Phương Pháp Điều Khiển Giảm Thiểu THD Dòng Điện cho Bộ Nghịch Lưu Ba Pha Nối Lưới Trong Điều Kiện Tải Nhiễu Lẫn Mất Cân Bằng

Control Method for Reducing a THD of Grid Current at Three-Phase Grid-Connected Inverters Under Distorted and Unbalanced Grid Voltages

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Tóm tắt
Bài báo trình bày phương pháp điều khiển để giảm thiểu hệ số méo dạng (THD) và triệt tiêu thành phần không cân bằng của dòng điện nối lưới, dưới điều kiện nhiễu lẫn mất cân bằng của điện áp lưới, trong một hệ thống nghịch lưu kết nối lưới ba pha. Sự mất cân bằng dòng điện lưới gây ra do điện áp lưới không cân bằng được bù trừ bởi biên độ cơ bản của thành phần điện áp lưới thứ tự nghịch. Hệ số méo dạng của dòng điện liên quan tới méo dạng của điện áp lưới do sai lệch về pha và biên độ của tính hiệu hồi tiếp được phân tích kỹ. Bất đẳng thức Cauchy-Schwarz được sử dụng để tìm giá trị mà hệ số méo dạng dòng điện (THD) là nhỏ nhất. Tín hiệu bù cho hệ thống điều khiển được tính toán dựa theo cả góc pha và biên độ nhằm giảm tối đa độ méo dạng (THD) do tần số cắt của bộ lọc thông thấp gây ra. Đề tài trình bày cả mô phỏng và thực nghiệm để kiểm chứng cho giải thuật được đề xuất.
Từ khóa: điều khiển dòng điện, nghịch lưu nối lưới, độ méo dạng sóng hài

Abstract:
This paper proposes the control method for reducing the THD and eliminating an unbalanced component of a grid current under the distorted and unbalanced grid voltages in a three-phase grid-connected inverter system. The unbalance of grid current caused by unbalanced grid voltage is compensated by the magnitude of fundamental negative-sequence voltage from grid voltage. The THD of a grid current due to grid voltage harmonics by considering the phase delay and magnitude attenuation due to the hardware LPF is derived. The THD can be simplified by using the Cauchy-Schwarz inequality theory, the minimum point of THD is searched easily. The variation of both the gain and phase angle of the compensation voltage for minimizing the THD of the current are investigated according to a cut-off frequency of the hardware LPF. Simulated and experimental results will be shown for verification.
Keywords: current control; grid-connected inverter; harmonic distortion; total harmonic distortion.

Symbols

Symbol	Unit	Meaning
V_{ga}, V_{gb}, V_{gc}	V	The phase grid voltage in the abc coordinate
$V_{g\alpha}, V_{g\beta}$	V	The grid voltage in the αβ coordinate
V_{gd}, V_{gq}	V	The grid voltage in the dq coordinate
f_c	Hz	The cut-off frequency of LPF
θ	^{o}	The output angle

Abbreviations

THD	Total harmonic distortion
LPF	Low-pass filter
PI	Proportional-integral
PR	Proportional resonant
PLL	Phase locked loop
FFT	Fast Fourier Transform

1. Introduction

Nowadays, the need of renewable energy sources (RESs) such as solar energy, wind energy, and hydrogen energy has been significantly surged in order to reduce the energy caused polluted as fossil fuel. Wind farms or solar power plants are usually linked to the utility grid through the grid-connected PWM inverters, which transfer the active and reactive powers to the main grid [1-2]. In grid-connected inverters for small distributed system , an output current control is preferred, in other words, the most considerable issue in the current controlled grid-connected inverters is that the grid current harmonics regulation is tighter than other power electronics applications. Criteria for the grid-connected inverter such as IEEE 1547 [3-4] provide guidance on the levels of the total harmonic current distortion.

