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왜곡된 전원 전압하에서 Composite 관측기를 이용한 단상 PWM 컨버터의 정현파 전류 제어

Thanh Hai Nguyen*, 李東椿†, 李錫圭**

Sinusoidal Current Control of Single-Phase PWM Converters under Voltage Source Distortion Using Composite Observer

Thanh Hai Nguyen, Dong-Choon Lee, and Suk-Gyu Lee

요 약

본 논문에서는 composite 관측기를 이용하여 전원전압 왜곡시 단상 PWM 컨버터의 고성능 전류제어를 제안한다. composite 관측기를 적용함으로써 전원 전압 및 전류의 기본파와 고조파 성분을 시간지연 없이 추출할 수 있다. 추출된 기본파 성분은 전원단의 페이저 각을 찾는 PLL시스템에 이용된다. 멀티 비례-공진 제어기로 단상 입력전류를 정현파로 제어하고 고조파 성분을 제거한다. 시뮬레이션과 실험 결과로 제안된 방법의 타당성을 검증한다.

ABSTRACT

In this paper, a high-performance current control for the single-phase PWM converter under distorted source voltages is proposed using a composite observer. By applying the composite observer, the fundamental and high-order harmonic components of the source voltage and current are extracted without a delay. The extracted fundamental component is used for a phase-lock loop (PLL) system to detect the phase angle of the source voltage. A multi-PR (proportional-resonant) controller is employed to regulate the single-phase line current. The high-order harmonic components of the line current are easily eliminated, resulting in the sinusoidal line current. The simulation and experimental results have verified the validity of the proposed method.

Key Words : Composite observer, PLL, PR controller, single-phase PWM converters.

1. Introduction

Recently, single-phase PWM converters have been widely used in industrial applications and the grid connection of renewable energy conversion systems [1]-[4]. A simple application of a single-phase PWM converter is shown in Fig. 1. The phase, frequency, and amplitude of the single-phase voltage are important information for the precise control of single-phase PWM converters.

The phase-lock loop structure for the single-phase system is more difficult than that of in the three-phase systems.

Usually, for the control of the three-phase PWM converter, the voltage and current are transformed into dq-variables by Park transformation, being the DC quantities [5]-[7]. However, for the single-phase PWM converter system, the line current is controlled instantaneously in an AC sinusoidal waveform. In this case, the PR current controller is preferable to the simple PI(proportional and integral)

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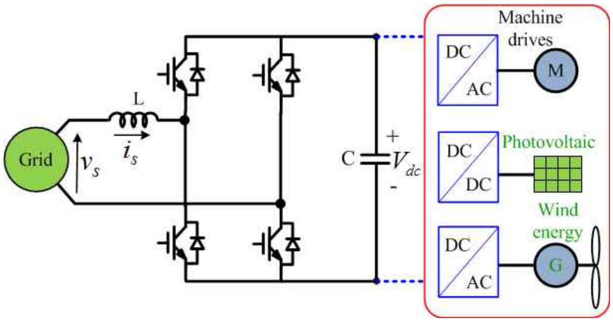

Fig. 1 Single-phase PWM converter

controller [8].

The source voltage disturbance such as harmonics, magnitude and frequency fluctuations, and phase shifts, etc. often occur. Nevertheless, a PLL should operate accurately for stable control.

Otherwise, potentially harmful situations arise such as false protection tripping and even system stability issues. Due to the nature of single-phase systems, specific challenges in obtaining accurate estimates of the frequency and phase angle under varying line conditions have been paid attention [6].

For detecting and extracting the harmonic components, several research results have been reported [9]-[10]. Passive filters with a fixed cut-off frequency may not give a good performance [9], when the operating frequency drifts far away from the resonance frequency. The fast Fourier transform (FFT) has been proposed to extract the individual harmonic components [10]. However, its accuracy is low under time-varying conditions and its performance is sensitive to noise.

The control schemes for a single-phase PWM converter have been presented in [11]-[13]. A PR regulator was used to control the source current [11]-[12]. However, these studies focus only on the control of the fundamental component of the source current without elimination of the high order harmonics. In [13], the single-phase inverter is functioned as an active power filter to compensate for the load harmonic currents. However, the source voltage distortion was not considered in the research.

In this paper, a novel control scheme of single-phase PWM converters is presented to improve the control performance and the THD (total harmonic distortion) of the source current even under distorted line voltage conditions. For this, a composite observer is applied to estimate the fundamental and high-order harmonic components of the line voltage and current precisely. By employing the fundamental component of the source voltage for the PLL, the phase angle is detected accurately for the control. A multi-PR controller is employed to regulate the line current, in which the high-order harmonic components of the line current are significantly reduced, resulting in a sinusoidal current waveform flowing into the source. The validity of the proposed control scheme is verified by the simulation and experimental tests.

2. Composite observer

A periodic signal, $y(t)$, of the fundamental angular frequency, ω_1 , including its harmonics can be expressed as [14]

$$y(t) = \sum_{m=0}^{N} y_m(t) \tag{1}$$

where $y_0(t), y_1(t), y_2(t), \ldots, y_m(t)$ represent the DC fundamental, and harmonic components, respectively. The maximum number of harmonic components considered is N. The state equation of the composite observer can be expressed as [15]-[16].

