한국박용기관학회지 제27권, 제6호, pp. 767~775, 2003 (ISSN 1226-9549)
Journal of the Korean Society of Marine Engineers

AC/DC 컨버터의 고조파 제거 방법

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(원고접수일 : 2002년 10월 31일, 심사완료일 : 2003년 7월 25일)

An Elimination Method of Harmonics in AC to DC Converter

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Key words : Harmonic Elimination(고조파 제거), Converter(컨버터), Hybrid(하이브리드), Elimination Strategy(제거 방법)

Abstract

This paper considers the method of elimination harmonics in AC/DC converters. There are few practical methods to reduce the harmonics in AC/DC converters, particularly in filter design and control strategy. In this paper, a harmonic elimination methods are proposed, which includes hybrid PWM control strategy. These methods achieve precise output control along with the optimum performance simultaneously. The control method in this paper is developed to eliminate a fixed number of harmonics in AC to DC converter. The higher order harmonics can be easily eliminated by using filter proposed in this paper. The validity of these methods is confirmed experimentally.

1. Introduction

Many loads driven by power converters need a low harmonic content than the converters can give. The optimal AC/DC converter has a pure DC output and pure sinusoidal input current at unity power factor from AC line. However, converter with these requirements cannot be realized in practice. Various control strategies have been proposed in recent work on converters. Although these control strategies can achieve the same goals, their performances are not similar. Proposed method in this paper includes the PWM control strategy and harmonic elimination method.

This hybrid PWM control strategy provides good switching pattern to reduce lower order harmonics and output ripples. The higher order harmonics can be attenuated by using filters in the output

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stage of the converter.

However, it has a DC component that appears on the AC side of the converter, which deteriorates the DC load current and voltage waveform during transients.

The main switching strategy described in this paper is the HE(Harmonic Elimination). The HE strategy can be selectively eliminated several lower order harmonics. The performance of this converter is analysed and clarified. The input characteristics of the proposed converter are discussed, and then the waveforms of voltage and current, the input and output characteristics, and the harmonic characteristics of the converter are discussed and verified.

The proposed harmonic elimination method of the converter contributes to a reduced harmonic components. The control algorithm and harmonic elimination strategy can be carried out using a PC with minimal external hardware. This may result in advantages such as minimizing harmonic components, obtaining minimum losses in load, minimizing the generated acoustic noise and less energy loss.

2. Converter Configuration

The system in the Fig. 1 is the proposed converter with switching technique for AC to DC converter. All circuit elements are assumed to be linear and time invariant. All switches and source voltages are ideal. The system uses six thyristor switches that are capable of conducting current.

The factor determining which thyristors will conduct at any instant is determined on the combination of the source voltages v_{an}, v_{bn}, v_{cn}, which give the largest value of load voltage v_0 at that instant. The thyristors are fired at an interval of $\pi/3$. The firing angle difference has a large effect on the magnitude of the higher order harmonics. The firing angle is controlled by harmonic elimination algorithm.

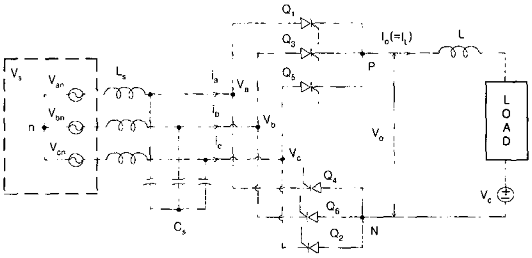


Fig. 1 Three phase AC/DC converter

For a three-phase inductive load, it is assumed[1] that the input AC voltage is a balanced three-phase supply as follows:

$$\begin{bmatrix} v_{an} \\ v_{bn} \\ v_{cn} \end{bmatrix} = V_m \begin{bmatrix} \cos\omega t \\ \cos(\omega t - \frac{2\pi}{3}) \\ \cos(\omega t + \frac{2\pi}{3}) \end{bmatrix} \qquad (1)$$

where V_m and ω are the maximum amplitude of the phase voltage and angular frequency of the power source, respectively[1].

