Harmonic Injection PWM of Multiple Inverter for Ripple Torque Reduction

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In this paper, a novel harmonic injection PWM method is proposed for harmonic reduction. The third harmonic is injected to the reference voltage, of which amplitude and phase angle are regulated so that the dominant ripple torque components are reduced.

In a large capacity power converter, GTOs are commonly used as the switching devices and a multiple configuration of unit power converters has been applied. The use of GTOs allows higher voltage and larger current to be handled. However, it results in increased harmonics, because of their relatively low switching frequency of about 500Hz. Therefore, harmonic reduction method for large capacity applications is of great interest, which is suitable for a multiple power converter without increasing the cost. The harmonic injection PWM fulfills the requirement.

The harmonic components of output voltage, output current and torque when a harmonic component is injected are analyzed in detail. The most suitable amplitude and phase angle are derived from theoretical analysis. Simulation results show the effectiveness of the method.

Key words : PWM, Multiple power converter, Harmonic, Ripple torque, Harmonic injection

1. Introduction

These days, power converters are widely used for their high efficiency and controllability⁽¹⁾. Even large capacity applications such as rolling mill drives⁽²⁾⁽³⁾, converters for SVCs⁽⁴⁾, and inverters of magnetically levitated transportation system^{(5)~(8)}, can make use of power converters of multiple configuration.

In most large capacity application, GTOs are used as switching devices, often in series connection. For their relatively low switching frequency, a large amount of harmonics is generated. Harmonic voltage components cause current harmonics, and ripple torque in the case of a motor drive. They result in noise, vibration and heat loss of the load. Therefore, reduction of the harmonics is of great

interest^{(6)~(7)}.

There are several approaches to reduce harmonics. Multiple inverters of configurations where larger numbers of unit inverters are connected in one phase contribute to the harmonic reduction. On the other hand, such configurations increase cost and size of the inverters, sometimes impractically.

PWM methods using space vectors are effective to reduce harmonics and suitable for digital control circuit⁽⁹⁾⁽¹⁰⁾. But it is difficult to apply them to a multiple inverter, because the number of output voltage vectors is so large that a much longer time is needed to choose the suitable output vector.

Some PWM methods with harmonic injection have also been proposed^{(11)~(13)}. In Refs (11) and (12), the third harmonic is added to the sinusoidal reference in order to increase the maximum output

voltage of the inverter, which results in harmonic reduction. In Ref (13), a rectangular waveform is injected and the amplitude is controlled so that the harmonics are reduced.

In Refs (5) and (6), harmonic characteristics of multiple inverters using subharmonic method are investigated using theoretical analysis and digital simulation. In this paper, a novel injection PWM is proposed, where the third harmonic is injected into the sinusoidal reference voltage, for which the amplitude and phase angle are actively controlled so that the harmonic components are reduced. First, the relations between harmonic components of voltage, current and torque are investigated when a harmonic component is injected into the sinusoidal reference. Next, suitable conditions of the injected component needed to reduce ripple torque are clarified. Then, simulation results are given showing the effectiveness of the method.

2. Main circuit configuration

Fig. 1 shows the main circuit configuration of a multiple inverter. A synchronous motor (SM) is connected to the multiple inverter, which consists of twelve full-bridge inverters (three phases, four

Fig. 1. Main circuit configuration.

stages), sharing a common DC source. The secondary windings of the transformers of each phase are connected in series, and the sum of the output voltage of each full-bridge inverter is the output voltage of the multiple inverter.

3. Analysis of waveforms generated using the subharmonic method

Fig. 2 shows the minimum unit of a voltage source inverter, which is called a unit inverter in this paper. Fig. 3 shows the basic strategy of the subharmonic method for a unit inverter. The switches turn on and off every time the modulation wave y_m and the carrier wave y_c intersect. As a result, the output voltage becomes a pulse train, of which pulse width varies depending on the modulation wave.

