DEAD-TIME COMPENSATION METHOD WITH HARMONIC COMPENSATOR

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Abstract: This paper aims at harmonic analyzing and compensating the dead-time effects in the vector-controlled AC system. On the basis of the analysis is designed harmonic compensator, which should suppress the occurrence of parasitic harmonics components in the phase current. The simulation results demonstrate the validity of the analysis and verify the effectiveness of the proposed compensation strategy.

Keywords: Dead-time compensation, PWM inverter, induction motor

1. INTRODUCTION

PWM (pulse width modulation) inverter is used to create the desired waveforms of current and voltage independent of frequency the source, which the inverter supplies. Therefore, their use is very popular in industrial applications, especially in the control of AC drives. Unfortunately PWM inverter has undesirable characteristics, such as dead-time, turn-on/off time of switching devices, and voltage drops on switching devices and diodes. Dead-time is short switching delay time that is necessary inserted in switching signals to prevent the short circuit of the DC link, which causes the command voltage disagrees with the output voltage of the inverter. The voltage distortion increases with switching frequency and introduces harmonic components that mainly increased the size of the fifth and seventh harmonics in the phase current in the stationary reference frame. It causes known dead-time effects which evokes ripple of phase current, torque pulsations and decline in performance of the vector control. Therefore, it is necessary to compensate the dead-time and other undesirable characteristics of the PWM inverter. It has been suggested several compensation solutions [1-5].

In most cases, compensation strategies are based on an average value of the lost voltages [1-2]. Other methods are based on the accurate detection of polarity of the phase currents. 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. In [2] a dead-time compensation schemes is utilized depending on the threshold of current hysteresis.

In [3], the method compensates the fundamental and sixth harmonics of the inverter-output distortions in the synchronous reference frame. To compensate the harmonic distortion is proposed the harmonic compensator with all-pass-based adaptive bandpass filter. The compensation fifth and seventh-order harmonics in phase current and sixth-order harmonics in the dq-axes currents is also performed [4-5]. The Gray-Markel filter is also often used as an adaptive filter.

In this paper, harmonic analysis of dead-time effects is performed. On the basis of the analysis is designed harmonic compensator for the vector-controlled induction motor, which should suppress the occurrence of parasitic harmonics. The compensation strategy is implemented in the synchronous reference frame. It is software and independent of the polarity of the phase currents. The proposed compensation strategy is verified by simulations in Matlab R2012a.

2. ANALYSIS OF DEAD-TIME EFFECTS

Analysis of the dead-time effects is performed on one phase leg of the three-phase voltage PWM inverter with induction-motor load, where the IGBTs are used as active switching devices. Assume that the phase current is positive when phase current flows from inverter to induction motor as is shown in Fig. 1(b). 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, during on-period T_{on}, upper switch T1 is in on-state and lower switch T4 is in off-state, the current flows to motor through switching device T1. Bud during dead-time period T_d, both switches are in off-state and the phase current can flow through only free-wheeling diodes D4 and the direction of the stator phase current remains unchanged. This phenomenon produces the output voltage error of the inverter [1,5].

2.1. THE INFLUENCE OF THE DEAD-TIME EFFECTS TO THE INVERTER OUTPUT VOLTAGE

The switching patterns and relationships between ideal and actual output voltages to the positive direction of the phase current i_a are shown in Fig. 1(a). The ideal gate signal patterns PWM1 and PWM4 is shown in Fig. 1(a1), where high level of PWM wave represents turn-on and low level represents turn-off. The real gating signals for the two switches in the presence of a dead-time are shown in Fig. 1(a2). u_{an} is the ideal phase output voltage of the inverter. u_{an}^1 is actual output voltage considering the dead time and switching delay as turn-on time t_{on} and turn-off time t_{off} of switches devices. Finally, the difference between ideal and actual inverter output voltages becomes ΔU_{era} [1,2,5].

