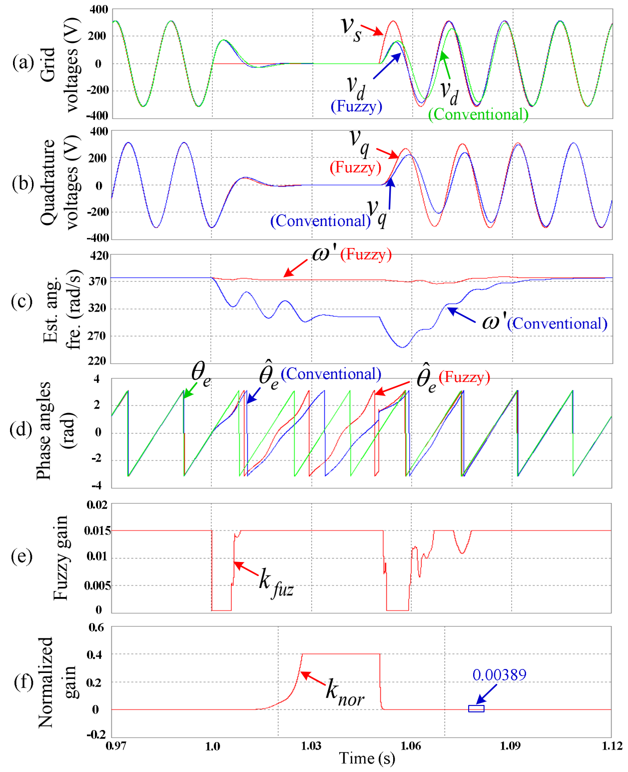


Fig. 10. Performance of the conventional and proposed methods during the grid fault. (a) Grid voltage and estimated in-phase ones. (b) Estimated quadrature voltages. (c) Estimated angular frequencies. (d) Phase angles. (e) Gain in the fuzzy method. (f) Normalized gain.

with the variation of the grid voltage, as is illustrated in Figs. 9(b) to 9(e). Fig. 9(g) provides the outputs of the SOGI-FLL, in which the estimated voltage by the conventional method cannot track the grid voltage closely. However, with the proposed method, the estimated voltage rapidly follows the actual current in a cycle. Fig. 9(h) shows the grid voltage and the grid current reference.

Fig. 10 demonstrates the performance of the FLL with the conventional and proposed methods when the grid voltage is fully interrupted from 1.0 s to 1.05 s, as shown in Fig. 10(a). Figs. 10(a) and 10(b) respectively illustrate the in-phase and quadrature voltage components estimated by the FLL in which the waveforms prove that the use of the proposed method enable the estimation of the grid voltages within a cycle. Meanwhile, the use of the conventional method requires approximately two cycles for the estimated voltage to track the actual current. Fig. 10(c) shows the estimated frequencies. The central frequency is well estimated using the proposed method. However, with the conventional scheme, a large estimation error exists, as shown in Fig. 10(d). The use of the proposed scheme enables the phase angle to be well estimated within a cycle in a manner is faster than that with the conventional scheme. Figs. 10(e) and 10(f) show the integral gain with the proposed and conventional methods,

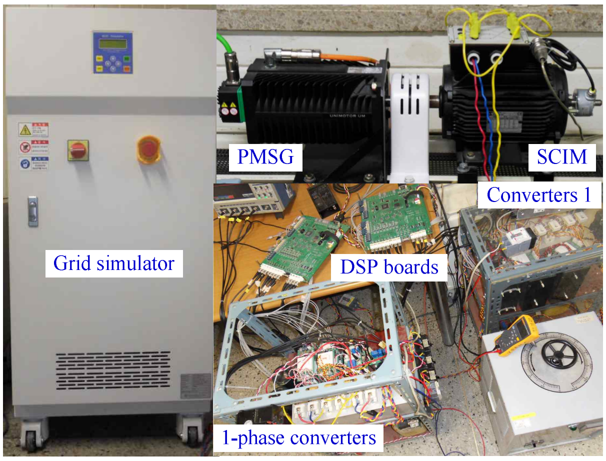


Fig. 11. Experimental setup.

respectively, where the normalized gain, k_{nor}, is increased to its limit, as shown in Fig. 10(f). The limit of the normalized gain is set as 0.4, which is determined from (6) considering the case of 90% grid voltage sag.