The output voltage of the unit inverter, e , can be decomposed using a Fourier series⁽⁵⁾⁽¹⁴⁾:

$$e = \frac{E_d A_1}{2} \sin(\omega_1 t + \theta_1) + E_d \sum_m \sum_k S_{(m,k)} \sin(\omega_{(m,k)} t + \theta_{(m,k)}) + E_d \sum_m \sum_k C_{(m,k)} \cos(\omega_{(m,k)} t + \theta_{(m,k)}) \dots (1)$$

where,

$S_{(m,k)}$, $C_{(m,k)}$: amplitude indices of harmonic components shown in Table 1

$$\omega_1 = 2\pi f_1$$

Fig. 2. Configuration of unit inverter.

Fig. 3. Principle of subharmonic method.

$$\omega_{(m,k)} = 2\pi f_{(m,k)}$$

$$f_{(m,k)} = mf_c + kf_1$$

$$\theta_{(m,k)} = m\theta_c + k\theta_1$$

m, k : integers

E_d : DC voltage

A_1 : modulation index

f_1 : inverter output frequency

θ_1 : phase angle of modulation wave

f_c : carrier frequency

θ_c : phase angle of carrier wave

The output voltage contains higher order harmonics, of which amplitudes, frequencies and phase angles are described using the integers m and k , as is shown in Table 1.

The output voltage of the multiple inverter in Fig. 1 can be considered the sum of those generated by eight unit inverters as in Eq. (1). For harmonic reduction, all the unit inverters are given the same modulation wave, and the phase angles of triangular carrier waves are shifted at equal intervals $\Delta\theta^{(5)}$:

$$\Delta\theta = 360/2N \quad (\text{deg}) \quad \dots\dots\dots (2)$$

where multiple index N is defined as the number of full-bridge inverters in one phase.

Therefore, the output voltage of the multiple inverter, e_s , can be expressed as:

$$e_s = wNE_d A_1 \sin(\omega_1 t + \theta_1) + wNE_d \sum_m \sum_k A_{(m,k)} \sin(\omega_{(m,k)} t + \theta_{(m,k)}) \quad \dots\dots\dots (3)$$

where

w : winding ratio of output transformers

N : number of full-bridge inverters in one phase

Table 1. Amplitude indices of harmonic components in Eq.(1).

(a) $S_{(m,k)}$

m	k	$S_{(m,k)}$
2, 4, 6, ...	$\pm 1, \pm 3, \pm 5, \dots$	$\frac{k2(-1)^{m/2}}{ k m\pi} J_{ k }\left(\frac{m\pi}{2} A_1\right)$
other combinations		0

(b) $C_{(m,k)}$

m	k	$C_{(m,k)}$
1, 3, 5, ...	$0, \pm 2, \pm 4, \dots$	$\frac{2(-1)^{(m+1)/2}}{m\pi} J_{ k }\left(\frac{m\pi}{2} A_1\right)$
other combinations		0

$J_n(x)$: Bessel function of first kind of order n

$A_{(m,k)}$: amplitude index of harmonic component shown in Table 2

m, k : integers

In Eq. (3), harmonic components are located in the neighborhood of the equivalent carrier frequency f_{CE} . The frequency of a harmonic component is expressed as:

Table 2. Amplitude index of harmonic components in Eq.(3).

m	k	$A_{(m,k)}$
2N, 4N, 6N, ...	$\pm 1, \pm 3, \pm 5, \dots$	$\frac{k4(-1)^{m/2}}{ k m\pi} J_{ k }\left(\frac{m\pi}{2} A_1\right)$
other combinations		0

(a) Equivalent for main circuit.

I_{o1} : current component generated by E_1

I_{m1} : current component generated by E_{m1}

(b) Vector diagram for fundamental component.

$$|\dot{E}_{(m,k)}| = \frac{wNE_d A_{(m,k)}}{\sqrt{2}}$$

$I_{(m,k)}$: current component generated by $\dot{E}_{(m,k)}$

(c) Vector diagram for harmonic components.

