DEAD-TIME COMPENSATION IN VECTOR CONTROLLED AC SYSTEM

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Abstract: It is necessary to insert a switching delay time in pulse width modulation (PWM) voltage inverters to prevent a short circuit in the DC link. This causes known dead-time effect which evokes distortion of output voltage inverter and ripple of phase current. This paper aims at analyzing and compensating the dead-time effects in the vector-controlled AC system. The results of the experiment show the validity of the analysis and verify the effectiveness of the proposed compensation method. The method can be implemented with software without any extra hardware.

Keywords: dead-time compensation, induction motor, AC drives

1. INTRODUCTION

PWM inverters have gained increasing popularity in industrial applications recently. The developed switching devices in the PWM inverter such as IGBT, MOSFET are commonly used due to the fast switching frequency above tens of kHz. Unfortunately, command voltage disagrees with actual fundamental phase voltage because PWM inverter has undesirable characteristics, such as dead-time, turn-on/off time of switching devices, and on-voltages of switching devices and diodes. Dead-time is important to avoid short-circuit of inverter legs. The value of the time is determined by the characteristics of the switching device. During dead-time period, both switches (upper and lower) are turned off, and the output voltage of PWM inverter depends on the direction of the phase current. The detection of the phase current polarity is important to the method. However, due to the high frequency interference and zero clamping phenomena the phase current polarity is difficult to judge around the current zero-crossing point [1]-[4].

This paper presents dead-time compensation strategy for PWM voltage-source inverter. The compensation strategy is implemented in the two axes stationary scheme. And the proposed method was verified in induction motor vector controlled system.

2. ANALYSIS OF DEAD-TIME EFFECT

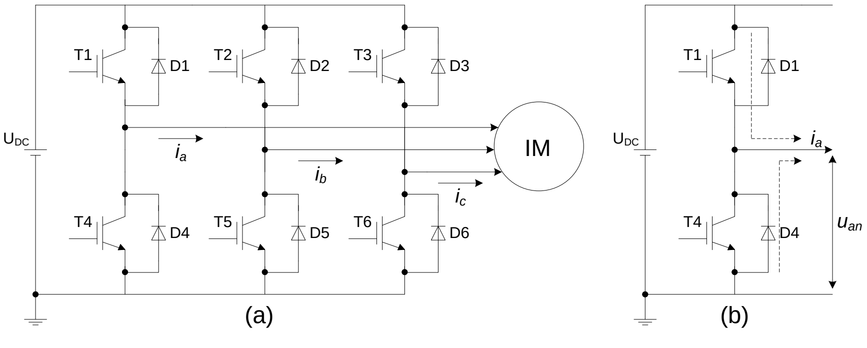

Figure 1: AC motor-drive system. (a) 3-phase PWM voltage source inverter with induction motor load. (b) One phase leg of the PWM inverter ($i_a>0$).

A power circuit of a three-phase voltage PWM inverter to drive the induction motor is show in Figure 1(a), where the IGBTs are used as active switching devices. Figure 1(b) shows the one phase leg of the PWM inverter with induction-motor load. During the dead-time, the current can flow through only freewheeling diodes regardless of the phase current direction. In this case, the output voltage of the inverter may be different from the desired reference voltage [1].

Assume that the a-phase current i_a is positive when phase current flows from inverter to induction motor. On the contrary the polarity of the phase current is negative when it flows from induction motor to inverter. When phase current i_a is greater than zero, upper switch T1 is in on-state and lower switch T4 is in off-state, the current flows to motor through T1. But during dead-time period T_d both switches T1 and T4 are in off-state, the phase current flows through lower diode D4 and the direction of the phase current remains unchanged. This current causes the deviation of the output voltage inverter. In the second case, when the phase current i_a is less than zero, lower switch T4 is in on-state and upper switch T1 is in off-state, the phase current flows through lower switch T4. But during dead-time period T_d both switches T1 and T4 are turned off, the phase current flows through upper diode D1. This phenomenon produces the output voltage error of the inverter [3].