The voltages after the input L-C filter v_a, v_b, v_c are given as the following expressions :

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = V \begin{bmatrix} \cos(\omega t - \lambda) \\ \cos(\omega t - \lambda - \frac{2\pi}{3}) \\ \cos(\omega t - \lambda + \frac{2\pi}{3}) \end{bmatrix} \qquad (2)$$

V is the amplitude of the voltages after the input L-C filters, and λ is the phase lag caused by the input L-C filter.

The average value of the input current during the sampling period $\bar{i}_a$, $\bar{i}_b$, $\bar{i}_c$ are obtained as

$$\begin{bmatrix} \bar{i}_a \\ \bar{i}_b \\ \bar{i}_c \end{bmatrix} = A_a \cdot I_L \begin{bmatrix} \cos(\omega t + \phi_s) \\ \cos(\omega t + \phi_s - \frac{2\pi}{3}) \\ \cos(\omega t + \phi_s + \frac{2\pi}{3}) \end{bmatrix} \quad (3)$$

The input currents are sinusoidal. ϕ_s is the demand of the phase difference between the input voltages. A_a determines the amplitude of the output voltage on DC side in Fig. 1. I_L is load current of DC side.

The current i_0 flows through one of the thyristors of the top group (1, 3, 5) and one of the bottom group(2, 4, 6). The firing sequence can easily be found out . Since there are six thyristors, every 60° a thyristor will be fired. It should be remembered that on firing, only that thyristor will conduct whose anode at a positive potential than its cathode. In this condition, the load voltage v_0 may be represented by the series as follow :

$$v_0 = V_{d\alpha} + \sum_{n=1}^{\infty} K_n \cos(nwt - \theta_n) \quad [V] \quad (4)$$

Where $K_n = [\, C_n{}^2 + D^2{}_n]^{\frac{1}{2}}$,

$\theta_n = \tan^{-1}\frac{C_n}{D_n}$ $[rad]$

$V_{d\alpha} = \frac{3\sqrt{2}\,V}{\pi}\cos\alpha$ $[v]$, V is rms value of ac line voltage.

It is possible to define the coefficient C_n and D_n in the more readily integrable forms that follow, namely :

$$C_n = \frac{6}{\pi}\int_{\alpha-\frac{\pi}{6}}^{\alpha+\frac{\pi}{6}} v_o \sin n\,\omega t\; d(\omega t) \quad [V]$$

$$: n=6,12,18\ldots\ldots. \qquad (5)$$

$$D_n = \frac{6}{\pi}\int_{\alpha-\frac{\pi}{6}}^{\alpha+\frac{\pi}{6}} v_o \cos n\omega t\; d(\omega t) \quad [V]$$

$$: n=6,12,18\ldots\ldots. \qquad (6)$$

Where α is a delay angle and $V_{d\alpha}$ is average DC output voltage, at $\alpha=0$ and $L_S=0$, $V_{d\alpha}(=V_{do})$ is 1.35V. For any particular value of firing angle the following relation can be derived as $V_{d\alpha} = 1.35\,V\cos\alpha$. The volt area A_α(every $\frac{\pi}{3}$) results in the reduction in the average DC voltage with a delay angle α compared to V_{d_0}. A_α is given as $\frac{\pi}{3}(V_{d_0} - V_{d\alpha})$[2], [3] .

The switches $Q_1 - Q_6$ are controlled as shown in Fig. 2. For real-time control, switching patterns are generated at every sampling period T.

A control function for each switch is defined as a duty ratio within each T. For instance, Q_{1u} is defined as follows :

$Q_{1u} = T_{on}$

(On-time of Q_1 during T)/T (7)

The following constraints are imposed on the control functions :

$$Q_{1U} + Q_{3U} + Q_{5U} = 1 \qquad (8)$$

$$Q_{4L} + Q_{6L} + Q_{2L} = 1 \tag{9}$$

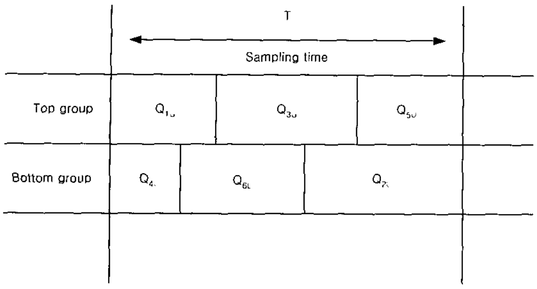


Fig. 2 Switching pattern of converter

3. Harmonic Eliminating Algorithm

The AC ripple in v_0 repeats at six times the line frequency. The harmonic components can be obtained by means of fourier analysis.