In the case that the voltage of grid is distorted and/or unbalanced, the distorted grid voltage and/or the unbalanced grid voltage act(s) as an external disturbance for the grid current control system, resulting in a distorted grid current and/or unbalanced grid current. The low-order harmonics in the grid current are not attenuated by the natural filtering effect of the grid inductance, and so the bulky and costly passive filters are required. In the normal grid voltage with balance and no disturbance, a typical current controller as a typical proportional-integral controller (PI) employed due to their sufficient steady-state performances. Disturbance in DG was generated by the unbalance and harmonics of utility voltage [5]. Under unbalance and distortion of input grid voltage, a harmonic compensator must be added to obtain the THD standard of injected grid current [6].

An improved PI controller was suggested to eliminate well the low-harmonic frequency in synchronous reference frame under unbalanced grid voltage [6]. And a dual current control method also proposed which can be obtained the output current under unbalanced input voltage condition by using two feed-back proportional integral (PI) controllers with separately positive sequence and negative sequence of measured current [7]. However, these controllers absolutely require multiple frame transformations if there are many harmonic components of input grid voltage. It's difficult to realize because so many calculation must be done in control system. This drawback can be solved with some proposed methods which replace the conventional PI controllers with the PR controllers in the stationary frame, the controller reduced from 4 conventional PI controllers to 2 PR controllers [8]. With advantages of PR controllers which cancel the harmful harmonic components, many studies have been focused on improving the performances of injected grid current [9]-[11]. However, when a grid voltage includes low-order harmonics the proportional resonant controller and the proportional-integral controller do not have sufficient function for compensation. Hence, many control strategies of predictive controller have been studied to track the frequency component corresponding to the unbalanced condition of grid voltage and low-order harmonics [13]-[15]. Unfortunately, the predictive controller needs a high sampling frequency at four times the switching frequency due to the control delay. This requirement is difficult to apply in the real applications with a normal micro-processor. A multi-loop control strategy [15] was proposed to reduce the high frequency disturbance by using proportional compensator plus feed-forward control strategy based on low-pass filter for differential feedback has a reliable, efficient and fast response but it has not shown the minimum of reducing the TDH of injected grid current.

This paper presents the control method for reducing a THD of the grid current under the distorted grid voltages at the three-phase grid-connected inverter systems. The THD of the grid current caused by grid voltage harmonics is derived, and then both the gain and phase angle of the compensation voltage for minimizing the THD of the current are derived. The simulation and experimental results are carried out in order to validate the performance of control method proposed by this paper.

2. Current Control Method

2.1 Proposed control method

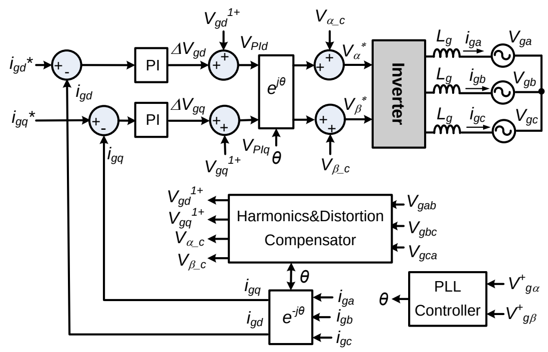
Fig. 1 shows the current control loop for suppressing the low-order harmonic grid current at the three-phase grid-connected inverter system. The *d-q* grid current references can be calculated from the desired active and reactive powers, and the PI controllers are used to regulate the *d-q* grid currents. The outputs of the d-q grid current controllers ΔV_{gd} and ΔV_{gq}, which denote a variation of the inverter voltage, are added to the fundamental *d-q* grid voltages in order to obtain a good dynamic response with the feed forward of the grid voltage. In order to reduce the harmonic grid current, the compensating voltages V_{α_c}, V_{β_c} are added to the α-β reference voltages. The PLL controller is used to synchronize the inverter voltage to the grid voltage.

A hardware low-pass filter (LPF) has been usually used to reduce the high frequency noises or ripples at the grid voltage. A transfer function of the hardware LPF is expressed as $1/[1+s/(2\pi f_c)]$, where f_c is a cut-off frequency of the LPF.

$$A_{fk} = \frac{1}{\sqrt{1+(f_k/f_c)^2}} \qquad (1)$$

$$q_{fk} = \tan^{-1}\left(\frac{f_k}{f_c}\right) \qquad (2)$$

The filtered grid voltages are used at both the current control system and PLL controller



H. 1 *Current control for suppressing harmonic grid current*

The magnitude attenuation and phase delay for k'th harmonic due to the LPF are expressed as follows, respectively:

2.1.1 PLL Controller

Fig. 2 shows a block diagram of the PLL controller based on the *pq* theory [16], [17], which is used to synchronize the phase of inverter output voltage with a grid voltage.

