Online Dead Time Effect Compensation Algorithm of PWM Inverter for Motor Drive Using PR Controller

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Abstract – This paper proposes the dead time effect compensation algorithm using proportional resonant controller in pulse width modulation inverter of motor drive. To avoid a short circuit in the dc link, the dead time of the switch device is surely required. However, the dead time effect causes the phase current distortions, torque pulsations, and degradations of control performance. To solve these problems, the output current including ripple components on the synchronous reference frame and stationary reference frame are analyzed in detail. As a results, the distorted synchronous d-and q-axis currents contain the 6th, 12th, and the higher harmonic components due to the influence of dead time effect. In this paper, a new dead time effect compensation algorithm using proportional resonant controller is also proposed to reduce the output current harmonics due to the dead time and nonlinear characteristics of the switching devices. The proposed compensation algorithm does not require any additional hardware and the offline experimental measurements. The experimental results are presented to demonstrate the effectiveness of the proposed dead time effect compensation algorithm.

Key words: Dead time, Compensator, PWM inverter, PMSM drive

1. Introduction

Voltage Source Inverter(VSI) vector controlled motor drives have been widely developed. There are several causes to distort output voltage. Some is caused by the dead time that is to avoid shoot-through in the dc link. Others originate from the nonlinear characteristics of the switching devices such as turn-on/off time and voltages drop of switches and diodes. The distortion of the output voltage results in phase current distortions, torque pulsations, and degradations of control performance [1-5]. Since these undesirable ripples bring about bad influences to motor driving system, a compensation algorithm must be needed in the control algorithm of the motor drive. To solve the nonlinear characteristics of the VSI, various solutions have already been suggested [1-13]. The lost voltage average value calculation [2, 3], the pulse width modulation(PWM) pulse based technique [6], voltage feed forward method [7-12], and the support vector regression(SVR) method [13] are the main categories of the conventional dead time compensation methods.

In PWM pulse based technique, the compensation is realized for each PWM pulse. In [8, 9], the methods are dependent on the phase current polarity. In the voltage feed forward method, the methods are based on a feedforward method, where the compensated voltages are fed to the reference voltages in order to generate a modified voltage.

The compensation voltages are calculated by using the dead time, switching period, current command, and dc-link voltage. This approach can compensate the fundamental and harmonic components of the voltage error in the d- and q-axis frame. In the calculation of the compensating signals, nonlinear characteristics of the switching devices such as finite switching times and voltage drops are also considered. However, these methods can be implemented only by offline methods because the switching times and voltage drops of switching devices and diodes are varied with operating conditions such as dc-link voltage, phase currents, and motor speed. Thus, it is difficult to accurately compensate for the dead time effects by offline methods [12]. In [13], this method is based on an emerging learning technique SVR. The SVR technique is difficult to implement because SVR model method is required some parameters, online computation, and extra memory to construct the regression function.

In this paper, the output current including ripple components on the synchronous reference frame and stationary reference frame are analyzed in detail. Moreover, a new dead time effect compensation algorithm using proportional resonant(PR) controller is also proposed to reduce the output current harmonics due to the dead time and nonlinear characteristics of the switching devices. The proposed compensation algorithm does not require any additional hardware and the off-line experimental to detect the dead time effect contrast with the existing method. Also, it is a very simple controller by adding feed-forward compensation. The simulation and the experimental results are presented to verify the usefulness of the proposed algorithm.

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2. System Modeling

2.1 Dead time effects analysis [4, 15]

The switching device has a finite switching time, a blank-time or normally called dead-time must be inserted into the PWM gating signals in order to avoid the conduction overlap of two switching devices in the same leg. This dead-time causes the phase error, output voltage distortions and fundamental voltage drop, which degrade the control performance.

The commonly used three-phase PWM VSI with a permanent magnet synchronous motor (PMSM) load is shown in Fig. 1.

