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Research on Dead-zone Compensation of AC Servo System based on voltage feed forward decoupling and FOC

Abstract. *For the problem that the dead-zone time of the inverter of field-oriented control (FOC) alternating current (AC) servo leads to current distortion, torque impulse and degrades the control performance while the traditional compensation methods ignore incomplete decoupling and leads to compensation error, this paper presents an improved dead-time compensation method. First, the d and q-axis current of permanent magnet synchronous motor (PMSM) are completely decoupled, then the relationship of the electrical angle and the direction of the three-phase current is deduced by the principle of FOC. With the accurate direction of the three-phase, the dead-time compensation can be achieved effectively. The simulation results and analysis show that the wave of current is normal after compensation and the output is steady at low speed, which demonstrates the good effect of the proposed compensation method.*

Streszczenie. *Martwa strefa czasowa przekształtnika serwomechanizmu ze sterowaniem FOC powoduje zniekształcenie prądu I pogorszenie możliwości sterowania. W artykule zaprezentowano ulepszona metodę kompensacji strefy martwej. Najpierw prądy w osiach d i q silnika synchronicznego są kompletnie odsprzężone, następnie jest określana zależność między kątem elektrycznym a kierunkami prądów trójfazowych. Wtedy kompensacja strefy martwej jest efektywna. (**Badania martwej strefy kompensacji w serwomechanizmie ac bazującym na sterowaniu FOC i odsprzężeniu typu feed forward**)*

Keywords: Dead-zone compensation; Voltage feed forward decoupling; PMSM; FOC
Słowa kluczowe: martwa strefa, FOC, PMSM, serwomechanizm

Introduction

FOC [1] is the most common technology employed in AC servo control. AC servo control based on FOC [2] can achieve high control performance by using space vector pulse width modulation (SVPWM) technology.

Due to the inconsistency between the open and off time of the power device, the switching tubes of the same arm may be conducted simultaneously, which may lead to short circuit. In order to solve this problem, dead-zone time must be added to pulse width modulation (PWM) impulse of the input power device [3].

However, in the dead-zone time, the two switching tubes of the same arm of the power device are off simultaneously and the current continuously flows though the diode, which makes the tree-phase current distorted and introduces torque impulse. Dead-zone may greatly degrade the control performance, especially when the motor is in low speed and light load.

Time compensation method is a commonly used dead-zone compensation method in the engineering, as it has good compensation effect and is easy to realize. In order to realize time compensation method, accurate directions of the three-phase current are needed. In the early detection methods, the directions of the three-phase current were directly detected by precision device in the feedback loop. However, because the phenomenon of zero-current clamping exists, accuracy cannot be guaranteed by the early detection methods. For there is a relationship between the electrical angle and the three-phase current in AC servo control, an indirect prediction method based on electrical angle was proposed in [5-7]. Nevertheless, all the methods neglect the case in which the d-axis and the q-axis are incompletely decoupled. In practice, when the AC servo runs, the current in d-axis i_d is usually not identically equal zero, that is, incompletely decoupled, which leads to inaccurate corresponding relationship between the electrical angles and the directions of the three-phase current.

For the problem mentioned above, voltage feed forward method is employed in this paper. First, the current in d-axis i_d is controlled to be identically equal zero and completely decoupled. Then, the corresponding relationship between the electrical angles and the three-phase current is established by the principle of FOC and the accurate current direction is obtained. Thus, the time is compensated.

Analysis of dead-zone effect

The PWM inverter of typical PMSM is shown in Fig.1. Define the direction that the current goes into to the motor load from the inverter as the positive direction and the direction that the current goes out as the negative direction. Although the dead-zone time added to the PWM impulse is only in microsecond, it brings significant effect on the control performance [3]-[7].

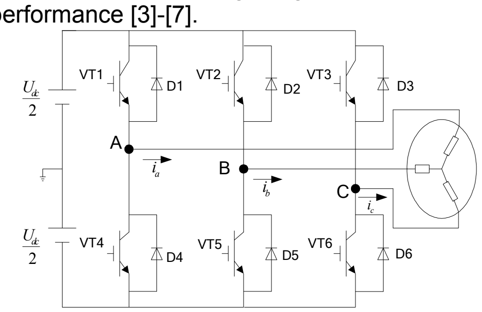

Fig.1 Circuit of PWM inverter

Since the three-phase current of a motor has the same characteristics, we will take a-phase current as an example and analyze it in the following. The ideal PWM impulse and the real PWM impulse in which dead-zone is added are depicted in Fig.2.