In order to synchronize the PLL output angle θ with the grid voltage angle θ_g, the α and β components of the input voltage at the PLL can be calculated from the measured line grid voltages V_{gab}, V_{gbc} through

$$V_{ga} = \frac{2}{3}V_{gab} + \frac{1}{3}V_{gbc} = V_p\cos(q_g - q_{f1}) \qquad (3)$$

$$V_{gb} = \frac{1}{\sqrt{3}}V_{gbc} = V_p\sin(q_g - q_{f1}) \qquad (4)$$

where V_p, θ_g are the peak and phase angle of the grid voltage, respectively, and θ_{f1} is a phase angle of the fundamental grid voltage.

The α and β components of the input voltage $V_{g\alpha}$, $V_{g\beta}$ lags to the grid voltage by θ_{f1} due to the hardware LPF. Two feedback signals labeled as f_α and f_β are obtained by the cosine and sine of the PLL output angle θ. By the sum of products of the feedback signals and α-β input voltages which are two-axis voltages in the stationary reference frame, a variation of the angular frequency $\Delta\omega$ corresponding to a phase detector (PD) can be expressed as

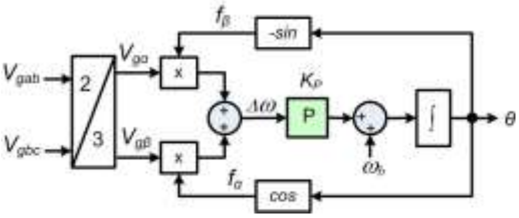
$$\Delta\omega = V_{g\alpha} \times f_\beta + V_{g\beta} \times f_\alpha \quad (5)$$

Substituting (3) and (4) into (5), the PD is derived as follows

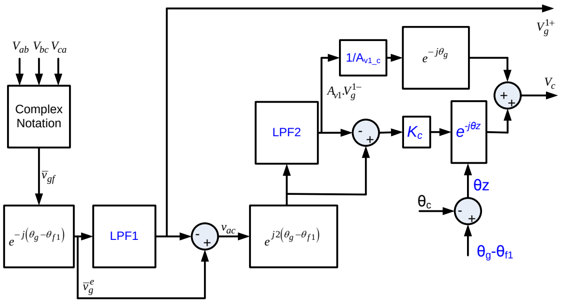
$$\Delta\omega = V_p \cos(\theta_g - \theta_{f1} - \theta) \quad (6)$$

Through the *P*-controller and the feed forward of the base angular frequency ω_b=2π×60Hz and an integrator, the PLL output angle θ can be obtained from

$$\theta = \int (K_P \Delta\omega + \omega_b)dt \quad (7)$$



H. 2 *Block diagram of the PLL controller*



H. 3 *Block diagram of the harmonics compensator*

When the PLL output angle θ approaches to θ_g-θ_{f1}, the phase is locked.

2.1.2 Harmonic and Unbalance Compensation

Under unbalance and distortion condition, the grid voltage can be expressed as

$$\bar{v}_g = V_g^{1+}.e^{j\theta_g} + V_g^{1-}.e^{-j\theta_g} + \sum_{k=3}^{\infty} V_h^k.e^{jk\theta_g} \quad (8)$$

Fig. 3 shows a block diagram of the harmonics compensator for suppressing the low-order harmonic grid current. Using complex notation, the distorted grid voltage can be expressed as

$$\bar{v}_{gf} = A_{f1} \cdot V_g^{1+} e^{j(\theta_g - \theta_{f1})} + A_{f1}.V_g^{1-}.e^{-j(\theta_g - \theta_{f1})} + \sum_{k=5}^{\infty} A_{fK} \cdot V_g^k e^{j(k\theta_g - \theta_{fk})} \quad (9)$$

where V_g^{1+} is a fundamental voltage, V_g^k is k'th harmonic voltage, and θ_{fk} is a phase angle of k'th harmonic voltage.