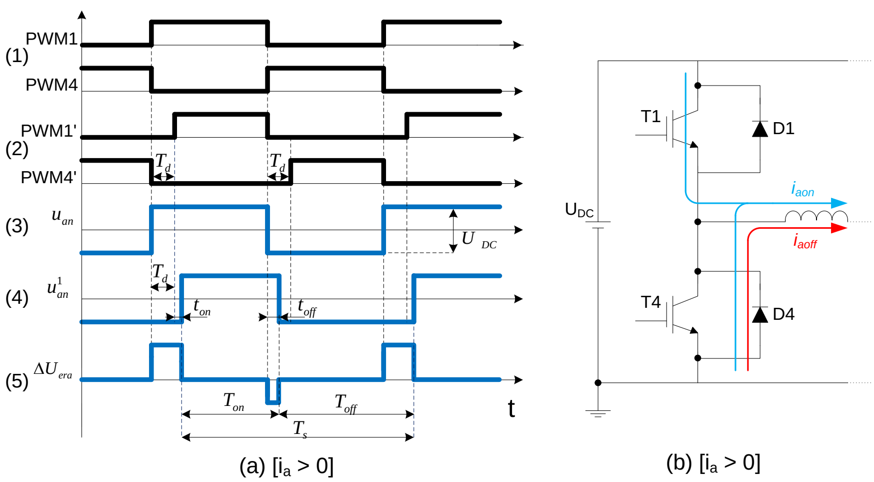

Fig. 1. (a) Switching patens and output voltage. (b) Basic configuration of one phase leg of the PWM inverter [5].

The analysis of the Fig. 1 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 [3]

$$\Delta T_a = (T_d + t_{on} - t_{off}) \cdot sign(i_a) \quad (1)$$

$$\Delta \mathrm{U_{era}} = \frac{\Delta T_a}{T_s} U_{DC} = U'_{dead} \cdot sign(i_a) \quad (2)$$

where

$$sign(i_a) = \begin{cases} 1, & i_a > 0 \\ -1, & i_a < 0 \end{cases} . \quad (3)$$

ΔT_a represent a-phase dead-time compensation time during one switching cycle T_s of the inverter and U_{DC} is the DC-link voltage of the inverter. U'_{dead} gives the magnitude of the voltage error due to the nonlinear switching. If you expand the equation (2) of voltage drops of the switching devices, U_{dead} can be given as

$$U_{dead} = \frac{T_d + t_{on} - t_{off}}{T_s} \cdot (U_{DC} - U_{sat} + U_d) + \frac{U_{sat} + U_d}{2} \tag{4}$$

where U_{sat} is the on-state voltage drop across the switch, and U_d is the forward voltage drop of the diode. U_{dead} represent the resulting error output voltage, which is caused nonlinear characteristics of the inverter [3].

3. PROPOSED DEAD-TIME COMPENSATION

The distorted output voltage of the inverter causes the occurrence of odd harmonics in the phase current in the stationary reference frame. The even harmonics and higher order odd harmonics have little effects, dominant are the fifth, seventh, eleventh and thirteenth harmonic component. Dead-time effect also negatively affects currents in the dq-axes. These harmonic components causes ripple dq-currents and the existence of sixth and twelfth harmonic components in the dq-currents in the synchronous reference frame. On the basis of the harmonic analysis is designed harmonic compensator, which should suppress the occurrence of parasitic harmonics [5].

3.1. HARMONIC ANALYSIS

Voltage errors ΔU_α and ΔU_β are obtained so that voltage error in the three-phase stationary frame is transformed to the voltage error in the two-phase stationary frame as

$$\begin{bmatrix} \Delta U_\alpha \\ \Delta U_\beta \end{bmatrix} = \begin{bmatrix} \frac{2}{3} & -\frac{1}{3} & -\frac{1}{3} \\ 0 & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{3}} \end{bmatrix} \begin{bmatrix} \Delta U_{era} \\ \Delta U_{erb} \\ \Delta U_{erc} \end{bmatrix} \tag{5}$$

where ΔU_{erb} and ΔU_{erc} represent the output voltage error of b-phase and c-phase, respectively, which are obtained by the same way with (4). The voltage errors are analyzed by Fourier analysis and is derived following equation

$$\begin{bmatrix} \Delta U_\alpha \\ \Delta U_\beta \end{bmatrix} = \frac{4U_{dead}}{\pi} \begin{bmatrix} cos\varphi + \frac{1}{5}cos5\varphi - \frac{1}{7}cos7\varphi - \frac{1}{11}cos11\varphi + \frac{1}{13}cos13\varphi + \cdots \\ sin\varphi - \frac{1}{5}sin5\varphi - \frac{1}{7}sin7\varphi + \frac{1}{11}sin11\varphi + \frac{1}{13}sin13\varphi - \cdots \end{bmatrix}. \tag{6}$$