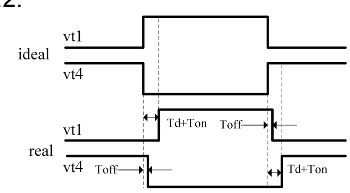

Fig.2 Principle of the generation of dead-zone

In Fig.2, the impulse is on at high level and off at low level. The dead-zone time, off time and on time of the switching tube are T_d, T_{off} and T_{on}, respectively. The purpose of adding dead-zone time is that when one switching tube is off the other tube is on after the dead-zone time. Considering the on and off time of the switching tube, the time error introduced by the delayed on time is expressed in (1):

(1) $$T_{er} = T_d + T_{on} - T_{off}$$

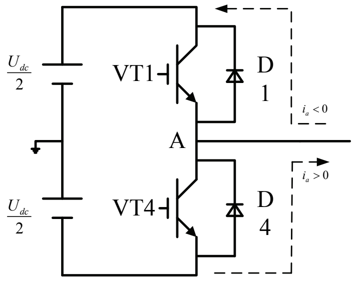

Fig.3 Current direction of a-phase arm of the inverter during the dead-zone time

Fig.3 shows the a-phase arm of the inverter. During the dead-zone time, the switching tubes of the same arm are off simultaneously. Since the motor is perceptual load and the current of the inverter cannot change suddenly, the current continuously flows through diode at this time.

When $i_a>0$, the current of the inverter continuously flows through D4 and the voltage of the a-phase in the dead-zone time is $-U_{dc}/2$. This amounts to the situation that the negative impulse voltage with Udc/2 amplitude and Ter time length is added to the ideal output voltage. It also amounts to the situation that the on time of the lower tube is added Ter. When $i_a<0$, the current of the inverter continuously flows through D1 and the voltage of the a-phase in the dead-zone time is $U_{dc}/2$. This amount to the situation that the positive impulse voltage with $U_{dc}/2$ amplitude and T_{er} time length is added to the ideal output voltage. It also amounts to the situation that the on time of the upper tube is added T_{er}. The error voltage can be expressed by (2):

$$\Delta V=-\frac{T_{er}}{2T_s}*U_{dc}*sign(i_a) \tag{2}$$
$$sign(i_a)=\begin{cases}1 & i_a>0\\ -1 & i_a<0\end{cases}$$

Because the error voltage of the dead-zone exists, the tree-phase current is distorted and torque impulse is introduced, which greatly degrades the control performance especially when the motor is in low speed and light load.

Compensation strategy

Let's take the a-phase as an example to analyze the compensation strategy. As shown in Fig.3, in the dead-zone time, When $i_a>0$, the current of the inverter continuously flows through D4 and the voltage of the a-phase is $-Udc/2$. This amounts to the situation that the lower arm is on and the on time is added T_{er} while the on time of the upper arm is reduced T_{er} due to the complementarities of the on and off time of the upper and lower arm. Hence, the strategy of dead-zone compensation is to increase the on time of the upper arm, guarantee the concordance between the ideal on time of the inverter tubes and the real on time added dead-zone, and ensure the accuracy of the real output voltage of the inverter.

Similarly, we can analyze the situation when $i_a<0$. In this case, the on time of the upper arm is reduced T_{er}. According to the SVPWM control algorithm, the compensation equation is shown in (3):

$$\begin{cases}t'_{aon}=t_{aon}-T_{er}/2 & i_a>0\\ t'_{aon}=t_{aon}+T_{er}/2 & i_a<0\end{cases} \tag{3}$$

where t_{aon} is the ideal on time in the SVPWM algorithm, t'_{aon} is the compensated value. The analysis of the b-phase and c-phase are in a similar way.

From (3) it can be seen that the key point of accurately realizing dead zone compensation is to accurately detect the current direction of the present three-phase. However, because the phenomenon of zero-current clamping exists, accuracy cannot be guaranteed by the method which detects the current direction directly.

Current direction estimation by electrical angle based on voltage feed forward decoupling; FOC synthesizes the field direction produced by the current of the three-phase stator into the direction orthogonal to the rotor permanent magnet (PM) and obtains the biggest output. The direction of the three-phase current was predicted indirectly by electrical angle in [5]-[7]. However, this method is inaccurate when the d-axis and the q-axis are incompletely decoupled. In addition, although the control circuit of the traditional current feedback decoupling method is simple, this method is only an approximately decoupling control method. In practice, when the AC servo runs, the current in d-axis i_d is usually not identically equal zero. Therefore, decoupling must be considered. In this paper, the system is decoupled by voltage feed forward decoupling method.

The state equation of PMSM in d and q coordinates is:

$$\begin{bmatrix}\dot{i}_d\\ \dot{i}_q\\ \dot{\omega}_m\end{bmatrix}=\begin{bmatrix}-R/L & p_n\omega_m & 0\\ -p_n\omega_m & -R/L & -p_n\varphi_f/L\\ 0 & \frac{3}{2}p_n\varphi_f/J & 0\end{bmatrix}\begin{bmatrix}i_d\\ i_q\\ \omega_m\end{bmatrix}+\begin{bmatrix}u_d/L\\ u_q/L\\ -T_L/J\end{bmatrix} \tag{4}$$

From (4), it can be seen that the components of the d and q axis are coupled, I_d and I_q cannot be controlled by U_d and U_q, respectively. Thus, decoupling is needed.

