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The Analysis and Compensation of Dead Time Effects in a Vector-Controlled Induction Machine

벡터 제어 유도 전동기의 데드 타임 효과 해석 및 보상

Seong-Hwan Kim*, Young-Jae Ryoo*, Young-Hak Chang*
(金 成 奐*, 柳 泳 材*, 張 永 學*)

Abstract

Dead time which is inserted in PWM signals of VSI distorts the inverter output voltage waveforms and deteriorate the control performance of an induction machine by producing torque ripples. In this paper, dead time compensation method in a vector controlled induction machine is proposed. The method is based on a feedforward approach that compensates dead time effect by adding the compensating voltages to the inverter output voltage references in 2 phase stationary frame. The proposed method is only software intensive and easy to realize without additional hardware. The experimental results show the validity and effectiveness of the proposed method.

요 약

전압원 인버터의 PWM 신호에 삽입되는 데드 타임은 인버터 출력 파형을 왜곡시키고, 토크 리플을 발생시켜 유도 전동기의 제어 성능을 떨어뜨린다. 본 논문에서 벡터 제어 유도 전동기의 데드 타임 보상 방법이 제안된다. 제안된 방법은 2상 정지 좌표계에서 인버터 출력 기준전압에 보상 전압을 더하는 전향 보상에 근거한다. 제안된 방법은 부가적인 하드웨어 없이 소프트웨어적으로 실현 가능하다. 실험 결과를 통하여 제안된 방법의 타당성과 유용성을 확인한다.

Keywords : Dead Time, PWM, VSI, Vector Control, Induction Motor

Ⅰ. Introduction

Recently, PWM Inverter is frequently used in driving an induction machine because it can control the output voltage and frequency at the same time. Various PWM methods have been studied to synthesize precise output voltage and reduce the harmonics. And the development of the high speed switching devices such as Power Transistor, IGBT and Power MOSFET make possible to increase the PWM frequency(5 ~ 15kHz). As a result, fundamental component of the inverter output waveform is increased and high order harmonics are

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* 木浦大學校 制御計測工學科
(Dept. of Control & Instrumentation Eng., Mokpo National Univ.)

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reduced.

However, time delay called dead time(2 ~ 5μs) should be inserted in PWM patterns to prevent short circuit of the inverter arm with DC link voltage. Voltage error due to the dead time deteriorate the inverter output voltage, reduce the fundamental component and produce low order harmonics. Distorted inverter output voltage produce current ripples, increase torque ripples and reduce the control performance of an induction machine.[1]~[6] To reduce the dead time effects, various methods have been studied and applied. Conventionally, error voltages due to the dead time effect are pre-calculated and compensated by adding them to the each 3-phase voltage references feedforwardly according to their phase current polarity.[1]~[4] From the work in [5], a hardware compensator measure the time which instantaneous inverter voltage changes based on the current polarity. The measured times are fed back to compensate the next switching time. In [6], adjust the instantaneous gate pulse width considering the effects on the inverter output voltage by the dead time according to the current polarity. These conventional methods achieve satisfactory compensation results but they need additional hardware or software complicated.

In this paper, we propose a dead time compensation method which compensate fundamental, 5th and 7th harmonics of the compensation voltage feedforwardly in the 2-phase stationary frame. The proposed method uses the phase of the current vector which is calculated from the reference currents and the inverter output frequency as the phase of the dead time compensation voltage. The method does not need additional hardware or complicated software and it is easy to realize by applying the algorithm to the conventional vector controller.

II. Analysis of the Dead Time Effects

Dead time which is inserted to the PWM pulses to prevent the short circuit of the inverter arm causes distortion of the inverter output voltages. It is convenient to analysis the dead time effect from one phase of the inverter and extend the results to the 3-phase. Fig. 1 shows the basic configuration of the one phase of the PWM inverter which have bi-directional switches. The neutral point of DC voltage (o) is set as the reference of the inverter output voltage.