Fig. 2(a) shows the a-phase current i_{as} flow in positive direction and Fig. 2(b) displayed the a-phase current i_{as} flow in negative direction in a-phase leg of the PWM VSI. In Fig. 2(a), the a-phase current i_{as} flows through switching device $S1$ during the on-time of $S1$. Conversely, the a-phase current i_{as} flows through diode of $S2$ during both the off-time of $S1$ and dead time T_{dead} . In Fig. 2(b), the a-phase current i_{as} flows through switching device $S2$ during the on-time of $S2$. Conversely, the a-phase current i_{as} flows through diode of $S1$ during both the off-

Fig. 2. Three-phase PWM VSI with PMSM load

Fig. 3. Output voltage according to switching patterns

time of $S2$ and dead time T_{dead} . It means that the PWM VSI output voltage V_{an} has same characteristics during on, off-time of switching devices and during dead time T_{dead} . Hence, the PWM VSI output voltage V_{an} depends on the direction of the a-phase current i_{as} .

The relationship between ideal and real PWM VSI output voltage in case of positive and negative current direction is shown in Fig. 3. Where $S1$ and $S2$ are PWM gate signal, V_{an} is output voltage of the PWM VSI, ΔV is the distorted voltage respectively. As shown in Fig. 3, the real output voltage V_{an} of PWM VSI is directly influenced by the dead time and turn-on/turn-off delay time of switching device.

From Fig. 3, the average distorted voltage ΔV according to the direction of the a-phase current i_{as} can be represented as [14, 15].

$$\Delta V = \frac{-T_{dead} - t_{on} + t_{off}}{2T_s} V_{dc} \quad (i_{as} > 0) \quad (1)$$

$$\Delta V = \frac{T_{dead} + t_{on} - t_{off}}{2T_s} V_{dc} \quad (i_{as} < 0) \quad (2)$$

where T_s is the sampling period of the current regulator, t_{on} is the turn-on delay time of switching device, t_{off} is the turn-off delay time of switching device, respectively.

The absence of a neutral connection in the motor forces the constraint that [7]:

$$i_{as} + i_{bs} + i_{cs} = 0 \quad (3)$$

For any balanced load, the line to neutral voltages are constrained such that :

$$V_{as} + V_{bs} + V_{cs} = 0 \quad (4)$$

Therefore, the distorted voltage of three-phases are calculated by (5).

$$\begin{aligned} \Delta v_{as} &= \Delta V \frac{1}{3} \{2\text{sign}(i_{as}) - \text{sign}(i_{bs}) - \text{sign}(i_{cs})\} \\ \Delta v_{bs} &= \Delta V \frac{1}{3} \{2\text{sign}(i_{bs}) - \text{sign}(i_{cs}) - \text{sign}(i_{as})\} \\ \Delta v_{cs} &= \Delta V \frac{1}{3} \{2\text{sign}(i_{cs}) - \text{sign}(i_{as}) - \text{sign}(i_{bs})\} \end{aligned} \quad (5)$$

If the phase current flow in positive direction, $\text{sign}(i_{as,bs,cs})$ is +1. Conversely, if the phase current flow in negative direction, $\text{sign}(i_{as,bs,cs})$ is -1.

By (5), the distorted phase voltage Δv_s and three-phase current i_s can be drawn as Fig. 4. Also, Fig. 5. is shown the distorted voltage and the dq -axis currents of the stationary reference frame.

In order to analysis the harmonic component by dead time effect, Fourier series is applied. In case of square-

Fig. 4. Distorted phase voltage and phase current in PWM VSI

Fig. 5. Distorted voltage and the dq -axis currents of the stationary reference frame

wave voltage, the harmonic component of voltage is calculated as follows:

$$v_h = \frac{4V_{dc}}{\pi} \sum_{h=1,3,5,7,\dots} \frac{1}{h} \sin(h\omega_0 t) \quad (6)$$

where v_h is the harmonic component of voltage, V_{dc} is the square-wave voltage, h is harmonic order and ω_0 is the motor synchronous frequency (rad/s).