The waveform of i_a in the Fig. 1 is phase shifted by the delay angle α with respect to its waveforms with $\alpha=0$. The input current i_a is

$$i_a(\omega t) = \sqrt{2}\, I_1 \sin(\omega t-\alpha) - \sqrt{2}\, I_5 \sin 5(\omega t-\alpha) - \sqrt{2}\, I_7 \sin 7(\omega t-\alpha) \cdots \tag{10}$$

The abundant literature on harmonics almost without exception cite equations (11) and (12) as the means to determine the order and magnitude of the harmonic current draw by a six-pulse converter.

$$h = 6k \pm 1 \quad : \quad k = 1,2,3 \tag{11}$$

$$\frac{I_h}{I_1} = \frac{1}{h} \tag{12}$$

The equation (11) describe in harmonic orders or multiples of the fundamental frequency of the 5th, 11th, 13th, etc. Equation (11) is a fairly good description of the harmonic orders generally encountered.

Equation (12) values have often been described as magnitudes are somewhat lower.

Perfect square waves are clearly never encountered in actual power system. The current will decease in one thyristor while it increases in the other. The electrical angle which corresponds to this commutation period is a function of the magnitude of the ac system inductance and the angle of thyristor phase retard or firing angle.

The effect of the commutation angle is to slope off the vertical portions of the square wave, lowering the percentage harmonic currents from those derived from a 1/h calculation. Sloping of the vertical portion of the square wave attenuates the higher order harmonics in particular. The firing angle difference has a large effect on the magnitude of the higher order harmonics.

In this paper, the undesirable harmonics can be eliminated and the fundamental voltage component can be controlled by the HE (Harmonic Elimination) scheme. If the QWS (Quarter Wave Symmetry) and the HWS(Half Wave Symmetry) are maintained, as in the RSPWM(Regular Sampled PWM) scheme, and the firing angles for the HE scheme output waveforms given in the Table 1, then the waveform can be represented by a fourier series.

Table 1 Firing angles to eliminate various harmonics(modulation index=1.0)

Firing Angles / Eliminating Harmonics	α_1	α_2
5th	18(20)	-
7th	21(24)	-
5th, 7th	12(10)	17(17)

( ) : experiment values

It is assumed that the periodic waveform has HWS and unit amplitude. Therefore

$$f(\omega t)=-f(\omega t+\pi) \quad (13)$$

The waveform in the equation (13) can be represented by a fourier series as follows:

$$f(\omega t)=\sum_{n=1}^{\infty}[\,a_n\sin(n\omega t)+b_n\cos(n\omega t)] \quad (14)$$

Where the value of n is 0, 1, 2, ……, (R-1)/4, and the "R" is frequency ratio. For a waveform with the QWS and the HWS, only the odd harmonics with the sine components will exist. Therefore, the coefficient are given as[4], [5]

$$a_n=\frac{4}{n\pi}\left[1+2\sum_{k-1}^{N}(-1)^k\cos n\,\alpha_k\right] \quad (15)$$

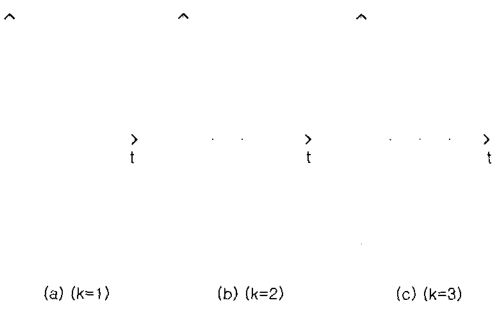
$$b_n=0 \quad (16)$$

where $k=1, 2, \ldots\ldots, N$ are the position of α angles per quarter cycle. If one degree of α angles, out of N, is used to control the amplitude of the fundamental frequency, then the remaining (N-1) degrees of α angles can be selected to eliminate the objectionable harmonic frequencies.