(d) Vector diagram for fundamental component when it is controlled in phase with induced voltage.

Fig. 4. Main circuit model and vector diagrams.

$$f = g f_{CE} + l f_1 \dots\dots\dots (4)$$

where $f_{CE} = 2Nf_c$, $g = 1, 2, 3, 4, 5, \dots$, $l = \pm 1, \pm 3, \pm 5, \dots$

In order to derive the harmonic current, the main circuit model of Fig. 4 (a) is supposed. For simplicity, the neutral point of the load is grounded and the induced voltage of SM has only the fundamental component. The fundamental and the harmonic components of the output current can be derived using vector diagrams Figs 4 (b) and (c):

$$\begin{aligned} i_s = & \frac{1}{Z_1} wNE_d A_1 \sin(\omega_1 t + \theta_1 - \phi_1) \\ & - \frac{1}{Z_1} \sqrt{2} E_m \sin(\omega_1 t - \phi_1) \\ & + \frac{wNE_d}{Z_{(m,k)}} \sum_m \sum_k A_{(m,k)} \\ & \times \sin(\omega_{(m,k)} t \\ & + \theta_{(m,k)} - \phi_{(m,k)}) \dots\dots\dots (5) \end{aligned}$$

where

$$\begin{aligned} Z_1 &= \sqrt{R^2 + (\omega_1 L)^2} \\ \phi_1 &= \tan^{-1}(\omega_1 L/R) \\ Z_{(m,k)} &= \sqrt{R^2 + (\omega_{(m,k)} L)^2} \\ \phi_{(m,k)} &= \tan^{-1}(\omega_{(m,k)} L/R) \\ e_m &= \sqrt{2} E_m \sin(\omega_1 t) \end{aligned}$$

Also for simplicity, the fundamental component of the output current is supposed to be controlled in phase with the induced voltage. Then, the fundamental output voltage, modulation index and phase angle of the modulation wave, and output current components can be expressed using the vector diagram in Fig. 4 (d):

$$\left. \begin{aligned} E_1 &= \sqrt{(E_{o1} + RI_1)^2 + (\omega_1 LI_1)^2} \\ E_{o1} &= \sqrt{(RI_1)^2 + (\omega_1 LI_1)^2} \\ A_1 &= \frac{\sqrt{2} E_1}{wNE_d} \\ \theta_1 &= \tan^{-1}\{\omega_1 LI_1 / (E_{o1} + RI_1)\} \\ i_s &= \frac{1}{Z_1} \sqrt{2} E_{o1} \sin(\omega_1 t) \\ &+ \frac{wNE_d}{Z_{(m,k)}} \sum_m \sum_k A_{(m,k)} \\ &\times \sin(\omega_{(m,k)} t \\ &+ \theta_{(m,k)} - \phi_{(m,k)}) \end{aligned} \right\} \dots\dots\dots (6)$$

where

I_1 : fundamental component of output current

From Eq. (6), the frequencies of the harmonic current components are the same as those of the harmonic voltage in Eq. (3).

The output currents of the three phases i_u , i_v and i_w are derived by making the phase angle $\theta_{(m,k)}$ in Eq. (6) as follows:

$$\begin{aligned} i_u : \theta_{(m,k)} &= m\theta_c + k\theta_1 \\ i_v : \theta_{(m,k)} &= m\theta_c + k\{\theta_1 - (2/3)\pi\} \\ i_w : \theta_{(m,k)} &= m\theta_c + k\{\theta_1 - (4/3)\pi\} \end{aligned}$$