V. Experimental Results

A laboratory prototype of the single-phase grid converter system, which is integrated with a 2.68 kW PMSG wind turbine, was built for experimental tests to verify the validity of the proposed strategy, as shown in Fig. 11. The parameters of the single-phase converter are the same as those in the simulation, as listed in Table II. For producing the grid voltage disturbances, a grid simulator is used. The normal grid voltage is set as 150 V and 60 Hz. The DC-link voltage is controlled at 240, V and the switching frequency of the converter is 10 kHz. The sampling time of the current controller and the fuzzy logic controller is at 100 µs.

The FLL performances by the conventional and proposed methods are shown in Figs. 12 and 13, respectively, under grid interruption of 100 ms, as shown in Figs. 12(a) and 13(a). The in-phase and quadrature voltage components with the proposed method are estimated to be faster than that with the conventional method, particularly after the grid fault clears. Figs. 12(b) and 13(b) show the estimated phase angles. In the conventional FLL, approximately three cycles of tracking time is required after the grid fault clears, whereas only one and a half cycles is required in the proposed method. The central frequency in the conventional method fluctuates significantly, as shown in Fig. 12(c), whereas with the frequency remains close to the actual value of 377 rad/s in the proposed method, as shown in Fig. 13(c). Fig. 12(d) shows the normalized gain of the conventional method, which reaches the limit. Fig. 13(d) shows the fuzzy gain, which is stable and precisely tuned.

Fig. 14 illustrates the control performance of the grid converter under the voltage sag condition, in which the grid voltage is fully interrupted at 100 ms, as shown in Fig. 13 (a). Fig. 14(b) shows the DC-link voltage, which is still

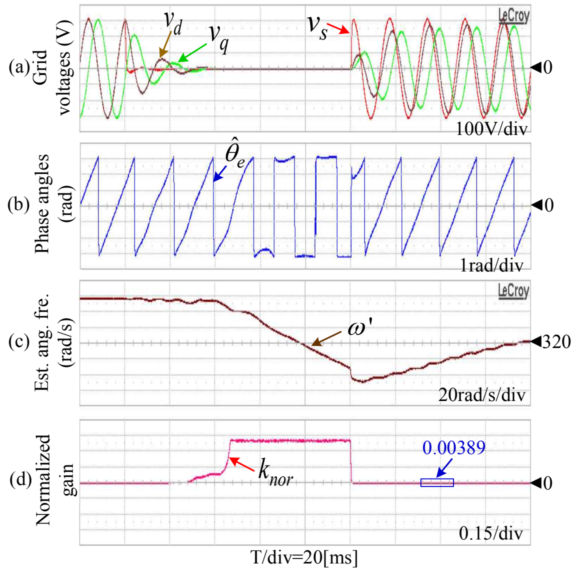


Fig. 12. Performance of the conventional method during the grid fault. (a) Grid voltage and estimated in-phase ones. (b) Phase angle. (c) Estimated angular frequency. (d) Normalized gain.

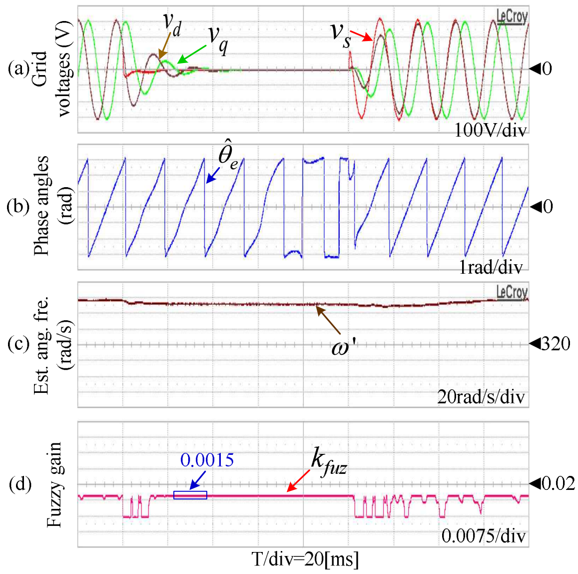


Fig. 13. Performance of the proposed method during the grid fault. (a) Grid voltage and estimated in-phase ones. (b) Phase angle. (c) Estimated angular frequency. (d) Fuzzy gain.

controllable after the grid voltage recovery. Fig. 14(c) provides the grid currents. The grid fault occurrence and recovery, the transient values in the DC-link voltage, and the grid current appear but are within the allowable range. Figs. 14(d) and 14(e) show the precisely estimated frequency and phase angle, respectively. Fig. 14(f) displays the frequency error, which is used for the fuzzy implementation. The fuzzy gain then is updated more precisely during the grid voltage sag, which is shown in Fig. 14(g).