The grid voltage in the synchronous reference frame rotating with (θ_g -θ_{f1}) is given by

$$\bar{v}_g^e = A_{f1} \cdot V_g^{1+} + A_{f1}.V_g^{1-}.e^{-j2(\theta_g - \theta_{f1})} + \sum_{k=5}^{\infty} A_{fk} \cdot V_g^k e^{j(k\theta_g - \theta_{fk} - \theta_g + \theta_{f1})} . \quad (10)$$

where A_g^{1+} and A_g^k are a fundamental component and k'th harmonic of the hardware LPF output, respectively.

As shown in Fig. 3, the LPF1 with low cut-off frequency is used to pass only fundamental positive-sequence component of grid voltage. By subtracting the fundamental positive-sequence voltage from grid voltage, the harmonic voltages and negative-sequence component can be extracted from (10) are given by

$$\bar{v}_g^k = A_{f1}.V_g^{1-}.e^{-j2(\theta_g - \theta_{f1})} + \sum_{k=5}^{\infty} A_{fk} \cdot V_g^k e^{j(k\theta_g - \theta_{fk} - \theta_g + \theta_{f1})} . \quad (11)$$

The harmonic voltages and negative-sequence component in equation (11) are rotated with 2(θ_g -θ_{f1}) is given by

$$\bar{v}_g^k = A_{f1}.V_g^{1-} + \sum_{k=5}^{\infty} A_{fk} \cdot V_g^k e^{j(k\theta_g - \theta_{fk} + \theta_g - \theta_{f1})} \quad (12)$$

The LPF2 with low cut-off frequency is used to pass only fundamental negative-sequence component of grid voltage. By subtracting the fundamental negative-sequence voltage from grid voltage, the harmonic voltages can be extracted from (12), and then it is multiplied by a compensation gain K_c.

$$K_c \cdot \bar{v}_g^k = K_c \cdot \sum_{k=5}^{\infty} A_{fk} \cdot V_g^k e^{j(k\theta_g - \theta_{fk} + \theta_g - \theta_{f1})} \quad (13)$$

In order to eliminate the voltages with a fundamental frequency and also include a compensation angle θ_c in (13), the equation (13) is multiplied by $e^{-j(\theta g - \theta f1 - \theta c)}$. The magnitude of unbalanced component $A_{f1}V_g^{1-}$, obtained by output of LPF2, is divided by A_{f1} and then is multiplied by $e^{-j\theta g}$ to generate the unbalancing compensation for grid current. Thus, a compensation voltage v_c is defined as follows, and it is split into the α-β compensation voltages V_{α_c}, V_{β_c}.

$$\bar{v}_c = V_g^{1-} e^{-j\theta_g} + K_c \cdot \sum_{k=5}^{\infty} A_{fk} \cdot V_g^k e^{j(k\theta_g - \theta_{fk} + \theta_c)} = V_{\alpha\_c} + jV_{\beta\_c} . \quad (14)$$

It can be seen that both the magnitude and phase of the compensation voltage can be adjusted by the compensation gain K_c and angle θ_c. As shown in Fig.

1, the α-β compensation voltages in the stationary reference frame, V_{α_c}, V_{β_c} are added to the α-β reference voltages at the grid current control loop for reducing the harmonic grid current caused by the distorted grid voltages.

2.2 Gain and angle compensation

The compensation gain K_c and angle θ_c are determined on minimizing a THD of the grid current. At first, from Fig. 1, the inverter output voltage vector, v_o can be expressed as

$$\bar{v}_o = \Delta V_g \cdot e^{j\theta} + V_g^{1+}.e^{j\theta} + \bar{v}_c \qquad (15)$$

where ΔV_g is a variation in grid voltage, which can be obtained from the *d-q* current controller outputs in Fig. 1.

Dividing the difference between the inverter output voltage vector and the grid voltage vector by an impedance of the grid-side inductor, the grid current vector can be derived as

$$\bar{i}_g = \frac{\bar{v}_o - \bar{v}_g}{Z_{gk}} \qquad (16)$$

where k'th harmonic grid impedance, $Z_{gk} = j2\pi f_k L_g$.