In order to achieve this goal, the fundamental frequency should be maximized while the objectionable harmonic frequencies are selected for elimination by weighting the resonant frequencies.

In this paper, the selected HE algorithm can be used with the firing angles, eliminating the one harmonic is eliminated in the range $58 \le f \le 62$.

Consider, for this condition (k=3) that the width of PWM pulse can be written from Fig. 3 as



(a) (k=1) (b) (k=2) (c) (k=3)

Fig. 3 Firing angles and waveforms for elimination harmonics

$$k=1: \quad t_{p\omega1}=T(\sin\frac{\pi}{2}-\sin\alpha_k) \quad (17)$$

$$k=2: \quad t_{p\omega1}=T\sin\alpha_1 \quad (18)$$

$$t_{p\omega2}=T(\sin\frac{\pi}{2}-\sin\alpha_k) \quad (19)$$

$$k=3: \quad t_{p\omega1}=T(\sin\alpha_{k-(k-2)}-\sin\alpha_{k-(k-1)}) \quad (20)$$

$$t_{p\omega2}=T(\sin\frac{\pi}{2}-\sin\alpha_k) \quad (21)$$

The nonlinear transcendental equations above can be solved numerically for the specified fundamental amplitude and α_1, α_2 and α_3 can be predetermined by the HE algorithm. Where t_{pw} is the width of PWM pulse, and T is switching period.

To accurately determine the magnitude of characteristic converter harmonics, a calculation procedure which takes into account the ripple of the DC current reflected back into the ac line current must be performed.

Evaluation of these ripple effects will tend to increase the magnitude of the fundamental component while decreasing the magnitude of the higher order characteristic harmonics.

The data in Table 1 illustrates the eliminating each (5th, 7th, 9th) harmonic with firing angles.

4. LC Filter Design

Fig. 4 shows a three phase AC/DC converter. In this figure, v_S represents the source voltage, L_S and C_S are the inductance and capacitance of the LC filter, respectively. A smoothing reactor is connected to the DC side of the converter. Fig. 4 shows a single-phase equivalent circuit of AC/DC converter shown in the Fig. 1.

Fig. 4 Single-phase equivalent circuit of AC/DC converter

In the Fig. 4, R is the total resistance of the filter inductor and AC line. i_s, v_c and i_o are the supply current, filter capacitor voltage, and load current. They contain both the fundamental and harmonic components. The f_r is the resonant frequency of the Ls-Cs filter when the effect of R is neglected.

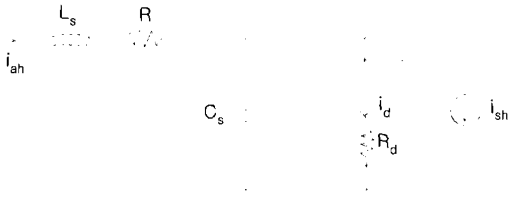


Fig. 5 Equivalent circuit of AC for harmonic components

R_d is the damping resistance, i_{ah} and i_{sh} donote a harmonic components of the AC line and supply line. If R_d is connected to this circuit of Fig. 5 as shown, the quality factor Q of the L_s-C_s filter for the harmonic components is reduced.