Fig. 15 demonstrates the performance of the SOGI-FLL under the grid frequency variation. Fig. 15(a) shows the grid

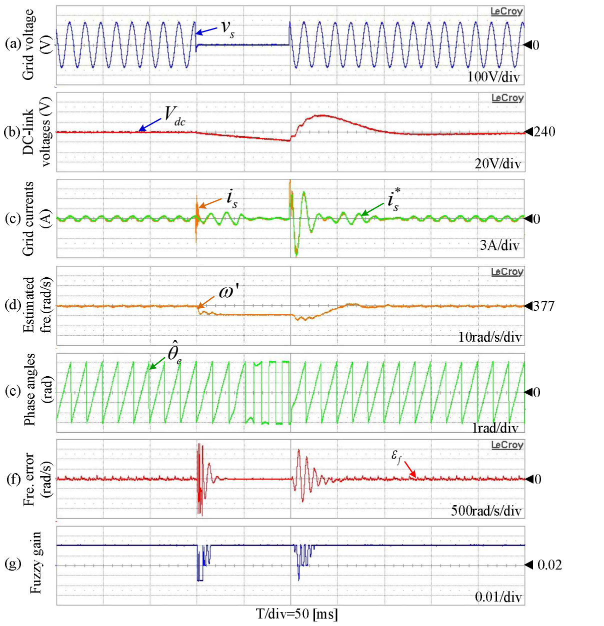


Fig. 14. Performance of the grid converter during the grid fault. (a) Grid voltage. (b) DC-link voltage. (c) Grid currents. (d) Estimated angular frequency. (e) Phase angle. (f) Frequency error. (g) Gain using the fuzzy logic.

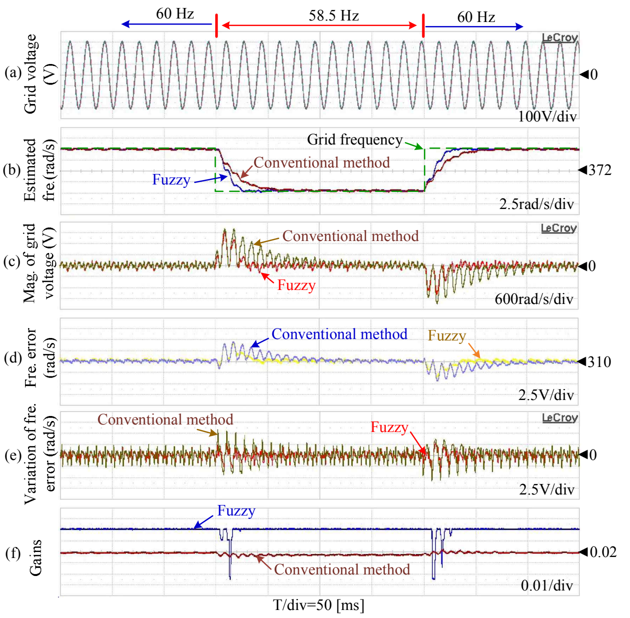


Fig. 15. Performance of the conventional and proposed methods for abrupt changes in the source' frequency. (a) Grid voltage. (b) Estimated frequency. (c) Frequency error. (d) Magnitude of the grid voltage. (e) Variation of frequency error. (f) Integral gain.

voltage, which is adjusted by the grid simulator. The grid frequency is changed from 60 Hz to 58.5 Hz without any phase jump. As shown in Fig. 15(b), the estimated angular frequency for the proposed method follows the actual process and provides faster response than that of the conventional approach. Figs. 15(c) and 15(e) indicate the frequency error and its variation for both methods, respectively. With the