The torque is expressed:

$$\tau = \frac{i_u e_{mu} + i_v e_{mv} + i_w e_{mw}}{\omega_1} \dots\dots\dots (7)$$

where

e_{mu} , e_{mv} , e_{mw} : induced voltage of phase u , v and w

$$\begin{aligned} e_{mu} &= \sqrt{2} E_m \sin(\omega_1 t) \\ e_{mv} &= \sqrt{2} E_m \sin(\omega_1 t - 2\pi/3) \\ e_{mw} &= \sqrt{2} E_m \sin(\omega_1 t - 4\pi/3) \end{aligned}$$

From Eqs (6) and (7), the torque when the subharmonic method is used, τ_s , is derived as:

$$\tau_s = \tau_0 + \sum_m \sum_k \tau_{h(m,k)} \dots\dots\dots (8)$$

where

$$\begin{aligned} \tau_0 &= \frac{3E_{o1}E_m}{\omega_1 Z_1} \\ \tau_h &= \frac{3\sqrt{2}wNE_dE_m}{2\omega_1} \\ &\times \left\{ \frac{A_{(m,k+1)}}{Z_{(m,k+1)}} \cos(\omega_{(m,k)} t + \theta_{(m,k+1)} - \phi_{(m,k+1)}) \right. \\ &\quad \left. - \frac{A_{(m,k-1)}}{Z_{(m,k-1)}} \cos(\omega_{(m,k)} t + \theta_{(m,k-1)} - \phi_{(m,k-1)}) \right\} \\ m &= 2N, 4N, 6N, \dots \quad k = 0, \pm 6, \pm 12, \dots \end{aligned}$$

τ_0 : DC component of torque

$\tau_{h(m,k)}$: ripple torque component

Eq. (8) shows that some components of the output current generate no ripple torque components. It is noted that the harmonic components in Fig. 1 (a three-phase three-wire system) are different from those in Fig. 4 (a), and that the difference is negligible because it results in the components canceled in Eq. (8).

The frequencies of the residual components are expressed as:

$$f = g f_{CE} + l' f_1 \dots\dots\dots (9)$$

where $g = 1, 2, 3, 4, 5, \dots$ $l' = t, \pm 6, \pm 12, \dots$

The harmonic components contained in the output voltage, output current and torque in the

Fig. 5. Relation between harmonic components of output voltage, output current and torque.

neighborhood of the equivalent carrier frequency are shown in Fig. 5. The harmonic components of output voltage and output current can be seen at intervals of $2f_i$, and the equivalent carrier frequency is located at the center of them. The ripple torque components are located at the intervals of $6f_i$, because some of the current harmonic components, such as $f_{ce} \pm 3f_i$, $f_{ce} \pm 9f_i$, ..., do not generate ripple torque components. Also, the frequencies are shifted by f_i from those of the output voltage.

4. Ripple torque reduction with harmonic injection

4.1 Analysis of harmonic components and the injected component

When a lower order harmonic is injected into the modulation wave, intersections with the modulation wave and the triangular carrier are shifted forward or backward, resulting in changes of amplitudes and phase angles of the contained harmonic components. Therefore, the injected component can change the harmonic component in an output voltage.

Table 3. Amplitudes of harmonic components in Eq. (10).

m	h	k	$A_{(m,h,k)}$
$2N, 4N, 6N, \dots$	$0, \pm 2, \pm 4, \dots$	$\pm 1, \pm 3, \pm 5, \dots$	$\frac{k4(-1)^{m/2}}{ k m\pi} J_{ k }\left(\frac{m\pi}{2}A_n\right) J_{ k }\left(\frac{m\pi}{2}A_1\right)$
	$\pm 1, \pm 3, \pm 5, \dots$	$0, \pm 2, \pm 4, \dots$	$\frac{h4(-1)^{m/2}}{ h m\pi} J_{ h }\left(\frac{m\pi}{2}A_n\right) J_{ k }\left(\frac{m\pi}{2}A_1\right)$
other combinations			0

Fig. 6. Modulation wave, injection component and induced voltage.