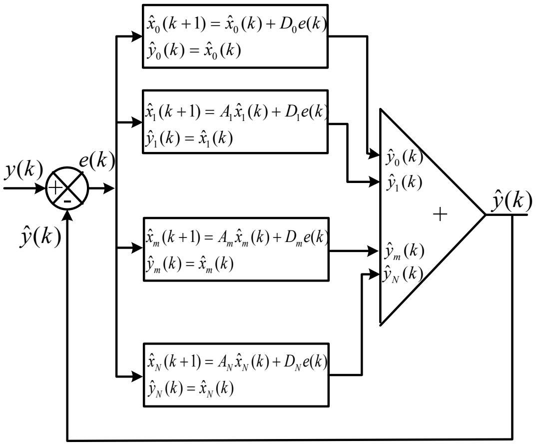

Fig. 2 Block diagram of composite observer

$$\begin{cases} \dot{x}(t) = Ax(t) \\ y(t) = B^t x(t) \end{cases} \tag{2}$$

where *x(t)* is a state vector, *y(t)* is an output, and

$$A = \begin{bmatrix} A_0 & 0 & 0 & \cdots & 0 & \cdots & 0 \\ 0 & A_1 & 0 & \cdots & 0 & \cdots & 0 \\ 0 & 0 & A_2 & \cdots & 0 & \cdots & 0 \\ & & & \vdots & & & \\ 0 & 0 & 0 & \cdots & A_m & \cdots & 0 \\ & & & \vdots & & & \\ 0 & 0 & 0 & \cdots & 0 & \cdots & A_N \end{bmatrix}$$

$$A_0 = 0$$

and the m^th sub-block in the matrix [A] is expressed as

$$A_m = \begin{bmatrix} 0 & m \cdot \omega_1 \\ -m \cdot \omega_1 & 0 \end{bmatrix}$$

and,

$$[B]^t = [1\ 1\ 0\ 1\ 0 \cdots 1\ 0]$$

A discrete composite observer is commonly used for practical applications [14]. Hence, the periodic signal, *y(t)*, is expressed in discrete time domain as $y(t) \Leftrightarrow y(kT)$,where *t=kT* for k=0,1,2,⋯,∞, and T is the sampling time.

The discrete observer model can be expressed as

$$\begin{cases} x(k+1) = Ax(k) \\ y(k) \quad = B^t x(k) \end{cases} \tag{3}$$

where the matrices of A and B are similar to those of in the continuous time domain, in which the m^th typical sub-block is given by

$$A_m = \begin{bmatrix} \cos(m \cdot \omega_1 T) & \cos(m \cdot \omega_1 T) - 1 \\ \cos(m \cdot \omega_1 T) + 1 & \cos(m \cdot \omega_1 T) \end{bmatrix}$$

The composite observer for extracting the harmonic components can be modeled as a closed-loop linear system, of which open-loop parts have the blocks arranged in parallel structures. The sum of all the individual (N+1) output variables is the scalar output of the observer,

$$\hat{y}(k) = \sum_{m=0}^{N} \hat{y}_m(k) \tag{4}$$

where the superscript of " ˆ " represents the estimated quantity.

Fig. 2 shows the structure of the discrete composite observer, in which the m^th block can be represented by the state vector $\hat{x}_m(k)$ and the output variable $\hat{y}_m(k)$ as

$$\begin{cases} \widehat{x_m}(k+1) = A_m \widehat{x_m}(k) + D_m e(k) \\ \widehat{y_m}(k) \quad = B_m^t \widehat{x_m}(k); \qquad m = 0,1,2,\cdots,N \end{cases} \tag{5}$$

where the observation error *e(k)* is defined as

$$e(k) = y(k) - \hat{y}(k) \tag{6}$$

Then, the closed-loop composite observer is expressed as

$$\begin{cases} \hat{x}(k+1) = A\hat{x}(k) + De(k) \\ \hat{y}(k) \quad = B^t \hat{x}(k) \end{cases} \tag{7}$$

where, D is the gain vector as

$$D = [D_0, D_1, \cdots, D_m, \cdots, D_N]$$

3. Control scheme of single-phase PWM converters

3.1 Single-phase PLL detection

To detect the phase angle of the source voltage varying in a sinusoidal waveform, a PLL algorithm is necessary, by which a reference frame for control is determined.

A phase angle detection method applied to a single-phase utility systems was described in [17], based on the modified three-phase instantaneous reactive power theory (p-q theory), and its PLL structure is shown in Fig. 3. As an input signal of the PLL block, the measured source voltage, v_s is set to $v_\alpha (v_\alpha = v_\alpha^{'})$ in the $\alpha\beta$-coordinate. The β-axis value, $v_\beta^{'}$, is obtained by introducing a phase delay of $\pi/2$ rad to the voltage $v_\alpha^{'}$, which is produced by the two-phase generator. A term of fictitious instantaneous power, $p^{'}$, is computed from the $\alpha\beta$-axis voltages and the $\alpha\beta$-axis fictitious currents, $i_{\alpha\beta}^{'}$, in which the magnitude of $i_{\alpha\beta}^{'}$ is unity. By controlling the DC component in the fictitious