Substituting (8), (14), and (15) into (16), the fundamental and harmonic components of the grid current are given by

$$\bar{i}_g^{1+} = \frac{\Delta V_g \cdot e^{j\theta}}{Z_{g1}} \qquad (17)$$

$$\bar{i}_g^{k} = \frac{\sum_{k=5}^{\infty} V_g^k e^{jk\theta_g}(K_c A_{fk} e^{j(-\theta_{fk}+\theta_c)} - 1)}{Z_{gk}} \qquad (18)$$

From (17) and (18), a THD of the grid current is derived as

$$THD = \frac{\left|\bar{i}_g^k\right|}{\left|\bar{i}_g^1\right|} = \sum_{k=5}^{\infty} \frac{V_g^k}{2\pi L_g I_g^1} \cdot \frac{\sqrt{1 + (K_c A_{fk})^2 - 2K_c A_{fk}\cos(-\theta_{fk} + \theta_c)}}{f_k} \qquad (19)$$

The Cauchy-Schwarz inequality theory is applied in order to search more easily for a minimum point of THD [20]. The Cauchy-Schwarz inequality is

$$\left|\sum_{k=1}^{n} x_k y_k\right|^2 \le \sum_{i=1}^{n} |x_k|^2 \sum_{i=1}^{n} |y_k|^2 . \qquad (20)$$

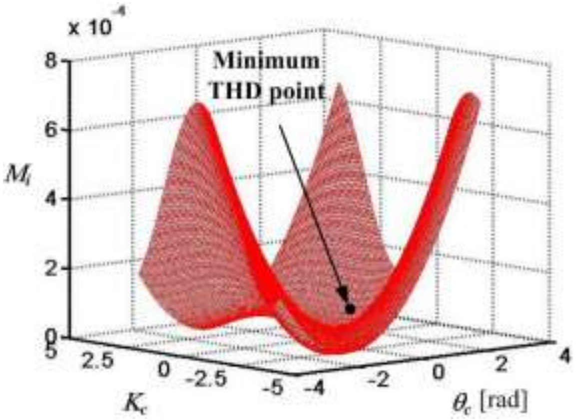
As the left side at the Cauchy-Schwarz inequality corresponds to the THD in (19), the right side at Cauchy-Schwarz inequality corresponds to the right side of equation (19) like

$$|x_k|^2 = \left|\frac{V_g^k}{2\pi L_g I_g^1}\right|^2 \qquad (21)$$

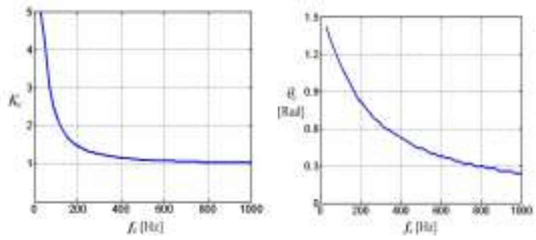
$$|y_k|^2 = \frac{1 + (K_c A_{fk})^2 - 2K_c A_{fk}\cos(-\theta_{fk} + \theta_c)}{f_k^{\,2}} . \qquad (22)$$

The M_i is defined as

$$M_i = \sum_{k=5}^{\infty} |y_k|^2 = \sum_{k=5}^{\infty} \frac{1 + (K_c A_{fk})^2 - 2K_c A_{fk}\cos(-\theta_{fk} + \theta_c)}{f_k^{\,2}} . \qquad (23)$$



H. 4 *Converging process to a minimum point of THD*



(a) (b)

H. 5 *Plots of compensation factors with a variation of* f_c *: (a) plot of* K_c*, (b) plot of* θ_c*.*

Because the THD has the minimum value when the M_i in (23) is minimized, the M_i is used instead of THD. Both the compensation gain K_c and angle θ_c are continuously changed until the M_i approaches to a minimum value. Finally, the values of K_c and θ_c at the minimum point of the M_i can be obtained.