First, the relationship between the harmonic components and the injected component is clarified. Waveforms of the output voltage when the n -th harmonic is injected can also be analyzed using the same method as Sec. 3:

$$e_t = \omega N E_a \{ A_1 \sin(\omega_1 t + \theta_1) + A_n \sin(\omega_n t + \theta_n) + \sum_m \sum_h \sum_k A_{(m,h,k)} \sin(\omega_{(m,h,k)} t + \theta_{(m,h,k)}) \} \quad (10)$$

where

$$\omega_n = 2\pi f_n (= 2n\pi f_i)$$

$$\omega_{(m,h,k)} = 2\pi f_{(m,h,k)}$$

$$f_{(m,h,k)} = m f_c + (nh + k) f_i$$

$$\theta_{(m,h,k)} = m\theta_c + nh\theta_n + k\theta_i$$

$A_{(m,h,k)}$: amplitude index of harmonic component shown in Table 3

m, h, k : integers

A_n : modulation index of n -th harmonic

f_n : frequency of n -th harmonic

θ_n : phase angle of n -th harmonic

Here, the amplitudes of the fundamental and the n -th components are decided by modulation indices A_1 and A_n respectively, entirely independent of each other. The frequencies, amplitudes and phase angles of the harmonic components depend on those of both fundamental modulation wave and the injected

n -th harmonic component.

The output current is expressed as follows:

$$i_t = \frac{1}{Z_1} \{ wNE_d A_1 \sin(\omega_1 t + \theta_1 - \phi_1) - \sqrt{2} E_m \sin(\omega_1 t - \phi_1) \} + \frac{1}{Z_n} wNE_d A_n \sin(\omega_n t + \theta_n - \phi_n) + \frac{wNE_d}{Z_{(m,h,k)}} \sum_m \sum_h \sum_k A_{(m,h,k)} \times \sin(\omega_{(m,h,k)} t + \theta_{(m,h,k)} - \phi_{(m,h,k)}) \dots \dots \dots (11)$$

where

$$Z_n = \sqrt{R^2 + (\omega_n L)^2} \\ \phi_n = \tan^{-1}(\omega_n L / R) \\ Z_{(m,h,k)} = \sqrt{R^2 + (\omega_{(m,h,k)} L)^2} \\ \phi_{(m,h,k)} = \tan^{-1}(\omega_{(m,h,k)} L / R)$$

The torque with harmonic injection, τ_t , is expressed:

$$\tau_t = \tau_0 + \tau_n + \sum_m \sum_h \sum_k \tau_{h(m,h,k)} \dots \dots \dots (12)$$

where

$$\tau_0 = \frac{3E_o I_m}{\omega_1 Z_1} \\ \tau_n = \begin{cases} 0 & (n=3, 6, 9, 12, \dots) \\ \frac{3\sqrt{2}}{2} \frac{A_n wNE_d E_m}{Z_n} \times \cos\{(n-1)\omega_1 t + \theta_n - \phi_n\} & (n=4, 7, 10, 13, \dots) \\ -\frac{3\sqrt{2}}{2} \frac{A_n wNE_d E_m}{Z_n} \times \cos\{(n+1)\omega_1 t + \theta_n - \phi_n\} & (n=2, 5, 8, 11, \dots) \end{cases} \\ \tau_h = \frac{3\sqrt{2} wNE_d E_m}{2\omega_1} \times \left\{ \frac{A_{(m,h,k+1)}}{Z_{(m,h,k+1)}} \cos(\omega_{(m,h,k)} t + \theta_{(m,h,k+1)} - \phi_{(m,h,k+1)}) - \frac{A_{(m,h,k-1)}}{Z_{(m,h,k-1)}} \cos(\omega_{(m,h,k)} t + \theta_{(m,h,k-1)} - \phi_{(m,h,k-1)}) \right\}$$