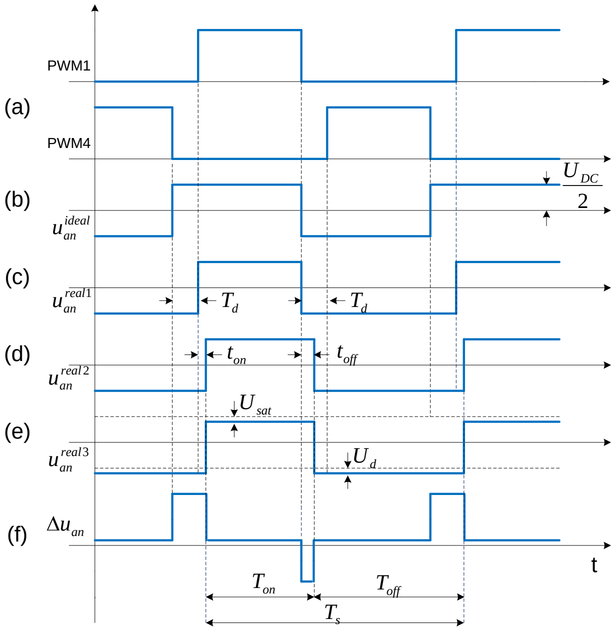

Figure 2: Dead-time effect of a-phase ($i_a>0$). (a) Gate signal considering the dead-time. (b) Ideal output voltage. (c) Output voltage considering the dead-time. (d) Actual Output voltage considering the dead-time and the turn-on/off time. (e) Actual output voltage. (f) Difference between ideal and practical inverter output voltage.

Figure 2 shows actual output voltage to the positive direction ($i_a>0$) of the phase current i_a. Figure 2(a) shows the gate signal patterns PWM1 and PWM4, where high level of PWM wave represents turn-on and low level represents turn-off. Figure 2(b) shows the phase ideal output voltage. Figure 2(c) shows the actual output voltage considering only the dead time. Due to the switching delay as turn-on time t_{on} and turn-off time t_{off} of switches devices, the output voltage becomes u_{an}^{real2}, which is shown in Figure 2(d). u_{an}^{real3} is actual output voltages considering the inserted dead time, the turn-on/off delay time, and the voltage drops of switching devices. Δu_{an} is difference between ideal and practical inverter output voltage. On the same way, the instance can be also deduced when $i_a<0$ [2]. The analysis of the Figure 2 shows that, the average voltage error over one PWM period of a-phase between the actual output voltage and the ideal output voltage can be expressed as

$$\Delta u_{era} = U_{DC}\frac{T_c}{T_s} + U_{ave}. \tag{1}$$

Where, U_{DC} is the DC-link voltage of the inverter and T_s represent the switching cycle of the inverter. T_c represent a-phase dead-time compensation time and it is define as

$$T_c = sign(i_a)(T_d + t_{on} + t_{off}) , \tag{2}$$

where $sign(i_a) = \begin{cases} 1, & i_a \geq 0 \\ -1, & i_a < 0 \end{cases}$.

U_{ave} represent average voltage error over one PWM period which is caused by the voltage drops of switching devices. U_{ave} can be given as

$$U_{ave} = \begin{cases} \dfrac{T_{on}U_{sat} + T_{off}U_d}{T_s}, & i_a \geq 0 \\ \dfrac{T_{on}U_d + T_{off}U_{sat}}{T_s}, & i_a > 0 \end{cases} , \tag{3}$$

where U_{sat} is the on-state voltage drop across the switch, and U_d is the forward voltage drop of the diode. The situations of b-phase and c-phase are similar as a-phase [2].

3. DEAD-TIME COMPENSATION STRATEGY

The dead-time compensation voltage depends on the polarity of phase current. Therefore it is very important to detect the zero-crossing point and the polarity of each phase current. In this case, method of current polarity detection is sampling the phase current through A/D converter of dSpace and judging the polarity directly. However, this method causes voltage error effect due to the error detection of phase current polarity around the zero-crossing point. The voltage error is usually caused by the odd harmonics and high-frequency noise phase current. The even harmonics and higher order odd harmonics have little effects to the inverter output voltage distortion, and hence, the third, fifth and seventh harmonics are dominant [4].