The frequency range between low band f_l and high band f_h is called the filter's bandwidth, usually abbreviated $B\omega$. The $B\omega$ is equal to $f_h - f_l$ and it can mathematically be shown that

$$B\omega = \frac{R}{2\pi L_S} \tag{22}$$

A quality factor, Q of the filter is a measure of how selective or narrow is its band-pass, as compared to its center frequency, f_r. Thus,

$$Q = \frac{f_r}{B\omega} \tag{23}$$

The half-power frequencies can be expressed in terms of the circuit elements, or in terms of f_r and Q, as follows :

$$f_h = f_r\left(\sqrt{1+\frac{1}{4Q^2}}+\frac{1}{2Q}\right) \quad (24)$$

$$f_l = f_r\left(\sqrt{1+\frac{1}{4Q^2}}-\frac{1}{2Q}\right) \quad (25)$$

Here, the amplification factor $H(f)$ of the harmonic components is defined as

$$H(f) = \frac{I_h(f)}{I_i(f)} \quad (26)$$

The harmonic component $I_h(f)$ of the supply current caused by $I_i(f)$ is then given by

$$I_h(f) = \frac{I_i(f)\,|1/(R+j\omega L_S)|}{|1/(R+j\omega L_S)+j\omega C_S|} \quad (27)$$

The $I_i(f)$ is the rms value of the harmonic component of i_o with frequency ″f″. From equations (26) and (27) is given by

$$H(f) = \sqrt{\frac{1}{(1-f_n^2)^2+(f_n/Q)^2}} \quad (28)$$

The f_n is harmonic frequency normalized with respect to the resonant frequency f_r. *In this paper, the quality factor Q is at* the resonant frequency of the LC filter. From equations (25) to (28) the L_S and C_S values of the LC filter may be determined by reference from Fig. 5.

5. Experimental Results

Fig. 6 shows the block diagram of the experimental system. The electrical angle of the source voltage is obtained by the ZCD (Zero- Crossings Detector) circuit. It is composed of the main source circuit, driving circuit and the driving signal generator with computer. The values of L_s, C_s and L were given: L_s = 2mH, C_s= 30μF, L=100mH.

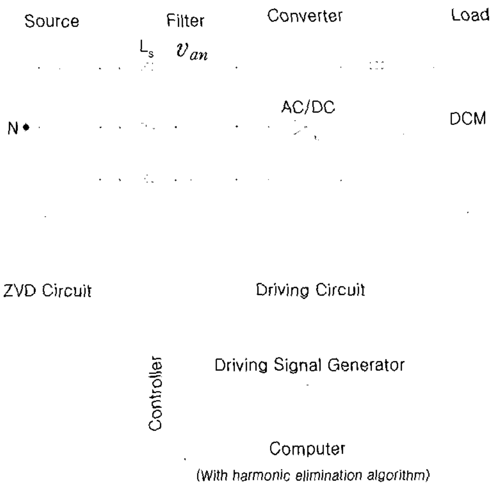
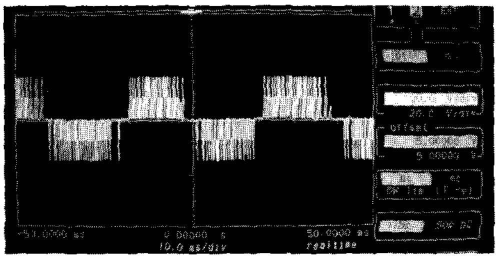
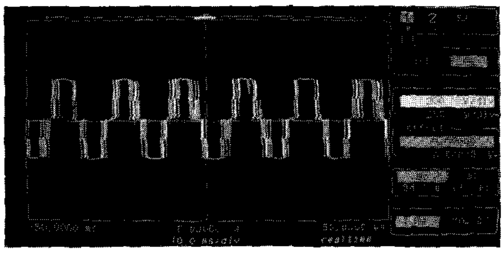


Fig. 6 Block diagram of experimental system



(a) RSPWM mode (x:10ms/div, y:10v/div)



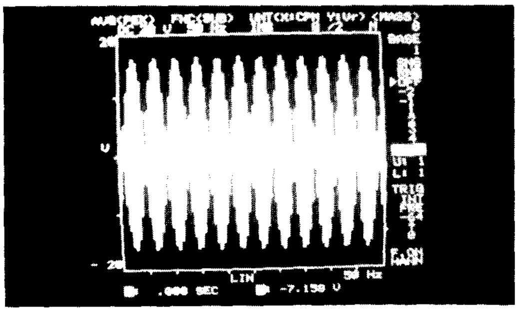
(b) HE mode (x : 10ms/div, y : 10v/div)