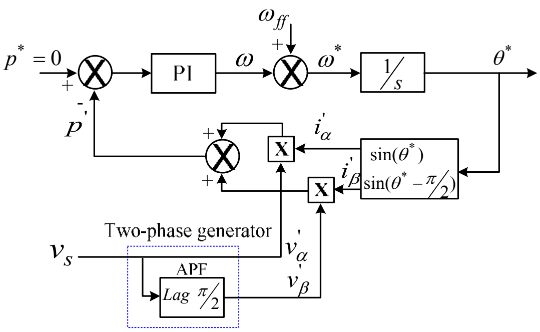

Fig. 3 Single-phase PLL structure

instantaneous power, p', to zero, the PLL system produces the angular frequency from the PI regulator. The phase angle is obtained by integrating the angular frequency as seen in Fig. 3. In order to get the instantaneous power information, the $\alpha\beta$-coordinate of fictitious currents should be orthogonal to the voltages v'_α and v'_β ,respectively.

In order to make a delay of $\pi/2$ rad in the source voltage, an all-pass filter (APF) is applied to the source voltage [18]. The transfer function of the APF is given as

$$H_{APF}(s) = \frac{s^2 - bs + c}{s^2 + bs + c} \tag{8}$$

where $b = 377$ [rad/s] and c=$\pi/2$.

In Fig. 3, ω_{ff} (=377rad/s) is a feed-forward frequency component given by the voltage source.

3.2 Multi proportional-resonant controller

The PR controller structure has been preferred for the single-phase PWM converter since the PI controllers gives a phase delay in the steady-state. The transfer function of the PR controller is expressed as [8]

$$H_{PR}(s) = K_p + K_I \frac{s}{s^2 + \omega^2} \tag{9}$$

where Kp is the proportional gain, KI is the integral gain ,and ω is the resonance frequency. This type of PR controllers can achieve a very high gain in anarrow-frequency band centered at the resonance frequency. The harmonic resonance frequency selection can also be included in the structure by cascading several integrator tuned for resonance at the desired frequency. The transfer function of a multi-PR controller for 3rd, 5th, and 7th-order harmonics which are dominant in the current spectrum, is given as

$$H_{PR}(s) = K_p + K_{I1} \frac{s}{s^2 + \omega_1^2} + \sum_{h=3,5,7\ldots} K_{Ih} \frac{s}{s^2 + (\omega_1 \bullet h)^2} \tag{10}$$

where h is the harmonic order, K_{I1} is the integral gain for the fundamental component, and K_{Ih} is the integral gain for the h^{th} harmonic component.

3.3 Proposed DC-link voltage and current controllers

The control block diagram of the proposed method for single-phase PWM converter is shown in Fig. 4, which consists of an outer DC-link voltage control loop and an inner current control loop. First of all, the fundamental and harmonic components of the line voltage and current, $v_{s-1st}, v_{s-3rd}, \cdots, v_{s-nth}$ and $i_{s-1st}, i_{s-3rd}, \cdots, i_{s-nth}$, respectively, are extracted by the composite observers. The fundamental components of the voltage and current are employed for the PLL algorithm to detect the phase angle, θ, for the current controller. In spite of the distorted source voltage, the line current is controlled sinusoidally by the multi PR controllers with the composite observer.

The DC-link voltage is controlled by a PI regulator. The output of the DC-link controller is the magnitude of the line current, I^*_{amp}. The source current reference is generated as

$$i^*_{s1} = i^*_{amp} \sin(\theta) \tag{11}$$

where θ is the phase angle of the fundamental component of the source voltage. Thus, the line current is controlled in phase with the source voltage. Notice that the source current reference is a 60 Hz AC sinusoidal signal in the steady state.

A feed-forward component for the current amplitude, I_{ff},,as shown in Fig. 4 is added to improve the dynamic performance of the DC-link voltage control under load change conditions. The