During the phase current polarity detection around the zero-crossing point, may cause the following problem. When phase current is less than zero but phase current with noise is greater than zero during PWM period, thus dead-time compensation is incorrect. The dead-time compensation voltage is calculated with opposite polarity. This causes distortion of output voltage inverter and ripple of phase current. This undesirable effect is minimized by introducing the dead zone hysteresis. The dead zone hysteresis is adopted around the current zero-crossing point. The threshold of the hysteresis is i_h that is shown in Figure 3. When $|i_a| \leq |i_h|$, dead-time compensation voltage is zero.

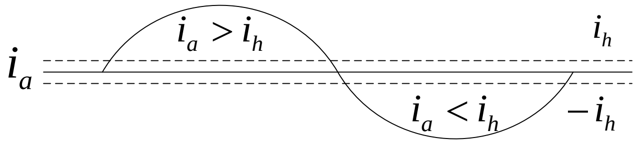

Figure 3: The phase current waveform with the dead zone hysteresis

The function of output dead-time compensation voltage is expressed as

$$\Delta u'_{era} = \begin{cases} 0 & |i_a| \leq |i_h| \\ \Delta u_{era} & |i_a| > |i_h| \end{cases} . \tag{4}$$

In accordance with the performed analysis, the output dead-time compensation voltages in the three-phase stationary frame are transformed to the voltage errors (Δu_α, Δu_β) in the α-β two-phase stationary frame as

$$\begin{bmatrix} \Delta u_{\alpha} \\ \Delta u_{\beta} \end{bmatrix} = \begin{bmatrix} \frac{2}{3} & -\frac{1}{3} & -\frac{1}{3} \\ 0 & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{3}} \end{bmatrix} \begin{bmatrix} \Delta u'_{era} \\ \Delta u'_{erb} \\ \Delta u'_{erc} \end{bmatrix}, \qquad (5)$$

where $\Delta u'_{erb}$ and $\Delta u'_{erc}$ represent the output dead-time compensation voltages of b-phase and c-phase, respectively, which are obtained by the same way with (4).

In vector control of induction motor, the dead-time compensation voltages are compensated to the input of the SVPWM module, where the error voltages (Δu_{α}, Δu_{β}) are summed with the voltage vectors u_{α} and u_{β}. Then the dead-time effect can be eliminated and the performance of the vector control induction motor can be improved.

4. EXPERIMENTAL RESULTS

The dead-time compensation strategy is verified on vector controlled AC system. The 3-phase AC induction motor 1LA7070-4AB10 is connected to Freescale power stage 00388 and system is controlled by dSpace platform. The parameters of switching devices and diodes smart power module FSBB20CH60CL are shown in Table 1[5]. The input DC link voltage of the inverter is 280 V and PWM frequency is 16 kHz.

Item	**Value**
Dead-time T_d	3 [μs]
Turn-on delay time t_{on}	0.2 - 0.3 [μs]
Turn-off delay time t_{off}	0.45 [μs]
Saturation voltage U_{sat}	2 [V]
Forward voltage U_d	2.5 [V]

Table 1: The parameters of IGBT module [5]