φ represents the angle which is given by following equations [3]

$$\varphi = \int \omega_e dt + \gamma = \theta_e + \gamma \tag{7}$$

$$\gamma = \tan^{-1}(i_q/i_d) \tag{8}$$

where ω_e is the synchronous angular velocity, which is estimated using flux observer. Estimator is based on a combination of voltage and current model of induction motor [3].

$$\Delta u_d = \frac{4U_{dead}}{\pi} \left\{ \begin{matrix} 1 + \frac{1}{5}\cos(5\varphi + \theta_e) - \frac{1}{7}\cos(7\varphi - \theta_e) \\ -\frac{1}{11}\cos(11\varphi + \theta_e) + \frac{1}{13}\cos(13\varphi - \theta_e) + \cdots \end{matrix} \right\} \tag{9}$$

$$\Delta u_q = \frac{4U_{dead}}{\pi} \left\{ \begin{matrix} \sin(\varphi - \theta_e) - \frac{1}{5}\sin(5\varphi + \theta_e) - \frac{1}{7}\sin(7\varphi - \theta_e) \\ + \frac{1}{11}\sin(11\varphi + \theta_e) + \frac{1}{13}\sin(13\varphi - \theta_e) - \cdots \end{matrix} \right\} \tag{10}$$

After applying the transformation to the synchronous reference frame are obtained resulting equations (9) - (10) compensation voltages. In vector control of induction motor, the dead-time effects are compensated in synchronous reference frame, where the compensation voltages (Δu_d, Δu_q) are summed with the voltage vectors u_d and u_q, which is obtained at the output of current controllers.

4. SIMULATIONS RESULTS

The proposed compensation strategy was verified on vector controlled AC system. The simulation experiment was performed in Matlab/Simulink R2012a. The parameters of the experiment were as follows: the switching frequency was set to *16 kHz*, corresponding to the PWM period $T_s = 62.5\ \mu s$, duration dead-time period T_d was $3\ \mu s$.

The results of the experiment are shown in Fig. 2 – 3. The performance of the proposed compensation scheme is compared with no compensation scheme. The results are present in a step-change speed from *0 rad/s* to *20 rad/s*. The spectrums of the a-phase current and dq-currents, which are shown in Fig. 3(a)-(d) are obtained using the FFT (Fast Fourier Transform). To demonstrate the efficiency improvement of the motor driven system by using the proposed dead-time compensation method is used nth harmonic ratio of the current (HRI_n) as an evaluation index, which can be defined as

$$\mathrm{HRI_n} = \frac{I_n}{I_1} 100\%, \tag{11}$$

where I_n denotes the amplitude of the nth harmonic component of the current, and I_1 denotes the amplitude of the fundamental component of the current.

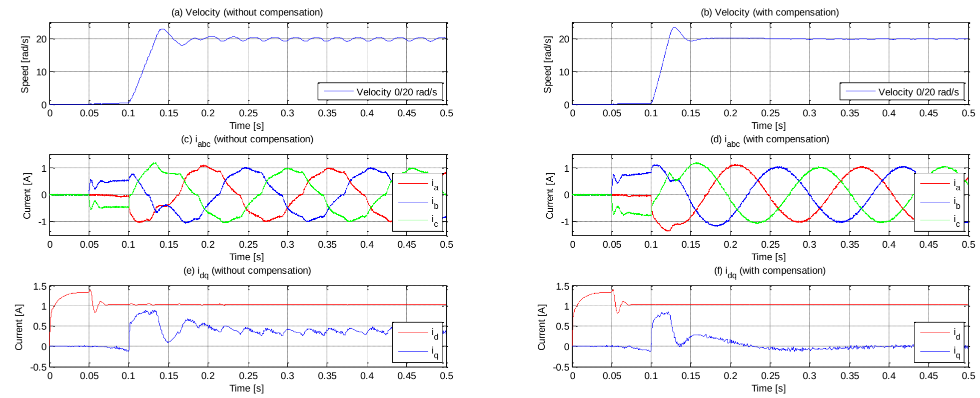

Fig. 2. Results of the experiment. (a)-(c) velocity, abc-phase, currents, dq-currents without compensation, (d)-(f) velocity, abc-phase currents, dq-currents with compensation.