In this paper, the 5th, 7th, and 11th harmonics of the grid current, which are the lowest harmonics in a three-phase grid-connected inverter are reduced. Fig. 4 shows the converging process to a minimum point of M_i with a variation of both the K_c and θ_c at f_c = 500Hz. The cut-off frequency of hardware LPF is determined by considering the phase delay and magnitude attenuation for a fundamental component of the grid voltage with 60Hz frequency.

Fig. 5 shows the plots of K_c and θ_c with a variation of cut-off frequency of hardware LPF. Both the K_c and θ_c are dependent on the cut-off frequency of LPF, and the both values decrease as the cut-off frequency increases.

3. Simulation and Experimental Result

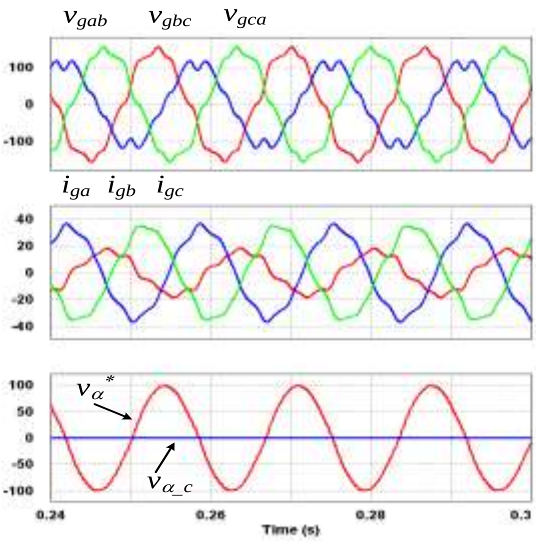
3.1 Simulation results

To verify the validity of the proposed control method, a simulation has been performed by using PSIM program. The circuit rating and parameters used at simulation and experiment is shown in Table I. As the cut-off frequency of hardware LPF is 500Hz, the K_c and θ_c are decides as 1.1 and 0.43 rad, respectively, from Fig. 5.

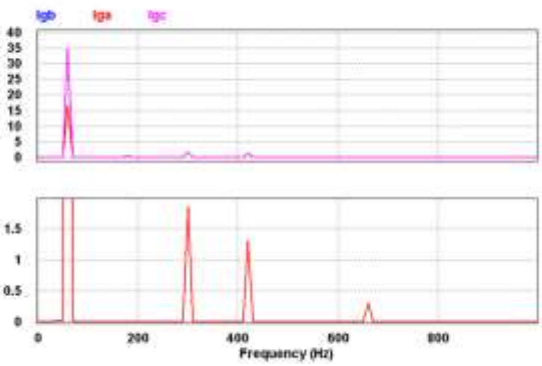
TABLE I

SYSTEM RATING AND PARAMETERS

Rated power	3 kVA
Grid voltage (Line-to-Line)	110 V
Grid frequency	60 Hz
DC input voltage	250V
Switching frequency	8 KHz
Grid-side inductance L_g	0.24 mH



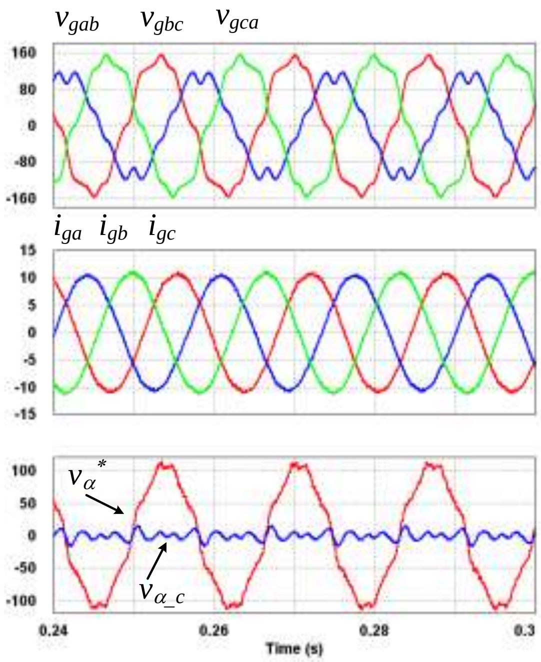
(a)