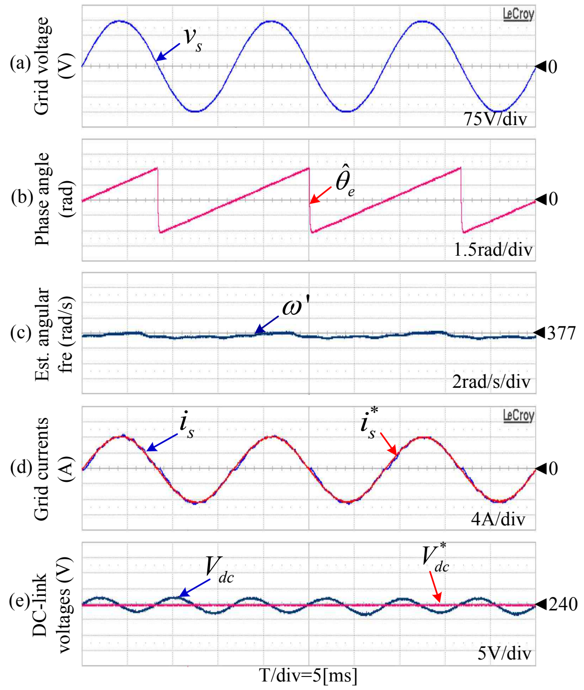


Fig. 16. Control performance of the grid converter. (a) Grid voltage. (b) Phase angles. (c) Estimated angular frequency. (d) Grid currents. (e) DC-link voltages.

proposed method, the frequency error and its variation decay faster. Fig. 15(d) shows the magnitude of the grid voltage. With the proposed method, the grid voltage magnitude reaches the correct value faster. Fig. 15(f) indicates the integral gains, which are tuned more precisely in the fuzzy logic scheme.

Now, we consider the small PMSG wind turbine system of which output is connected to the single-phase grid converter. The control of this small wind system is described in detail in [22]. A cascaded control structure consisting of an outer power control loop and an inner current control loop is applied to the boost converter. As a result, the maximum power point tracking (MPPT) control for the PMSG wind turbine is achieved [22]-[24].

Fig. 16 shows the control performance of the single-phase converter integrated with the small wind turbine. Fig. 16(a) shows the grid voltage, the phase angle and frequency of which are shown in Figs. 15(b) and 15(c), respectively, based on estimation. Fig. 16(d) shows the grid currents, the control performance of which is satisfied. The DC-link voltage is maintained close to the reference value of 240 V, as shown in Fig. 16(e).

Fig. 17 shows the performance of the PMSG wind turbine system. Fig. 17(a) shows the wind speed provided to the turbine blades. Then, with the MPPT control, the generator is mostly proportional to the wind speed, as shown in Fig. 17(b). Fig. 17(c) shows the generator power, which is controlled by the boost converter. Fig. 17(d) shows the boost currents. As shown in Figs. 17(c) and 17(d), the control performances of

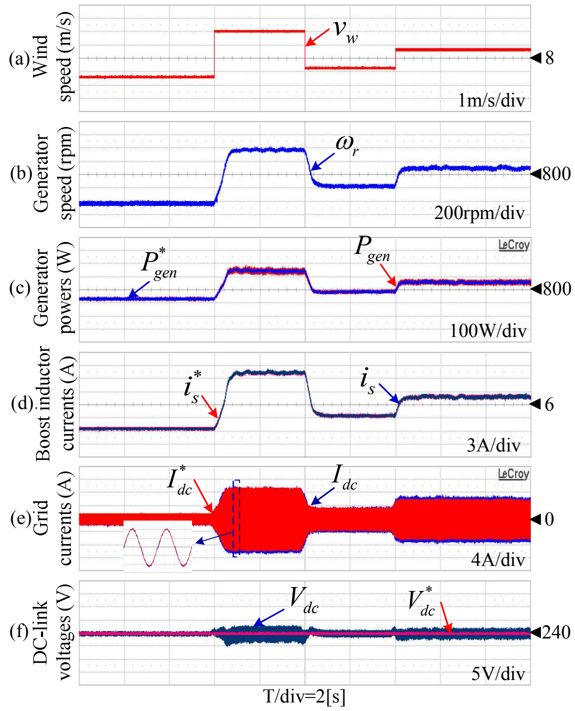


Fig. 17. Control performance of the PMSG wind turbine. (a) Wind speed. (b) Generator speed. (c) Generator powers. (d) Boost inductor currents. (e) Grid currents. (f) DC-link voltages.

the power and current of the boost converter are good. Fig. 17(e) shows the grid currents, the magnitude of which is proportional to the generator power. Fig. 17(f) shows the DC-link voltage, which is controlled to be close to its reference. Moreover, the transient value of the DC-link voltage is extremely low under the stepwise change of the wind speed.