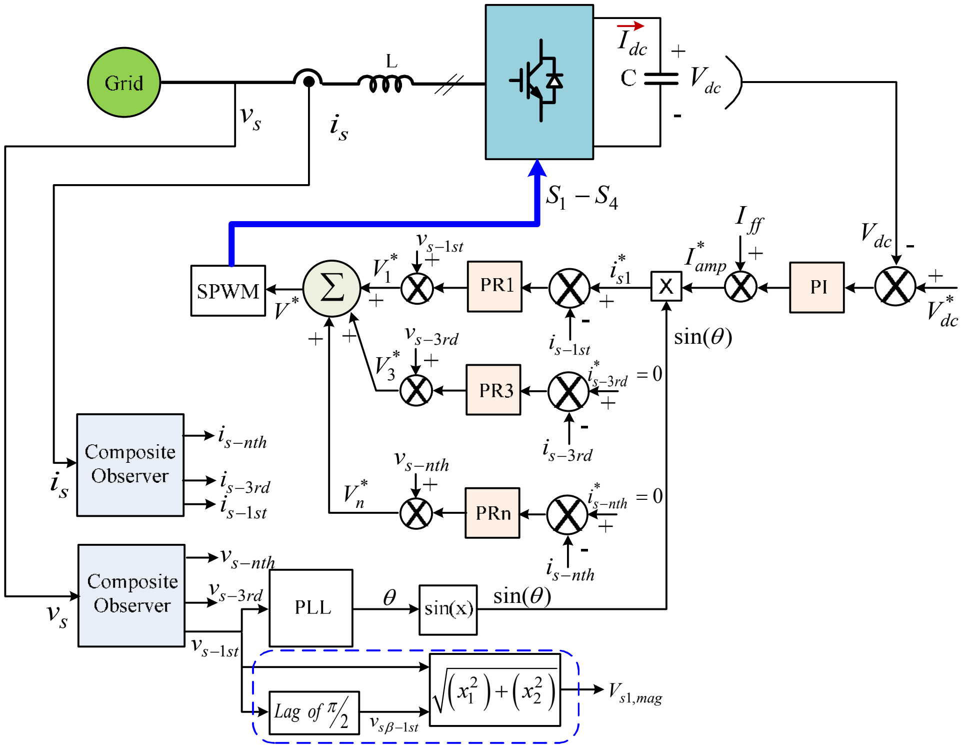

Fig. 4 Control block diagram of single-phase converters

input power, P_{IN}, of the converter is computed from the fundamental component since the harmonic source current components have been eliminated, which is expressed as

$$\begin{aligned}P_{IN} &= 1/2\,V_{s1,mag}I_{s1,mag}+1/2\,V_{s3,mag}I_{s3,mag}+1/2\,V_{s5,mag}I_{s5,mag}+\cdots\\ &= 1/2\,V_{s1,mag}I_{s1,mag}\end{aligned} \tag{12}$$

where $v_{s1,mag}$, $v_{s3,mag}$, $v_{s5,mag}$, and $I_{s1,mag}$, $I_{s3,mag}$, $I_{s5,mag}$ are the magnitude of the fundamental, third, and fifth order components of the source voltage and current, respectively.

The output power, P_{out}, is calculated from the DC-link quantities

$$P_{out}=V_{dc}I_{dc} \tag{13}$$

where V_{dc} is the DC-link voltage and I_{dc} is the output current of the converter which is reconstructed from the source current, I_s, and the switching time of the IGBTs [11].

By considering the power balance of the converter with the converter power loss neglected, the feed-forward component can be expressed from (12) and (13) as

$$I_{ff}=\frac{2\,V_{dc}I_{dc}}{v_{s1,mag}} \tag{14}$$

In order to obtain the magnitude of the source voltage, the fundamental component, v_{s-1st}, is set as the α-axis component, $v_{s\alpha-1st}$, in which it can be written as $v_{s\alpha-1st}=V_{s1,mag}\cos(\theta)$. The β-axis component, $v_{s\beta-1st}$, is obtained by delaying the α-axis component by $\pi/2$ rad. So, the $v_{s\beta-1st}$ becomes

$$v_{s\beta-1st}=V_{s1,mag}\cos(\theta-\pi/2)\;V_{s1,mag}\sin(\theta) \tag{15}$$

Then, the amplitude of the fundamental component is obtained as

$$V_{s1,mag}=\sqrt{v_{s\alpha-1st}^2+v_{s\beta-1st}^2} \tag{16}$$

A multi PR regulator is applied for the line current controller. The main PR controller, PR1, regulates the fundamental component of the line current. The high-order harmonic components, $i_{s-3rd}, \cdots, i_{s-nth}$, of the line current need to be eliminated before flowing into the source by the PR3, ⋯, PRn controllers, respectively, so the references of these controllers are set to zero. The feed-forward components of each harmonic voltage, $v_{s-1st}, v_{s-3rd}, \cdots, v_{s-nth}$, are compensated for each PR regulator as shown in Fig. 4.

4. Simulation results

To verify the effectiveness of the proposed method, the PSIM simulation has been carried out for a 2 kW single-phase PWM converter model. The system specification is listed in Table I.

In order to investigate the control performance under source voltage disturbance, the single-phase PWM converter is supplied by a distorted source voltage containing the 10%, 6%, and 2% of the 3rd, 5th, and 7th harmonic orders, respectively, which is shown in Fig. 5(a). Fig. 5 shows the estimation performances of the composite observer for the source voltage and current.

In addition, the fundamental and harmonic components of the source voltage have been also extracted individually as shown in Fig. 6. Fig. 6(a) shows the fundamental component which is a pure sinusoidal signal and the 3rd, 5th, and 7th order harmonic components are shown in Fig. 6(b)-(d), respectively. The harmonic spectrum of source voltage is shown in Fig. 7 by the Fast Fourier Transform (FFT). Fig. 7(a) shows the spectrum of the fundamental component, where the magnitude and frequency are 311.12 V and 60 Hz, respectively. Also, the magnitudes and frequencies of the 3rd, 5th, and 7th-order harmonic components, which are 31.1 V, 18.7 V, and 6.2 V, and 180 Hz, 300 Hz, and 420 Hz, respectively are shown in Fig. 7(b).