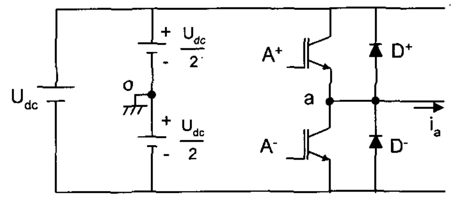

Fig. 1. One phase leg of PWM Inverter

When the commutation occurs, the dead time effects to the inverter output voltage show different manners according to the current polarity as follows.

i) When the current i_a is positive :

a) Upper Switch(A+) → On, Lower Switch(A-) → Off : During the dead time(Td), current flows through the lower diode(D-) and after the turn on time delay of the switching device (ton), current starts to flow through upper switch (A+). As a result, inverter output voltage error occurs during Td + ton time.

b) Upper Switch(A+) → Off, Lower Switch(A-) → On : After the turn off time delay(toff), the current which was flowing through the upper switch(A+) starts to flow through the lower diode(D-). So, there's an error during toff time between the inverter voltage and the reference voltage.

ii) When the current i_a is negative :

a) Upper Switch(A+) → On, Lower Switch(A-) → Off : After the turn off time delay(toff), the current which was flowing through the lower switch(A-) starts to flow through the upper diode(D+). So, there's an error during toff time between the inverter voltage and the reference voltage.

b) Upper Switch(A+) → Off, Lower Switch(A-) → On : During the dead time(Td), current flows through the upper diode(D+) and after the turn on time delay of the switching device (ton), current starts to flow through lower switch (A-). As a result, inverter output voltage error occurs during Td + ton time.

Fig. 2 shows the gate pulses, inverter output voltage reference and real output voltage according to the polarity of the phase current during one switching period.

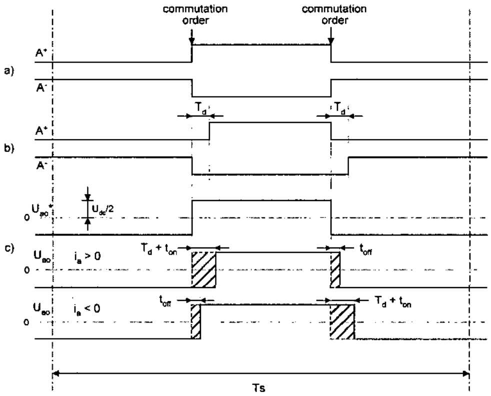

Fig. 2. Inverter Output Voltage and Gate Pulses
(a) gate pulse reference (b) gate pulse with dead time inserted (c) inverter voltage

From fig. 2, two commutations occur during one switching period and the average error between the inverter reference voltage and the real output is as follows.

$$\delta U_d = \begin{cases} -\dfrac{\delta T}{T_s} U_{dc} \ , & \text{if} \quad i_A > 0 \\ +\dfrac{\delta T}{T_s} U_{dc} \ , & \text{if} \quad i_A < 0 \end{cases} \tag{1}$$

where δU_d : average error voltage, U_{dc} : DC voltage

$\delta T = T_d + t_{on} - t_{off}$,

T_d : dead time, T_s : sampling time

t_{on} : turn-on time of the switching device

t_{off} : turn-off time of the switching device

So, the real inverter output voltages deviate from the references due to the dead time. Consequently, phase current waveforms are distorted and include low order harmonics. These low order harmonics of the phase current cause torque ripples and deteriorate the system performance.

Ⅲ. Dead Time Effect Compensation Method

Basically, the dead time effects can be solved by compensating feedforwardly the error voltages of Eq. (1) to the each phase inverter voltage reference according to the its current direction. In this conventional method, the informations of each current direction should be known. However, the noises of the system or the inaccuracy of the current sensors make it difficult to compensate properly.

In a vector controlled induction machine, the inverter voltage references are made by the current controller. The outputs of the torque current and flux current controller in the 2-phase rotationary frame are transformed to the 2-phase stationary frame and those are used as inverter voltage references. So, the inverter error voltages due to the dead time can be compensated feedforwardly in the 2-phase stationary frame. Dead time compensation voltages in the 3-phase stationary frame is transformed to the compensation voltages in the 2-phase stationary frame by Park's Transformation as follows.

$$\begin{bmatrix} \Delta U_{ds} \\ \Delta U_{qs} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} \Delta U_{an} \\ \Delta U_{bn} \\ \Delta U_{cn} \end{bmatrix} \tag{2}$$

The compensation voltage components in the 3-phase stationary frame ($\Delta U_{an}, \Delta U_{bn}, \Delta U_{cn}$) are calculated from Eq. (1) and Fig. (1) according to their current polarity. Fig. 3 shows the phase currents and the dead time compensation voltages which are calculated from Eq. (2).