Therefore, the distorted voltage Δv_{ds}^s and Δv_{qs}^s can be obtained by (7), (8).

$$\Delta v_{ds}^s = \frac{4\Delta V}{\pi} \left\{ \sin \omega_0 t + \frac{1}{5} \sin 5\omega_0 t + \frac{1}{7} \sin 7\omega_0 t + \frac{1}{11} \sin 11\omega_0 t + \frac{1}{13} \sin 13\omega_0 t + \dots \right\} \quad (7)$$

$$\Delta v_{qs}^s = \frac{4\Delta V}{\pi} \left\{ -\cos \omega_0 t + \frac{1}{5} \cos 5\omega_0 t - \frac{1}{7} \cos 7\omega_0 t + \frac{1}{11} \cos 11\omega_0 t - \frac{1}{13} \cos 13\omega_0 t + \dots \right\} \quad (8)$$

Similarly, the distorted current i_h which corresponds to the distorted voltage can be calculated by (9).

$$i_h = \frac{4\Delta v_s}{\pi} \sum_{h=1,3,5,7,\dots} \frac{1}{hZ_h} \sin(h\omega_0 t - \phi_h) \quad (9)$$

where Z_h is the load impedance, ϕ_h is the load impedance angle respectively.

From (9), the distorted dp -axis currents of the stationary reference frame can be expressed as (10), (11).

$$\Delta i_{ds}^s = \frac{4\Delta V}{\pi} \left\{ \frac{\sin}{Z} (\omega_0 t - \phi) + \frac{1}{5Z_5} \sin(5\omega_0 t - \phi_5) + \frac{1}{7Z_7} \sin(7\omega_0 t - \phi_7) + \frac{1}{11Z_{11}} \sin(11\omega_0 t - \phi_{11}) + \frac{1}{13Z_{13}} \sin(13\omega_0 t - \phi_{13}) + \dots \right\} \quad (10)$$

$$\Delta i_{qs}^s = \frac{4\Delta V}{\pi} \left\{ -\frac{\cos}{Z} (\omega_0 t - \phi) + \frac{1}{5Z_5} \cos(5\omega_0 t - \phi_5) - \frac{1}{7Z_7} \cos(7\omega_0 t - \phi_7) + \frac{1}{11Z_{11}} \cos(11\omega_0 t - \phi_{11}) - \frac{1}{13Z_{13}} \cos(13\omega_0 t - \phi_{13}) + \dots \right\} \quad (11)$$

In order to simple analysis, the distorted voltages and the distorted currents of the synchronous reference frame can be rewritten by (12)-(15).

$$\Delta v_{ds}^e = \frac{4\Delta V}{\pi} \left\{ \frac{12}{35} \sin 6\omega_0 t + \frac{24}{143} \sin 12\omega_0 t + \dots \right\} \quad (12)$$

$$\Delta v_{qs}^e = \frac{4\Delta V}{\pi} \left\{ -1 + \frac{2}{35} \cos 6\omega_0 t + \frac{2}{143} \cos 12\omega_0 t + \dots \right\} \quad (13)$$

$$\Delta i_{ds}^e = \frac{4\Delta V}{\pi} \left\{ \frac{12}{35Z_6} \sin(6\omega_0 t - \phi_6) + \frac{24}{143Z_{12}} \sin(12\omega_0 t - \phi_{12}) + \dots \right\} \quad (14)$$

$$\Delta i_{qs}^e = \frac{4\Delta V}{\pi} \left\{ -\frac{1}{Z} + \frac{2}{35Z_6} \cos(6\omega_0 t - \phi_6) + \frac{2}{143Z_{12}} \cos(12\omega_0 t - \phi_{12}) + \dots \right\} \quad (15)$$

As shown in (14) and (15), the distorted synchronous d- and q-axis current contain the 6^{th} , 12^{th} , and the higher harmonic components due to the influence of dead time effect. The 6^{th} harmonic component is dominated by (14) and (15). The dead time effect can be mitigated by the appropriately harmonic component mitigation, either in stationary or in synchronous reference frame.

3. Proposed Dead Time Compensation Algorithm

3.1 Design of PR controller

In general, PR controller is used to remove the certain

order harmonics for the current regulator because the PR controller has zero steady-state error for sinusoidal waveforms having the same synchronous frequency as ω_r [16-19].