Fig. 8 shows the control performance of the

Table 1 PWM converter parameters

Parameters	Value
Power rating	2[kW]
Input AC voltage	220 [V$_{rms}$], 60[Hz]
Input boost inductance	2.75[mH]
DC-link capacitance	1,600[uF]
Switching frequency	5[kHz]
DC-link voltage	340[V]
Sampling time	100[µs]

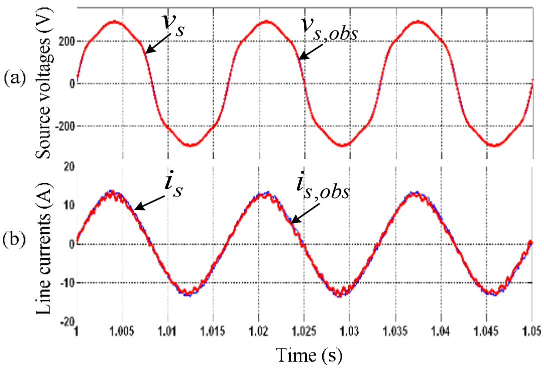

Fig. 5 Performance of composite observers
(a) Source voltage (b) Source current

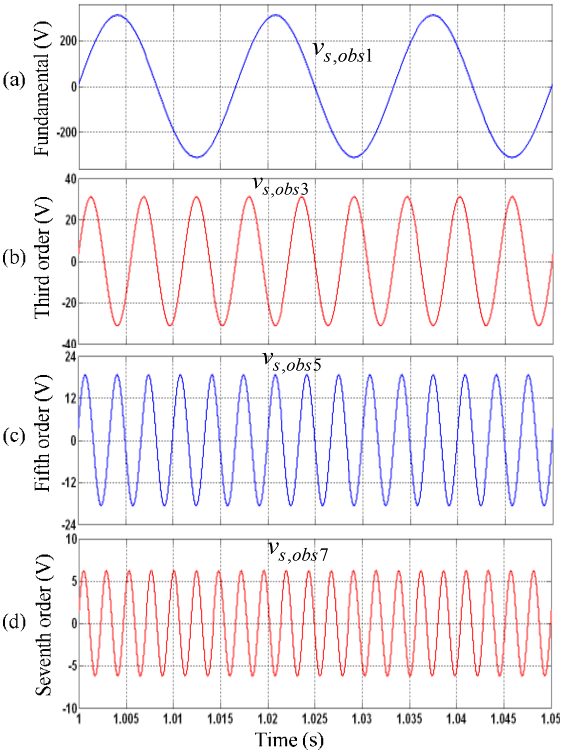

Fig. 6 Estimation performance of composite observer for source voltage
(a) Fundamental component (b) 3rd-order component
(c) 5th-order component (d) 7th-order component

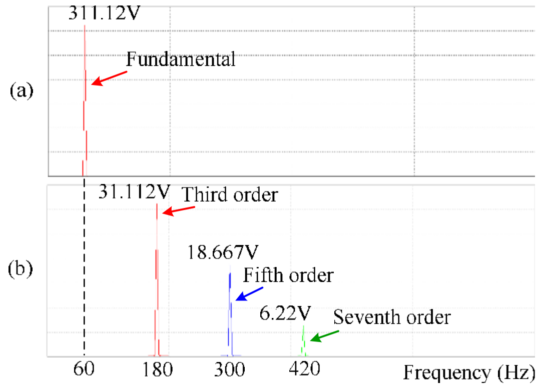

Fig. 7 Harmonic spectrum of source voltage
(a) Fundamental component (b) Harmonic components

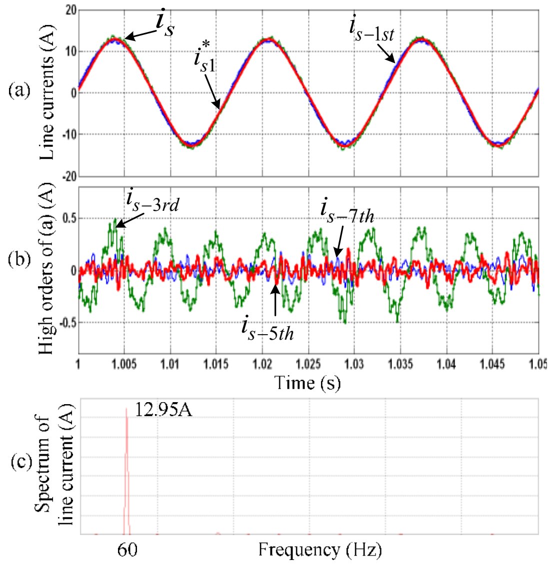

Fig. 8 Control performance of line current
(a) Line current and its reference and fundamental component (b) Harmonic components (c) Spectrum of line current

source current. The aim of the proposed method is to control the source current sinusoidally under a distorted source voltage. It can be seen in Fig. 8(a) that the source current is a pure sinusoidal waveform and the control performance is good. The high-order harmonics of the source current have been decreased as shown in Fig. 8(b), where the 3rd-order component is lower than 3% and the 5^{th}, and 7^{th} components are lower than 1%. Hence, the THD of the source current is about 3.3%. From the harmonic spectrum as shown in Fig. 8(c), the harmonic current components are negligible.