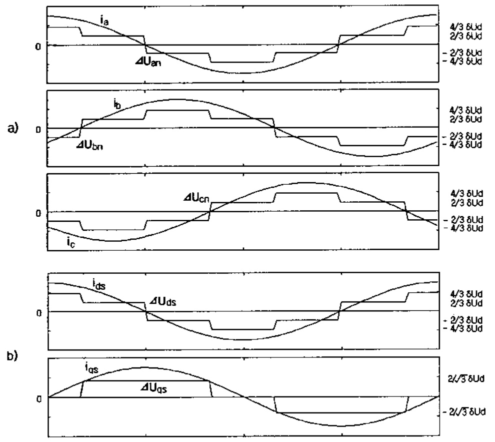

Fig. 3 Phase currents and dead time compensation voltages

(a) 3 phase currents and compensation voltages

(b) 2 phase currents and compensation voltages

Dead time compensation voltages in the 2-phase stationary frame consist of fundamental and odd harmonics. And the phase of the fundamental component is in phase with the current vector in the stationary frame. Compensation voltages (ΔU_{ds}, ΔU_{qs}) are analyzed as follows by Fourier analysis.

$$\begin{aligned}\Delta U_{ds} &= \frac{4}{\pi}\,\Delta U_d\,(\cos\varphi + \frac{1}{5}\cos 5\varphi \\ &\quad - \frac{1}{7}\cos 7\varphi + \ldots) \\ \Delta U_{qs} &= \frac{4}{\pi}\,\Delta U_d\,(\sin\varphi - \frac{1}{5}\sin 5\varphi \\ &\quad - \frac{1}{7}\sin 7\varphi + \ldots)\end{aligned} \tag{3}$$

where Φ : phase of the current vector,

$$\Delta U_d = \frac{\delta T}{T_s} U_{dc}$$

From Eq. (3), there are no zero-phase voltages such as 3-th, 9-th harmonics and high order harmonics have little effects to the inverter output voltage distortion.[8] Therefore, it is sufficient to remove the dead time effects by compensating feedforwardly only fundamental, 5-th and 7-th low order harmonics in the 2-phase stationary frame.

The phase of the current vector is calculated from the current references of the 2-phase rotationary frame and the inverter output frequency. In a vector controlled induction machine, the relation between the current references of the 2-phase rotationary frame (I^*_{ds}, I^*_{qs}) and the current references of the 2-phase stationary frame(I^{s*}_{ds}, I^{s*}_{qs}) are as follows.[7][8]

$$\begin{aligned}\begin{bmatrix} I^{s*}_{ds} \\ I^{s*}_{qs} \end{bmatrix} &= \begin{bmatrix} \cos\omega_e t & -\sin\omega_e t \\ \sin\omega_e t & \cos\omega_e t \end{bmatrix} \begin{bmatrix} I^*_{ds} \\ I^*_{qs} \end{bmatrix} \\ &= I^*_s \begin{bmatrix} \cos\varphi \\ \sin\varphi \end{bmatrix}\end{aligned} \tag{4}$$

where I^*_s and Φ are the magnitude and the phase of the current vector, ω_e is the inverter output frequency.

Fig. 4 shows the current vector in space coordinates of an induction machine.

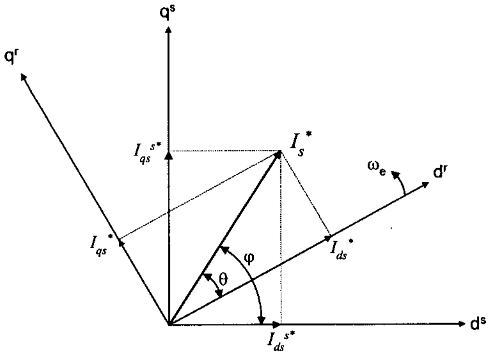

Fig. 4 Current Vector in Space Coordinates

The phase of the current vector Φ is expressed as follows.

$$\varphi = \int \omega_e t + \theta \qquad (5)$$

where : $\theta = \tan^{-1} \frac{I_{qs}^*}{I_{ds}^*}$

Fig. 5 shows the block diagram of the vector controller of an induction machine including the dead time compensation method which is proposed in this paper. The dead time compensator is made of equation (3). This method does not need additional hardware and easy to realize in software.