Fig. 18 shows the control performance of the PMSG wind turbine system under the grid frequency variation. Figs. 18(a) to 18(c) show the grid voltage and its estimated phase angle and frequency, respectively. Fig. 18(c) reveals that the grid frequency changed from 60 Hz to 58.5 Hz for 200 ms and 100 ms, through which the ripple of the estimated frequency during the frequency variation is less than 0.85%. Furthermore, the phase angle is detected accurately. The grid current and DC-link voltage are controlled well, as shown in Figs. 18(d) and 18(e), respectively. Likewise, the DC-link voltage remains unchanged, such that the control of the PMSG was unaffected during the grid frequency change, as confirmed in Figs. 18(f) and 18(g) for the inductor current and generator power, respectively.

VI. CONCLUSIONS

A novel SOGI-FLL with the self-tuning gain based on the fuzzy logic controller for the single-phase grid-connected converter is proposed in this paper. The SOGI-FLL with conventional gain tuning requires a linearization process of the nonlinear characteristic between the frequency error and

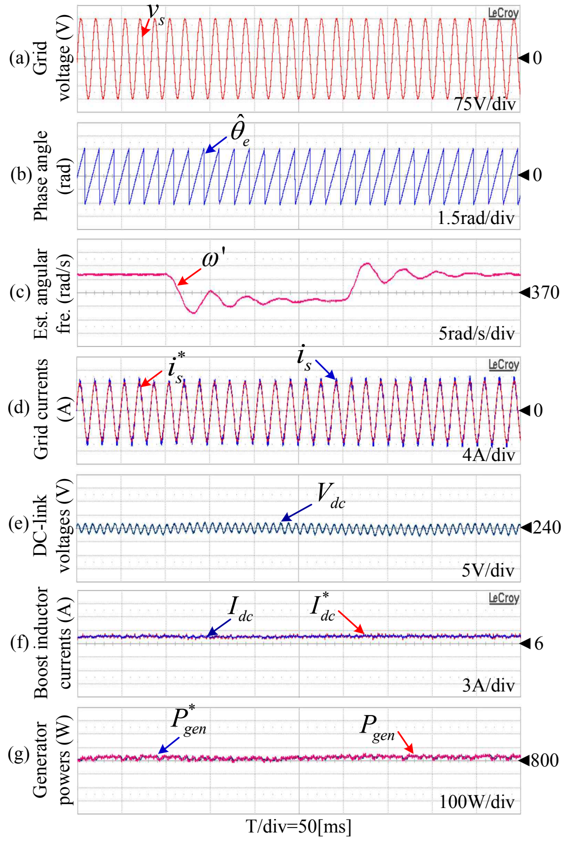


Fig. 18. Control performance of the PMSG wind turbine under grid frequency variation. (a) Grid voltage. (b) Phase angles. (c) Estimated angular frequency. (d) Grid currents. (e) DC-link voltages. (f) Boost inductor currents. (g) Generator powers.

the variation of the central frequency. However, fuzzy logic has solved the nonlinear characteristic for the gain tuning, in which the frequency error and its variations are used as input variables of the FL. With this proposed scheme, the grid converter still functions stably under the grid voltage sag or the grid frequency variation. The validity of the proposed SOGI-FLL method for the single-phase grid converter has been verified by the simulation and experimental results and has thus been applied to a small PMSG wind turbine.

APPENDIX

The parameters of the grid converter, controller gains, and generator are listed in Tables II and III, respectively.

TABLE II
PARAMETERS OF GRID CONVERTER

Rated power	3 kW
Grid voltage/frequency	220 V/60 Hz
Boost inductance	3 mH
DC-link capacitance	4,700 µF
DC-link voltage	340 V

TABLE III
PI AND PR CONTROLLER GAINS

K_p_PI	1.307
K_i_PI	328.72
K_p_PR	35
K_i_PR	350

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