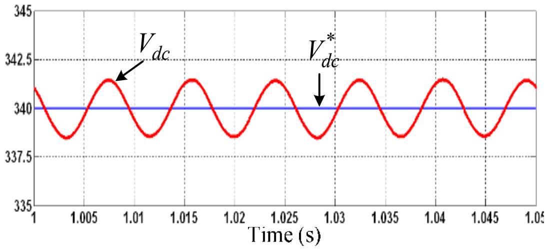

Fig. 9 DC-link voltages

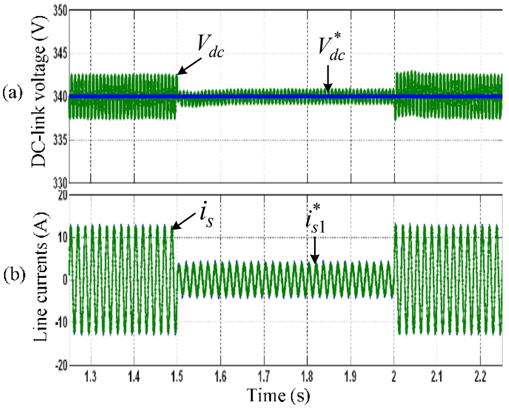

Fig. 10 Control performances under load change
(a) DC-link voltages (b) Line currents

Fig. 9 shows the DC-link voltage, in which its fluctuation is less than 1.5 V (less than 0.5% compared to the average value of 340 V).

Next, the control performance is also tested for a load change condition. During 1.5 s to 2 s, the load is reduced from 2 kW to 750 W for the converter. Fig. 10(a) shows the DC-link voltage, where the transient voltage overshoot disappears due to the feed-forward control effect. The fluctuation of the DC-link voltage is also reduced during the load reduction, in which its fluctuated amplitude is about 1 V. The line current is controlled well as shown in Fig. 10(b), in which the actual current tracks its reference well.

5. Experimental results

The experimental tests have been carried out for the single-phase PWM converter, in which the system parameters are the same with those of in the simulation. The distorted source voltage for

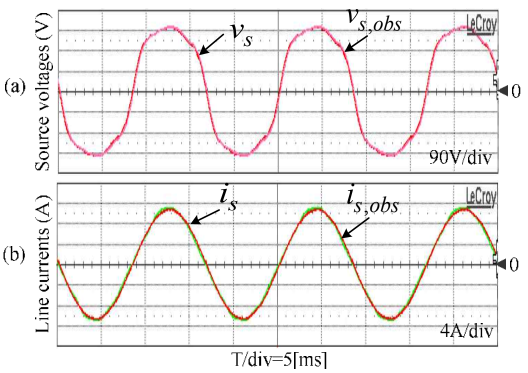

Fig. 11 Performance of composite observers for source voltage and current (experiment)
(a) Voltages (b) Currents

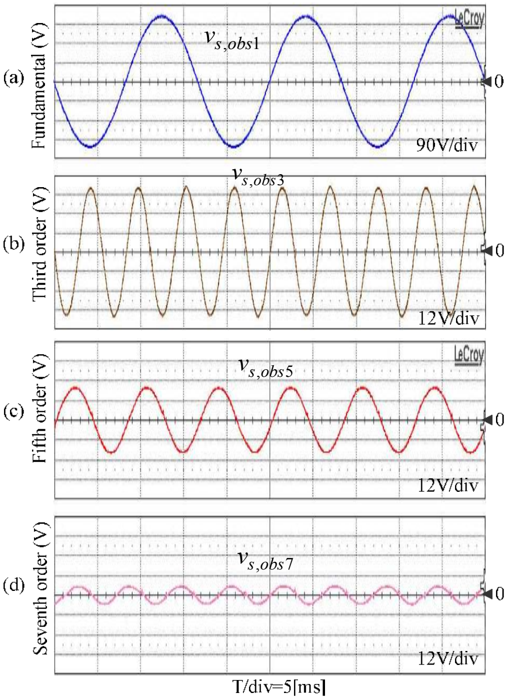

Fig. 12 Estimation performance of composite observer for source voltage
(a) Fundamental component (b) 3rd-order component
(c) 5th-order component (d) 7th-order component

experimental tests also contains the high-order harmonics as 13%, 6%, and 2% of the 3rd, 5th, and 7th-order harmonics, respectively as shown in Fig. 11(a). The estimation performances of the composite observer are shown in Fig. 11(a)-(b) for the source voltage and current, respectively. The results prove that the observer performance is good without delay

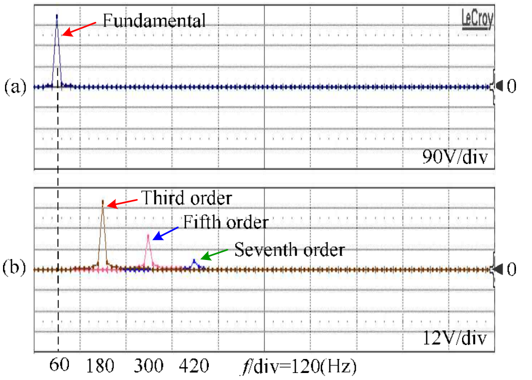

Fig. 13 Harmonic spectrum of source voltage (experiment)
(a) Fundamental component (b) Harmonic components