$$m = 2N, 4N, 6N, \dots$$

$$k = 0, \pm 6, \pm 12, \dots \text{when } h = 0, \pm 2, \pm 6, \dots$$

$$k = \pm 3, \pm 9, \pm 15, \dots \text{when } h = \pm 1, \pm 3, \pm 5, \dots$$

τ_0 : DC component of torque

τ_n : torque component caused by the injected component

$\tau_{h(m,h,k)}$: ripple torque component

The torque component τ_n , which is generated by the injection component, depends upon the integer n . When n is a multiple of three, it does not cause the ripple torque component τ_n . The lower the frequency of the injection component, the easier it is to control. Therefore, the third harmonic is selected as the injection component.

Also, when the order of the injection component is odd, the output frequencies of voltage, current and torque are the same as those in Eq. (9) when the subharmonic method is used, which makes the analysis easier. Eq. (12) shows that the amplitudes and the phase angles of the harmonic components can be changed by controlling those of the injected third harmonic A_3 and θ_3 .

4.2 Reduction of dominant ripple torque components

From the analysis above, it is clarified that the harmonic components of current and torque can be controlled by regulating the amplitude and the phase angle of the injection component. It is, however, difficult to find the conditions at which all the harmonic components of the current and the torque are reduced. Therefore, it is supposed that the dominant components of the ripple torque are to be minimized, because they directly result in noise and vibration of the load.

From simulation analysis⁽²⁾, it can be said that the dominant ripple torque components are located at the frequencies $(f_{CE} - 6f_1)$, f_{CE} and $(f_{CE} + 6f_1)$. Let $\tau_{(f_{CE})}$ be the ripple torque component of frequency f_{CE} . Then, it can be derived using Eq. (12):

$$\tau_{(f_{CE})} = \frac{3\sqrt{2} wNE_d E_m}{2\omega_1} \delta(f_{CE}) \sum_m \sum_h \sum_k \times \left\{ \frac{A_{(m,h,k+1)}}{Z_{(m,h,k+1)}} \cos(\omega_{(m,h,k)} t + \theta_{(m,h,k+1)} - \phi_{(m,h,k+1)}) - \frac{A_{(m,h,k-1)}}{Z_{(m,h,k-1)}} \cos(\omega_{(m,h,k)} t + \theta_{(m,h,k-1)} - \phi_{(m,h,k-1)}) \right\} \dots \dots \dots (13)$$

where

$$\delta(f_{CE}) = \begin{cases} 1 & (mf_c + (3h+k)f_1 = f_{CE}) \\ 0 & (mf_c + (3h+k)f_1 \neq f_{CE}) \end{cases}$$

Also, the other dominant components $\tau_{(f_{CE}-6f_1)}$ and

Fig. 7. Characteristics of ripple torque ratio.

$\tau_{(f_{CE}+5f_1)}$ can be derived in the same way.

Theoretically, there are innumerable combinations which make up the frequency of one of the dominant components. However, because of the characteristics of the Bessel function, the larger the integers m , h and k , the smaller the harmonic index $A_{(m,h,k)}$ becomes. Therefore, the amplitudes of dominant components can be given using the integers of the following ranges:

$$m=2N, -6 \leq h \leq 6, -10 \leq k \leq 10 \quad \dots (14)$$

The other amplitude indices are negligible, because they are much smaller.

Here, the injection ratio, injection angle and ripple torque ratio are defined as:

$$\left. \begin{aligned} r_A &= (A_3/A_1) \times 100 \quad (\%) \\ \theta_i &= \theta_3 \quad (\text{deg}) \\ r_r &= \frac{\Delta \tau_s}{\Delta \tau_t} \times 100 \quad (\%) \end{aligned} \right\} \dots (15)$$

where

r_A : injection ratio

A_1 : modulation index of fundamental component

A_3 : modulation index of third harmonic

θ_i : injection angle

r_r : ripple torque ratio

$\Delta \tau_s$: ripple torque with subharmonic method

$\Delta \tau_t$: ripple torque with harmonic injection PWM

Fig. 7 shows an example of the calculated ripple torque when $N=4$, $A_1=0.46$ and $\theta_i=41$ deg, which is the condition to output the rated current in phase with the induced voltage at the output frequency 37.5 Hz. Here, the injection ratio r_A ranges from 0 to 30%, so that the amplitude of the modulation

(a) Modulation index and phase angle.