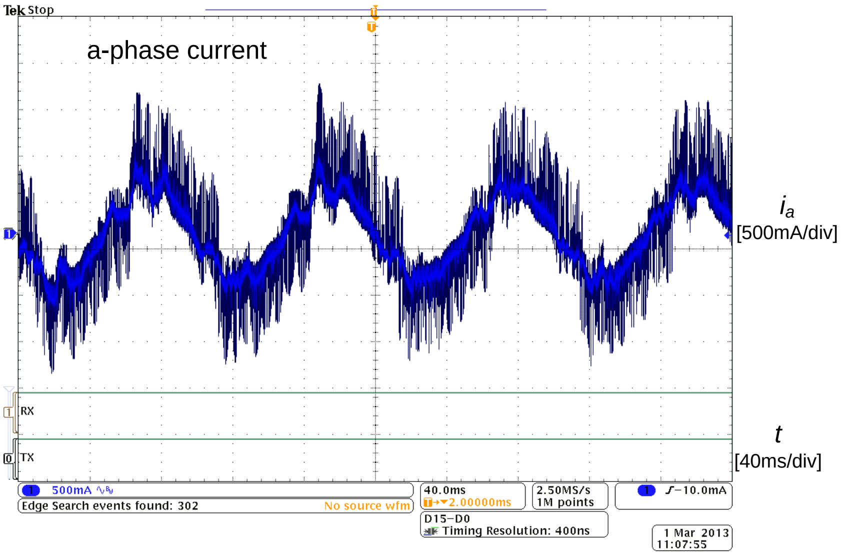

Figure 4: The phase current waveform without dead-time compensation

The result of the experiment with proposed compensation method is presented in the steady state, the reference motor speed is 30 rad/s. Figure 4 and Figure 5 compares phase current with/without dead-time compensation method. As can be seen in Figure 4, phase current is distorted due to dead-time effects. Figure 5 shows the distortion of phase current what is suppressed by applying the proposed dead-time compensation method. The algorithm of dead time compensation is performed by dSpace platform.

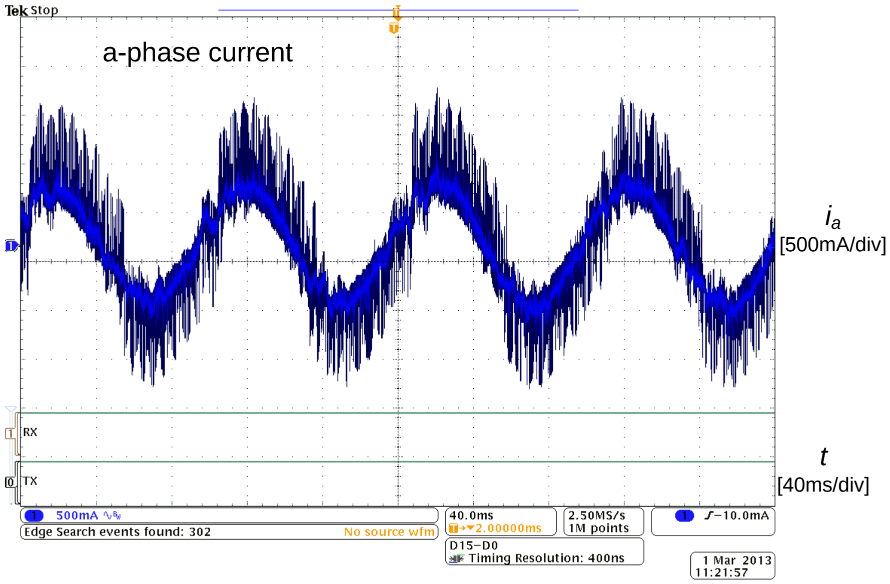

Figure 5: The phase current waveform with dead-time compensation

5. CONCLUSION

In this paper, the dead-time compensation method for a vector-controlled induction motor was proposed. In the first section of this paper is detail analysis of dead-time effects on the output voltage of PWM inverter, which includes the effect of dead-time, turn-on/off time of switching devices, and voltage drops of switching devices and freewheeling diodes. The second part describes the dead-time compensation strategy. The results demonstrate that the proposed method can suppress the current distortion of phase currents. When the dead-time effect is eliminated, the performance of the vector control can be improved. The experimental results prove that proposed method have good compensation effect and can be applied to induction motor drive systems. This method can be implemented with software without any extra hardware.

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REFERENCES

[1] SUL, S.-K.: Control of Electric Machine Drive Systems, IEEE Press Series on Power Engineering, John Wiley & Sons, 2011, pp. 324-354, ISBN 1118099567.

[2] WANG, H., WANG, J., WANG, Z., ZHAO, J.: A Novel Dead-time Compensation in Vector Controlled PMSM System, IEEE Proceedings of the 30th Control Conference, July 2011, pp. 3478-3483.

[3] ZHOU, L. Q.: Dead-time compensation Method of SVPWM Based on DSP. 4th IEEE Conference on Industrial Electronic and Applications, 2009, pp. 2355-2358.

[4] KIM, S.-Y., PARK, S.-Y.: Compensation of Dead-Time Effect Based on Adaptive Harmonic Filtering in the Vector-Controller AC Motor Drives, IEEE Trans., vol. 54, no. 3, June 2007, pp. 1768-1777.

[5] Fairchild Semiconductor Corporation: FSBB20CH60CL Smart Power Module, User Manual, August 2009, pp. 1-17.