The ideal PR control, which is based on an internal modern theory, is expressed as (16).

$$G_s = K_p + \frac{K_i s}{s^2 + \omega_r^2} \quad (16)$$

Where ω_r is the resonant frequency, K_p and K_i represent proportional and resonant gains respectively. For K_p , it is tuned in the same way as for a PI controller, and it basically determines the dynamics of the system in terms of bandwidth, phase and gain margin and K_i could be tuned for shifting the magnitude response vertically but this does not give rise to a significant variation in bandwidth [20]. The Bode plots of ideal PR control method are shown in Fig. 6.

The ideal PR controller has an infinite gain at the resonant frequency and no phase shift and gain at other frequencies. However, the controller's infinite gain may cause stability problems and has the practical limitations of signal processing systems. Because of these problems, the non-ideal PR controller transfer function (17) is used instead of ideal PR controller (16).

$$G_s = K_p + \frac{K_i \omega_c s}{s^2 + 2\omega_c s + \omega_c^2} \quad (17)$$

The Bode plots of non-ideal PR control method are shown in Fig. 7(a) and 7(b).

By applying the bilinear transformation S_z and substituting in to non-ideal trans function (17), the discrete trans function of the PR controller can be obtained by (18).

Fig. 6. Bode plots of ideal PR controller($\omega_0=100$ [rad/s])

Fig. 7. Bode plots of non-ideal PR controller($\omega_c : 10$ [rad/s], $\omega_r : 100$ [rad/s])

Fig. 8. Block diagram of non-ideal PR controller

$$S_z = \frac{2}{T_s} \frac{1-z^{-1}}{1+z^{-1}}, \quad G_z = \frac{n_0 + n_1 z^{-1} + n_2 z^{-2}}{1 + d_1 z^{-1} + d_2 z^{-2}} \quad (18)$$

where T_s is the sampling time,

$$n_0 = \frac{(4 + 4T_s \omega_c + \omega_0^2 T_s^2) K_p + 4K_i T_s \omega_c}{4 + 4T_s \omega_c + \omega_0^2 T_s^2};$$

$$n_1 = \frac{(-8 + 2\omega_0^2 T_s^2) K_p}{4 + 4T_s \omega_c + \omega_0^2 T_s^2};$$

$$n_2 = \frac{(4 - 4T_s \omega_c + \omega_0^2 T_s^2) K_p - 4K_i T_s \omega_c}{4 + 4T_s \omega_c + \omega_0^2 T_s^2};$$

$$d_1 = \frac{-8 + 2\omega_0^2 T_s^2}{4 + 4T_s \omega_c + \omega_0^2 T_s^2}; \quad d_2 = \frac{4 - 4T_s \omega_c + \omega_0^2 T_s^2}{4 + 4T_s \omega_c + \omega_0^2 T_s^2}$$

Therefore, the digital equation of non-ideal PR controller can be given by (19).

$$y(k) = n_0 u(k) + n_1 u(k-1) + n_2 u(k-2) - d_1 y(k-1) - d_2 y(k-2) \quad (19)$$

The block diagram of non-ideal PR controller is shown in Fig. 8.

Fig. 9. Block diagram of the proposed dead time effect compensation algorithm

Table 1. The properties of a SPMSM drive parameter

Properties SPMSM	Details
Rated voltage	25 [V]
Rated current	2.8 [A]
Rated speed	3000 [r/min]
Maximum speed	3500 [r/min]
Poles	4
Stator resistance	0.75 [Ω]
Stator inductance	0.85 [mH]
Properties motor drive	Details
Control processor	DSP TMS320F28335
Switching frequency	10 [kHz]
Current regulator period	100 [μs]
Speed regulator period	1000 [μs]
Dead time	3 [μs]
Turn on time of switch device	0.1 ~ 0.4 [μs]
Turn off time of switch device	0.2 ~ 1.1 [μs]

3.2 Proposed dead time compensation method

The distorted synchronous d-and q-axis currents contain the 6^{th} , 12^{th} , and the higher harmonic components due to the influence of dead time effect. Fig. 9. shows the block diagram of the proposed compensation algorithm.