(b) Suitable injection ratio.

(c) Suitable injection angle

Fig. 8. Suitable injection ratio and injection angle.

wave is smaller than 1 when the modulation index A_1 is less than about 0.7. The injection ratio of 20% and angle of 30 degrees, where the minimum point of ripple torque ratio is located, correspond to the suitable third harmonic to minimize the ripple.

Fig. 8 (a) shows the modulation index and the phase angle when the current is kept at the rated one and in phase with the induced voltage. Figs 8 (b) and (c) show the characteristics of a suitable injection ratio and angle under the conditions of Fig. 8 (a). In a practical use, a table of the suitable injection ratio and angle to the modulation index and the phase angle is calculated in advance.

5. Simulation results

Fig. 9 shows the simulation results. Figs 9 (a) and (c) compare the simulation waveforms (the output voltage and current in phase u and the torque), and Figs 9 (b) and (d) show the frequency spectra of the conventional subharmonic method

Fig. 9. Comparison of simulation results.

Table 4. Simulation constants.

output frequency	37.5Hz
switching frequency	300Hz
N (multiple index)	4
dc voltage	93%
resistance	25%
inductive reactance	80%
SM induced voltage	75%

and the harmonic injection PWM, respectively. The simulation constants, shown in Table 4, are normalized considering the induced voltage at the frequency 50Hz and the rated current as 100%. The

injection ratio and angle in Figs 9 (c) and (d) are suitable (20%, 30 degrees), as was given in Fig. 7. The ripple torque is expressed as a percentage of the DC component.

In Figs 9 (a) and (c), both output voltages are multilevel pulse trains, where the harmonics of each unit inverter cancel out. The ripple torque of the subharmonic method is 2.32%, while the harmonic injection PWM successfully reduces the ripple torque to 0.94%. Here, the third harmonic component is not contained in the output current of the

Fig. 10. Comparison of ripple torque.

harmonic injection PWM, as this is a three-phase three-wire system. It is noted that the third harmonic never affects ripple torque reduction with the harmonic injection PWM even when it is contained in the output current.

In the frequency spectra in Figs 9 (b) and (d), harmonic components can be seen near the frequencies 2.4kHz (the equivalent carrier frequency) and 4.8kHz, which accords with the theoretical analysis. Harmonic current components near the equivalent carrier frequency of the injection PWM are slightly reduced compared with those of the subharmonic method. The dominant ripple torque components of injection PWM are less than 0.1%, while those of subharmonic are about 0.5%.

Fig. 10 shows the effect of ripple torque reduction of the harmonic injection PWM with the condition shown in Fig. 8. At output frequencies under 20Hz, where the modulation index A_1 is relatively low, the ripple torque is as large as the conventional subharmonic method. However, at output frequencies higher than 20Hz, the ripple torque is successfully reduced to less than 1.2%.

6. Conclusion

In this paper, a harmonic injection PWM was proposed, which aimed at minimization of the harmonics of the multiple power converter.

First, the Fourier series of PWM voltage when a harmonic component is injected into the reference sinusoid was derived and the relation between the components of voltage, current and torque were clarified. Next, the suitable amplitude and phase angle of the injected third harmonics to minimize

the ripple torque were derived. The simulation results showed the effectiveness of the ripple torque reduction.

It is further noted this PWM method is suitable for multiple inverter PWM control, where the switching frequency is relatively low because high power GTOs are used as switching devices.

(Manuscript received Aug. 21, '92,

revised Dec. 24, '92)

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