Moreover, it solve the possible problems of conventional methods that inaccurate compensation may be applied by measuring the current polarity wrong due to the system noises and the inaccuracy of the current sensor.

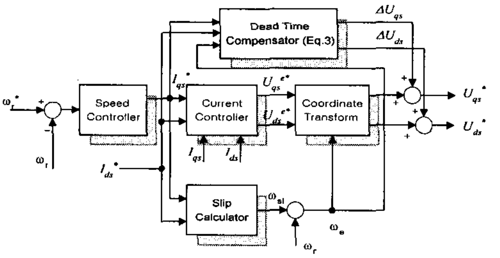

Fig. 5 Block Diagram of Vector Control with Dead Time Compensation

Ⅳ. Experimental Results

Experimental system consists of 2.2kW induction motor, VSI with IPM(Intelligent Power Module) and DSP(TMS320C31) control board. The ratings and the parameters are shown in table 1.

Gate pulse generation logic is made by using EPLD(Altera) and the dead time which is inserted in the PWM patterns is 5μs. The turn-on time and the turn-off time are 0.3μs and 0.5μs. PWM switching frequency is 10kHz and DC link voltage is 310V.

TABLE 1. RATINGS AND PARAMETERS OF INDUCTION MOTOR

Voltage	150 [V]	Rs 0.385 [Ω] Rr 0.342 [Ω] Ls 0.03257 [H] Lr 0.03245 [H] Lm 0.03132 [H] J 0.0088 [Kg·m^2] B 0.007781[Kg·m^2/s]
Frequency	50 [Hz]	
Current	14 [A]	
Rated Torque	14 [Nm]	

Fig. 6 shows the dynamic characteristics of the speed and the currents on the rotationary frame without dead time compensation. Fig. 7 shows the dynamic characteristics of the speed and the currents on the rotationary frame with dead time compensation. In the case of without compensation, an accurate current control is not made because inverter output voltages are deviate from the voltage references due to the dead time and show slow response. With dead time compensation, the response of the currents and the speed are improved. Fig. 8 shows the steady state characteristics of the speed, currents on the rotationary frame and the phase current without dead time compensation. There are ripples in the speed, torque and flux currents and the phase current is not pure sinusoidal. Fig. 9 shows in case of dead time compensation. No ripples are shown in the speed, torque and flux currents and the phase current is pure sinusoidal. Fig. 10 and 11 show the harmonics of the phase currents. In the case of without compensation, there are 5-th and 7-th harmonics in the phase current. However, almost no harmonics are shown in Fig. 11 and the fundamental component is larger than in Fig. 10. Fig. 12 and 13 show the dynamic response when the speed reference is reversed from +50 rpm to -50 rpm. As it is be shown in the experimental results, an accurate instantaneous current control is not made if dead time effect is not compensated. As a result, the speed response is slow because the torque current deviate from the reference value. However, in the case of dead time compensation, the torque current follows the reference accurately and show fast speed response. From the experimental results, the dynamic and steady state characteristics are improved by using the proposed dead time compensation method.