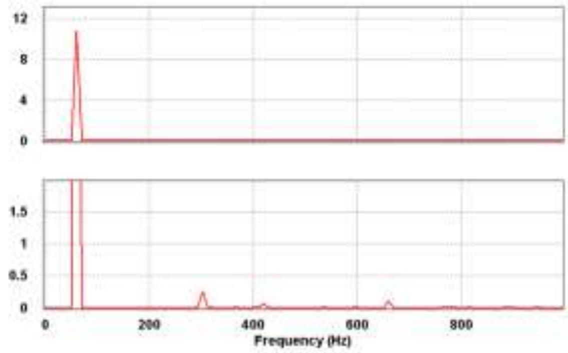
(b)

H. 6 *Simulation results without compensation method: (a) three-phase grid line voltages and currents, α-axis reference and compensation voltages , (b) FFT analysis of a-phase grid current*

Fig. 6 shows the simulation result without a compensation method. The α-axis reference voltage has a sinusoidal waveform, because the compensation voltage is zero. The grid current has low-order harmonics like 5th, 7th, and 11th due to the grid voltage harmonics, and so the THD of the grid current calculated by FFT analysis is 14.9%. Fig.7 shows the simulation result when the compensation method is applied. The α-axis reference voltage is not sinusoidal due to an α-axis compensation voltage. The THD of the grid current can be is reduced to 2.6%.

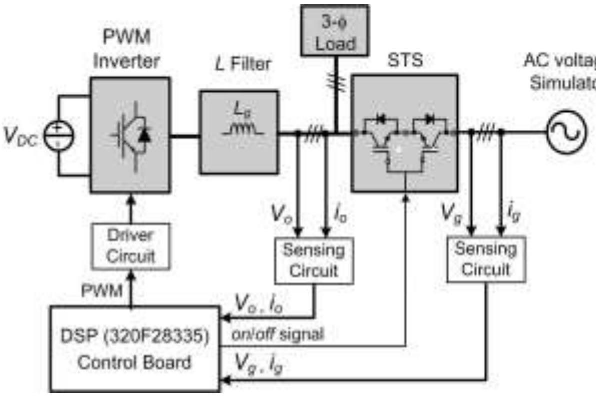


(a)



(b)

H. 7 *Simulation results with compensation method: (a) three- phase grid line voltages and currents, α-axis reference and compensation voltages (b) FFT analysis of a-phase grid current.*

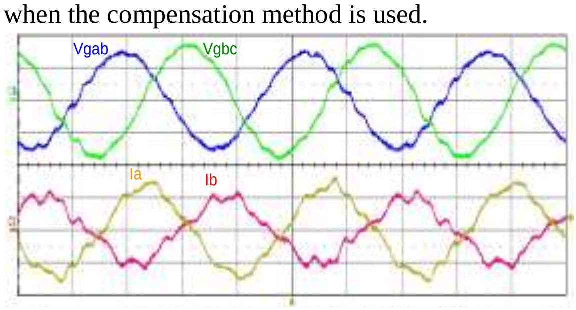


H. 8 *Hardware configuration*

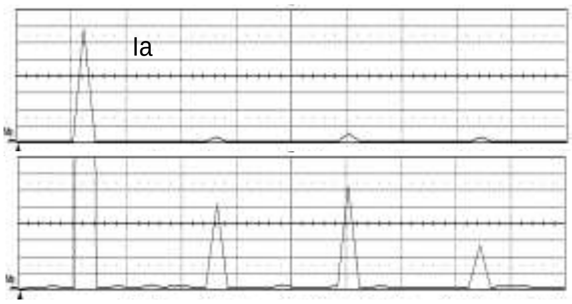
3.2 Experimental results

The experimental test was performed by using a 3kVA prototype three-phase grid-connected inverter in a DSP system based on TMS320F28335 as shown in Fig. 8. The output voltages and currents of the three-phase PWM inverter and 3-phase grid voltages and currents are measured and inputted through a 12-bit A/D converter embedded at the DSP. The three-phase AC switch, at which two IGBTs per phase are connected in anti-serial, is used as the STS and a grid-on/grid–off signal for the AC switch is generated by the DSP controller. A programmable three-phase ac source is used to emulate the main grid voltage such as distorted grid voltage generation.