Fig. 7 Waveforms of drive signal

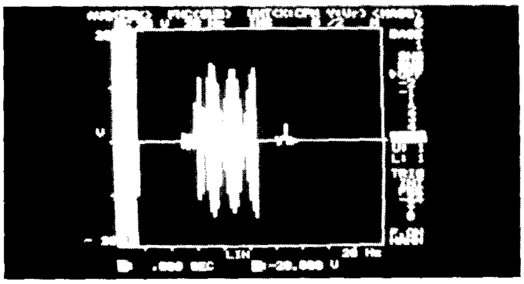
Fig. 7 shows the waveforms of drive signal in RSPWM and HE running mode.

It can be seen from Fig. 7 that the measured waveforms of drive signals are the same as RSPWM and HE algorithm. The top group thyristors(1, 3, 5) are drived by the upper signals and the bottom group ones(2, 4, 6) are drived by the lower signals.

An output current oscillograms from AC to DC converter working with L-C filter is shown in Fig. 8.



(a) without filter (x : 5ms/div, y : 2A/div)

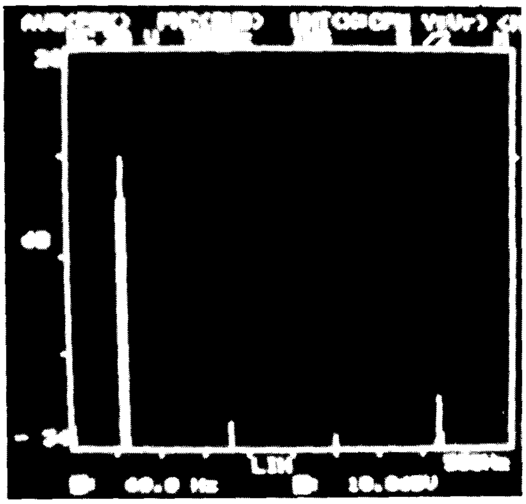


(b) with filter (x : 5ms/div, y : 2A/div)

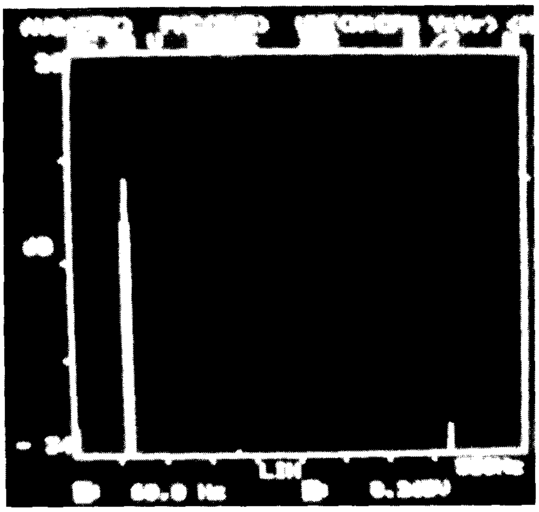
Fig. 8 Current oscillograms of the converter

It shows the experimental results of harmonic distortion of the converter output current in the steady state operation of the test system without and with filter. In the result without filter, the harmonic distortion is appeared when the DC output is small.

The firing angle for HE scheme output waveforms given in table 1. Fig. 9 shows the line current spectra of DC stage using the proposed HE algorithm(eliminating the 5th and 7th) with 60 Hz fundamental frequency. It has been shown that the harmonic elimination realized by the proposed HE algorithm.



(a) RSPWM algorithm(x:500Hz, y:-34 - 26dB)



(b) HE algorithm (x:500Hz, y:-34 - 26dB)

Fig. 9 Line current spectra of the converter

6. Conclusion

AC to DC converter with filter has been widely used as conventional DC sources.

In this paper, a new approach to the control of converter drives using the HE algorithm and the ripple suppression filter has been presented. The undesirable output components of AC to DC converter could be suppressed by using the HE algorithm and filters proposed in this paper. The experimental results illustrate the predicted advantages of the proposed the HE algorithm and the filter design method.

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