Without the use of some basic compensation strategy leads to significant distortion of the phase currents and ripple of the dq-currents and rotor speed during the steady state, as shown in Fig. 2(a)-(c). Dead-time effect causes the harmonic distortion of the phase currents, which reflects the occurrence of parasitic fifth, seventh, eleventh and thirteenth harmonics in the spectrum of current, as shown in Fig. 3(a).

These undesirable distortions are considerably reduced with the proposed compensation method, as shown in Fig. 2(d)-(f). Ripple steady speed of the rotor is eliminated. There was also a reduction in distortion of the phase currents, and increase the amplitude of 7.1%. Due to their waveforms are more sinusoidal. A comparison of the spectra of the phase currents, Fig. 3(a)-(b) shows that the influence of the compensation was a significant suppression of parasitic odd harmonic components in phase current and sixth and twelfth harmonic components in the dq-currents (Fig. 3(a)-(b)). Harmonic current ratio of fifth harmonic HRI_5 decreased from 3.04% to 0.29%, HRI_7 decreased from

5.41% to 0.35%, HRI_{11} from 1.08% to 0.16% and HRI_{13} from 1.22% to 0.12%, thus increasing the effectiveness of the control algorithm.

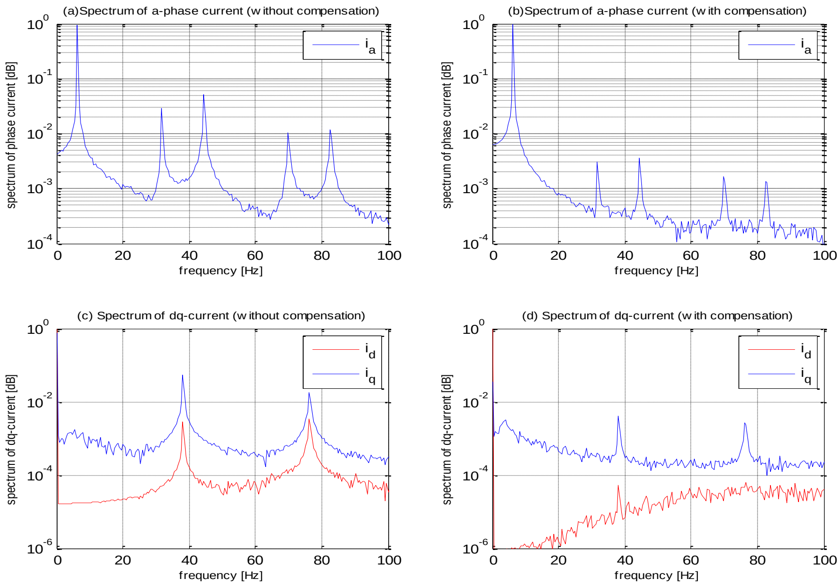

Fig. 3. Current spectrum. (a) a-phase spectrum without compensation, (b) a-phase spectrum with compensation, (c) dq-spectrum without compensation, (d) dq-spectrum with compensation.

5. CONCLUSION

The results demonstrate that the proposed method of solving suppress ripple of dq-currents, torque pulsations and parasitic odd harmonic components in the phase currents. The advantage of the method is a software implementation without additional extra hardware and independent of the polarity of the phase currents. The simulation results demonstrate the effectiveness of the proposed method and this method can be applied to another vector-controlled AC drive systems.

ACKNOWLEDGEMENT

The completion of this paper was made possible by grant No. FEKT-S-14-2429 - "The research of new control methods, measurement procedures and intelligent instruments in automation", and the related financial assistance was provided from the internal science fund of Brno University of Technology.

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