Fig. 9 shows the experiment results of a grid voltage and current, the result of FFT analysis of the grid current without the compensation method. As the grid current has some low-order harmonics like 5th, 7th, and 11th due to the distorted grid voltage, the measured THD of the current is about 15.2%. Fig. 10 shows the experiment results when the compensation method is applied. It can be seen that the measured THD of the grid current is significantly reduced to 2.8%. Fig. 11 shows the α-axis reference and compensation voltages, and β-axis reference and compensation voltages without and with the compensation method, respectively. As shown in Fig. 11 (a), the α-β reference voltages have a sinusoidal waveform, because the compensation voltages are zero. As shown in Fig. 11 (b), the α-β reference voltage are distorted due to compensation voltages when the compensation method is used.

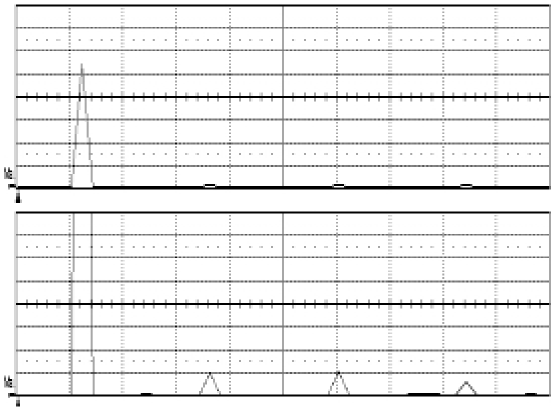


(a)

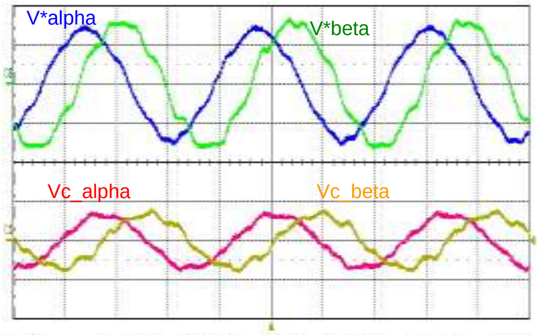


(b)

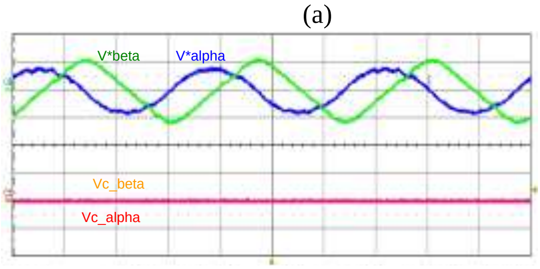
H. 9 *Experimental results without compensation method: (a) grid line voltages and a-phase grid current [2A/div], (b) FFT analysis of a-phase grid current [0.2 A/div]*



H. 10 *Experimental results with compensation method: FFT analysis of a-phase grid current [0.2 A/div]*



(a)



(b)

H. 11 *Waveforms for α-axis reference and compensation voltages, and β-axis reference and compensation voltages: (a) with compensation method, (b) without compensation method.*

4. Conclusion

This paper proposes the control method for reducing a THD and eliminating an unbalanced component of a grid current under the distorted and unbalanced grid voltages in a three-phase grid-connected inverter system. The unbalance of grid current caused by unbalanced grid voltage is compensated by the magnitude of fundamental negative-sequence voltage from grid voltage. The THD of a grid current due to grid voltage harmonics by considering the phase delay and magnitude attenuation due to the hardware LPF is derived. As the THD can be simplified by using the Cauchy-Schwarz inequality theory, it is easy to search for a minimum point of THD. The variation of both the gain and phase angle of the compensation voltage for minimizing the THD of the current are investigated according to a cut-off frequency of the hardware LPF. When the unwanted harmonics are changed, the gain and phase angle of the compensation voltage are only changed. Through the simulation and experimental results, it can be verified that a THD of the grid current under distorted grid voltage condition can be significantly reduced by more than three times, when the proposed compensation method is used.

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