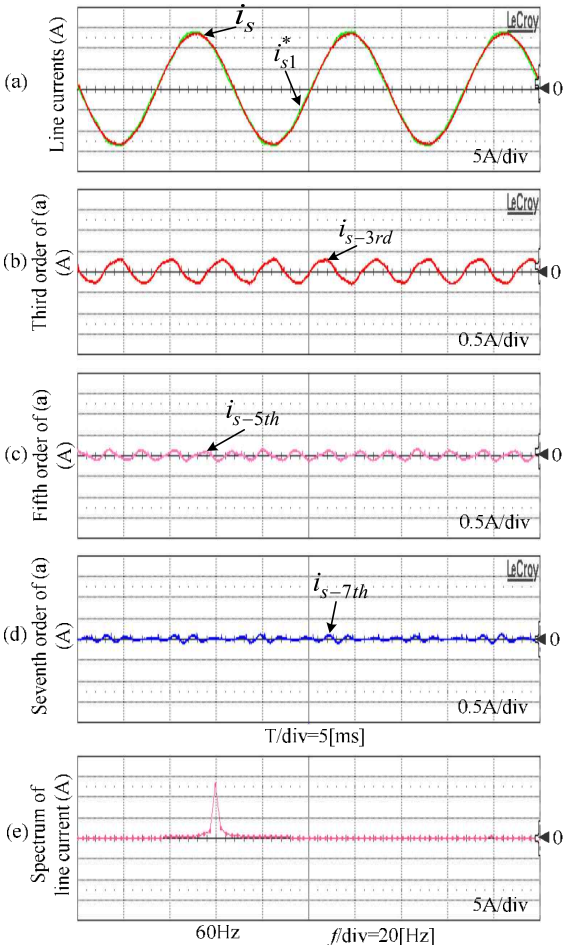

Fig. 14 Control performance of line current (experiment)
(a) Line current and its reference (b) 3rd order
(c) 5th order (d) 7th order (e) Harmonic spectrum of line current

phase and deterioration of the magnitude. Each component of the source voltage has been extracted for the frequency and amplitude exactly for the fundamental and 3rd, 5th, and 7th - order harmonic components, as shown in Fig. 12(a)-(d), respectively. Also, the harmonic spectrum is shown in Fig. 13(a)-(b) for the fundamental and high-order harmonic components, respectively.

The control performance of the source current is shown in Fig. 14. Fig. 14(a) shows almost sinusoidal waveform of the source current. The high-order harmonic currents are less than 2% for 3rd-order, and 1% for 5th, and 7th-orders as seen in Fig. 14(b)-(d), respectively. Also, the THD of the source current is about 2.5%. The spectrum of the source current is shown in Fig. 14(e).

The DC-link voltage contains the ripple as shown in Fig. 15, in which the variation is about 3 V (less than 1%).

Similarly to the simulation, the experimental tests have been also investigated for a load change which is the same condition as that of simulation. At instant of the load change, the DC-link voltage is slightly changed by 2~3 V as shown in Fig. 16(a). Fig. 16(b) shows the control performance of the line current in transient state, in which the actual current tracks its reference well.

Fig. 17 shows the comparison of control performance for the source currents between the proposed scheme and conventional methods [11]-[12]. Fig. 17(a) shows the source current control performance without any compensation for the high-order harmonics, where the line current is much distorted. The proposed method with the elimination of the line current harmonics by using the composite observer gives a sinusoidal source current waveform, which is shown in Fig. 17(b).

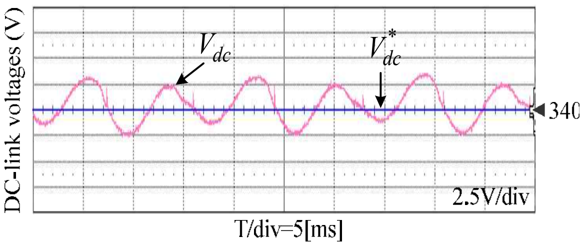

Fig. 15 DC-link voltages (experiment)

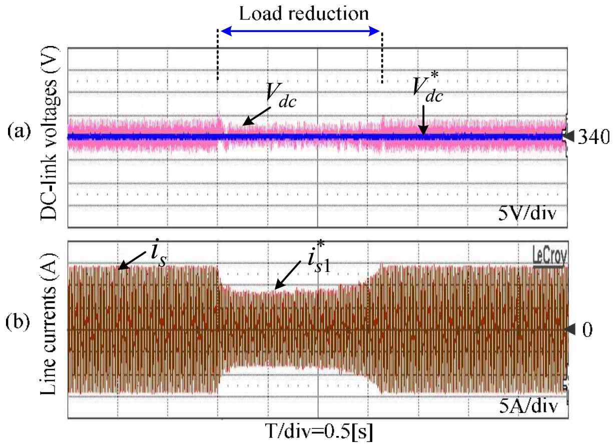

Fig. 16 Control performances under load change (experiment)
(a) DC-link voltages (b) Line currents

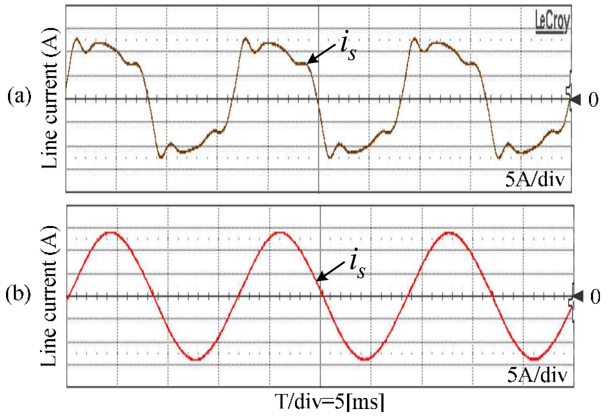

Fig. 17 Control performance of line current (experiment)
(a) Without compensation (b) Proposed method

5. Conclusions

This paper has proposed a new algorithm to eliminate the high-order harmonics of the source current for the single-phase PWM converter under distorted voltage source. The fundamental and harmonic components of the source voltage and current are extracted by using the composite observer. The multi-PR controller is employed to control these components of the source current, in which the high-order harmonics have been much lowered. The THD of the source current in the simulation is less than 3.3% and that of experiment is less than 2.5%. The validity of the proposed method has been verified by the simulation and experimental results.