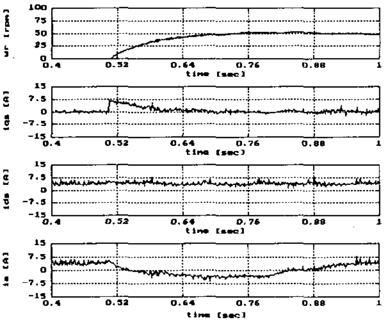

Fig. 6 Dynamic characteristics without dead time compensation

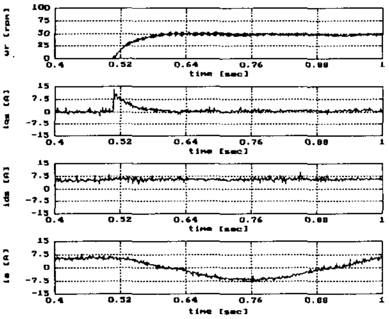

Fig. 7 Dynamic characteristics with dead time compensation

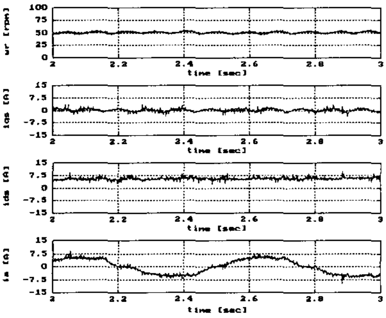

Fig. 8 Steady state characteristics without dead time compensation

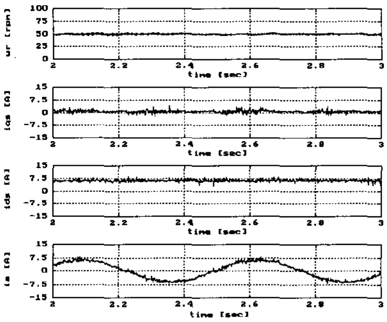

Fig. 9 Steady state characteristics with dead time compensation

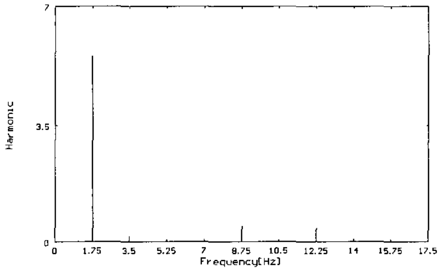

Fig. 10 Harmonics of Phase Current without dead time compensation

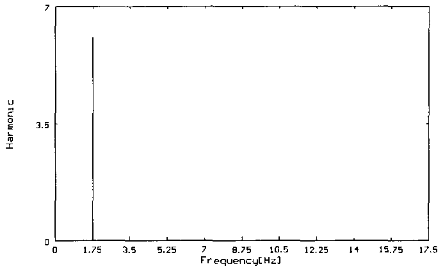

Fig. 11 Harmonics of Phase Current with dead time compensation

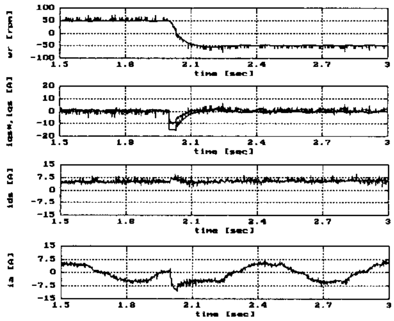

Fig. 12 Without dead time compensation (+50 → -50rpm)

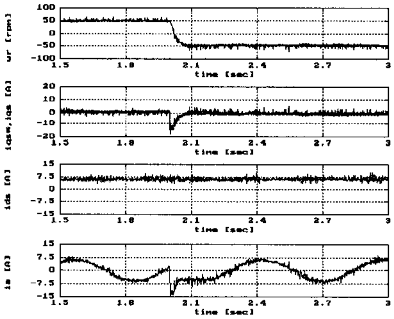

Fig. 13 With dead time compensation (+50 → -50rpm)

V. Conclusion

In this paper, dead time compensation method to compensate the inverter output voltage distortion due to the dead time is proposed. The proposed method calculate the phase of the current vector from the current references on the 2-phase rotationary frame and the inverter output frequency. And it compensate the fundamental, 5-th and 7-th harmonics of the compensation voltage in the 2-phase stationary frame feedforwardly. The method does not need additional hardware or complicated software and achieve sufficient results by adding the simple algorithm to the conventional vector controller.

From the experimental results, it is verified that the proposed method improve the dynamic and steady state characteristics of an induction machine.

Ⅳ. References

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저 자 소 개

Seong-Hwan Kim received the B.S., M.S. and Ph. D degrees in Electrical Engineering from Korea University, Seoul, Korea in 1991, 1995 and 1998, respectively. He is currently an professor in the Department of Control & Instrumentation Engineering, Mokpo National Univesity, Korea. His main research interests are in the application of intelligent control to ac motor drives and power electronics.

Ryoo, Young-Jae was received BS, MS, Ph.D degree in electrical engineering from Chonnam National University at 1991, 1993, 1998 respectively. He is a professor in Mokpo National University currently. He is interested in mobile robot, autonomous vehicle, and intelligent control.

Younghak Chang was born in Chonnam, Korea, in 1960. He received the M.S., and Ph.D. degrees in electrical engineering from Chonnam National University, Korea in 1984, 1991, respectively. He was with Monash University in Australia as a visiting professor in 1997. He is currently a associate professor in the school of electrical and control engineering, Mokpo National University, Korea. His research interests include power electronic applications, fuzzy system, neural networks.