Firstly, the synchronous d- and q-axis currents are passed through the PR controller to extract the 6th, 12th harmonics components in parallel with PI current regulator.

Secondly, the output of PR controller is used to feed-forward compensation of PI current regulator output.

Hence, the harmonic components due to the dead time effect can be eliminated.

4. Experimental Results

The proposed dead time effect compensation algorithm was implemented with a SPMSM drive system. The parameters given in Table 1. The drive system for experimental is shown in Fig. 10.

Fig. 11(a), (b), and (c) show the experimental waveforms without the dead time compensation when the motor operates at 3000[r/min] at no-load. Fig. 11(a) displays

Fig. 10. Experimental system setup

the hexagonal x-y plot. The phase current i_{as} with distorted waveform is shown in Fig. 11(b). As shown in Fig. 11(b), the FFT result of the phase current i_{as} has the 5th and 7th harmonic components, and the higher harmonic components. However, the FFT result contains very small 11th and 13th harmonic components rather than 5th and 7th harmonic components by (10). It means that the distorted waveform is not significantly affected by the 11th and 13th harmonic components. The d- and q-axis currents of the synchronous reference frame have the 6th harmonic component, as shown in Fig. 11(c).

Fig. 13 shows the experimental results waveforms of the proposed compensator. With the proposed method, the x-y plot of the Fig. 12(a) displays circular waveforms rather than Fig. 11(a) and the phase current i_{as} has the nearly sinusoidal waveform as shown in Fig. 12(b). The harmonic components of the phase current i_{as} are considerably reduced by the proposed algorithm. Likewise, the dq-axes currents of the synchronous reference frame and the FFT results show the reduced harmonics, as shown in Fig. 12(c).

Fig. 13(a), (b), and (c) illustrate the experimental results without the dead time compensation when the motor operates at 3000[r/min] in the 30[W] output. Similar to the

(a) x-y plot

(b) harmonics of $i_{as}(=i_{ds}^s)$ current

(c) harmonics of d- and q-axis currents

Fig. 11. Current waveforms without dead time compensation under no-load

no-load condition, the x-y plot of the stationary reference frame current i_{ds}^s and i_{qs}^s display the hexagonal wave form. The FFT result of the phase current i_{as} have the 5th and 7th harmonic components, and the higher harmonic components. Also, the FFT result contains small 11th and 13th harmonic components rather than 5th and 7th harmonics.

(a) x-y plot

(b) harmonics of $i_{as}(=i_{ds}^s)$ current

(c) harmonics of d- and q-axis currents

Fig. 12. Current waveforms with dead time compensation under no-load

Considering the proposed dead time compensation algorithm, the x-y plot of the Fig. 14(a) shows circular waveforms rather than Fig. 13(a) and the phase current i_{as} has the pure sinusoidal waveform as shown in Fig. 14(b). The harmonics of the phase current i_{as} are considerably reduced by the dead time compensation. Likewise, the dq-axes currents of the synchronous

(a) x-y plot

(a) x-y plot

(b) harmonics of $i_{as} (= i_{ds}^s)$ current

(b) harmonics of $i_{as} (= i_{ds}^s)$ current

(c) harmonics of d - and q -axis currents

(c) harmonics of d - and q -axis currents

Fig. 13. Current waveforms without dead time compensation under on-load

Fig. 14. Current waveforms with dead time compensation under on-load

reference frame and the FFT results show the reduced harmonics, as shown in Fig. 14(c).

5. Conclusions

The dead time compensation algorithm for the motor

drive system is proposed. The proposed algorithm is comprised of the PR controller in parallel with the general PI current regulator. The output of PR controller is used to feed-forward compensation of PI current regulator output. Hence, the harmonic components due to the dead time effect can be eliminated.

This algorithm does not require any external hard ware,

off-line experimental measurements. The proposed method can be easily implemented and applied in the system. The validity of the proposed algorithm is proved by the several experimental tests.

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