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References

[1] M. F. Schonardie and D. C. Martins, "Solar grid-connected three-phase system with active and reactive power control and input voltage clamped", *in Proc. IEEE Elec., Circuits and Systems Conf.*, pp. 463-466, 2007, Dec.

[2] J. P. Lee, B. D. Min, T. J. Kim, D. W. Yoo, and J. Y. Yoo, "Design and control of novel topology for photovoltaic DC/DC converter with high efficiency under wide load ranges", *Journal of Power Electronics*, Vol. 9, No. 2, pp. 300-307, 2009, Mar.

[3] B. Singh, B. N. Singh, A. Chandra, K. Al-Haddad, A. Pandey, and D. P. Kothari, "A review of three-phase improved power quality AC-DC converters", *IEEE Trans. Ind. Electron.*, Vol. 51, No. 3, pp. 641-660, 2004, Jun.

[4] S. Peng, A. Luo, Y. Chen, and Z. Lv, "Dual-loop power control for single-phase grid-connected converters with LCL filter", *Journal of Power Electronics*, Vol. 11, No. 4, pp. 456-463, 2011, Jul.

[5] F. D. Freijedo, J. D. Gandoy, O. Lopez, and E. Acha, "Tuning of phase-lock loops for power converters under distorted utility conditions", *IEEE Trans. Ind. Appl.*, Vol. 45, No. 6, pp. 2039-2047, 2009, Nov./Dec.

[6] T. Thacker, D. Boroyevich, R. Burgos, and F. Wang, "Phase-lock loop noise reduction via phase detector implementation for single-phase systems", *IEEE Trans. Ind. Electron.*, Vol. 58, No. 6, pp. 2482-2490, 2011, Jun.

[7] S. Shinnaka, "A robust single-phase PLL system with stable and fast tracking", *IEEE Trans. Ind. Appl.*, Vol. 44, No. 2, pp. 624-633, 2008, Mar./Apr.

[8] X. S. Pu, T. H. Nguyen, D. C. Lee, and S. G. Lee, "Identification of DC-link capacitance for single-phase AC/DC PWM converters", *Journal of Power Electronics*, Vol. 10, No.3, pp. 270-276, 2010, May.

[9] A. F. Zobaa, "Voltage harmonic reduction for randomly time-varying source characteristics and voltage harmonics", *IEEE Trans. Power Del.*, Vol. 21, No. 2, pp. 816-822, 2006, Apr.

[10] T. A. George and D. Bones, "Harmonic power flow determination using the fast Fourier transform", *IEEE Trans. Power Del.*, Vol. 6, No. 2, pp. 530-535, 1991, Apr.

[11] X.-S. Pu, T. H. Nguyen, D.-C. Lee, and S.-G. Lee, "Capacitance estimation of DC-link capacitors for single-phase PWM converters", *in Proc. IEEE Power Electronics and Motion Control Conf.*, pp. 1656-1661, 2009, May.

[12] H. S. Song, R. Keil, P. Mutschler, V. Weem, and K. Nam, "Advanced control scheme for a single-phase PWM rectifier in traction application", *in Proc. IEEE IAS Conf.*, pp. 1558-1565, 2003, Oct.

[13] R. I. Bojoi, L. R. Limongi, D. Rooiu, and A. Tenconi, "Enhanced power quality control strategy for single-phase inverters in distributed generation systems", *IEEE Trans. Power Electron.*, Vol. 26, No. 3, pp. 798-806, 2011, Mar.

[14] C. T. Chen, Linear System Theory and Design. NewYork: Oxford University Press, 1999.

[15] K. Selvajyothi and P. A. Janakiraman, "Extraction of harmonics using composite observers", *IEEE Trans. Power Del.*, Vol. 23, No. 1, pp. 31-40, 2008, Jan.

[16] K. Selvajyothi and P. A. Janakiraman, "Reduction of voltage harmonics in single phase inverters using composite observers", *IEEE Trans .Power Del.*, Vol. 5, No. 2, pp. 1045-1057, 2010, Apr.

[17] S. A. Oliveira da Silva, R. Novochadlo, and R.A. Modesto, "Single-phase PLL structure using modified p-q theory for utility connected systems", *in Proc. IEEE Power Electron. Spec. Conf.*, pp. 4706-4711, 2008, Jun.

[18] G.-M. Lee, D.-C. Lee, and J.-K. Seok, "Control of series active power filters compensating for source voltage unbalance and current harmonics", *IEEE Trans. on Industrial Electronics*, Vol. 51, No. 1, pp. 132-139, 2004, Feb.

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