From (4), the dynamic equation of the current loop is obtained as:

$$\dot{I}_{dq}=AI_{dq}+BU_{dq} \tag{5}$$

Introduce the state feedback matrix K and the dynamic equation of the current loop becomes:

$$\dot{I}_{dq}=(A+BK)I_{dq}+BU_{dq} \tag{6}$$

That is:

$$\dot{I}_{dq}=AI_{dq}+B(KI_{dq}+U_{dq}) \tag{7}$$

In order to realize decoupling, it is necessary to transform the transfer function of the system into a diagonal matrix:

$$K=\begin{bmatrix}0 & -P_nL\omega_m\\ P_nL\omega_m & 0\end{bmatrix} \tag{8}$$

The new u_d、u_q are expressed in (9):

$$u_d=u_d^*-p_n\omega_mLi_q \tag{9}$$
$$u_q=u_q^*+p_n\omega_mLi_d$$

Then the block diagram of the voltage feed forward decoupling is shown in Fig.4.

Using voltage feed forward decoupling, when load is suddenly added to the system, the system is nearly not suffered from disturbance and the current in d axis strictly keeps zero. Thus, the decoupling control effect is good. Compared with the traditional current feed forward decoupling, voltage feed forward decoupling is less affected by system parameters and is better in performance.

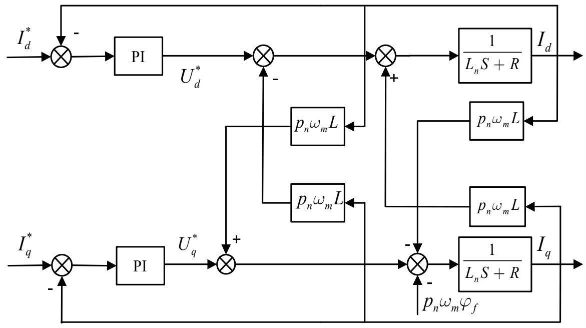

Fig.4 Block diagram of the voltage feed forward decoupling

In FOC, the tree-phase current is transformed into torque element i_q and excitation element i_d by vector transformation. When id is strictly kept to be zero, the PMSM is decoupled. At this time, the field direction produced by i_q is always orthogonal to the field direction of rotor PM and the motor obtains the biggest output effect. Set the direction of the three-phase current to stator as the positive direction, then the flux linkage direction of the stator produced by a, b and c positive current is shown in Fig.5. The goal of FOC is to control the elements in d-axis of rotor direction to be zero and finally the flux linkage direction of a, b and c-phase stator is synthesized to the q-axis elements orthogonal to the rotor to obtain the biggest torque. Based on the control principle of FOC, once the angle θ_e between the rotor and the a-phase, i.e., electrical angle, is measured, the current direction of a, b and c-phase can be obtained by coordinate decomposition.

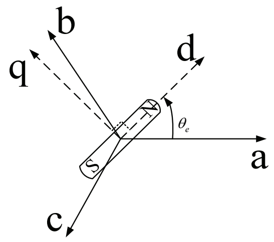

Fig.5 Direction of stator flux linkage

The transformation relationship between d and q axis and a, b and axis is expressed in (10):

$$\begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} \cos\theta_e & -\sin\theta_e & 1 \\ \cos(\theta_e - \frac{2\pi}{3}) & -\sin(\theta_e - \frac{2\pi}{3}) & 1 \\ \cos(\theta_e + \frac{2\pi}{3}) & -\sin(\theta_e + \frac{2\pi}{3}) & 1 \end{bmatrix} \begin{bmatrix} d \\ q \\ 0 \end{bmatrix} \quad (10)$$

Set i_q to be a unit value, then the given values of i_a 、 i_b 、 i_c according to the electrical angle θ_e can be deduced by (10) and the direction of the three-phase current can be got subsequently.

Using MATLAB set the unit of i_q to be 1. The electrical angle changes during $[0, 2\pi]$ in 0.01 per unit. Then the current wave of a, b and c-phase can be got and the zero-crossing point of the three-phase are calculated to be 60°, 120°, 180°, 240°, 300° and 360°.

According to the zero-crossing point and Fig.6, the direction of the three-phase current can be deduced. Now, the relationship of the electrical angle, direction of three-phase current and the compensation time is shown in Table 1.

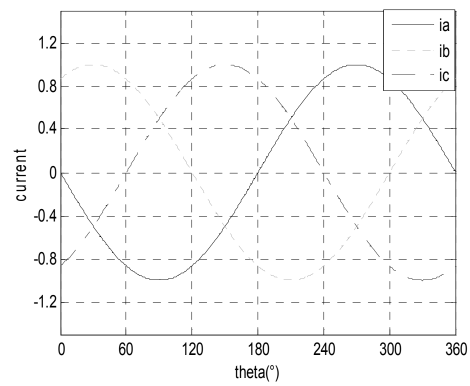

Fig.6 Relationship between the electrical angle and the wave of the three-phase current.

Table 1. Relationship of electrical angle, direction of three-phase current and the compensation time

θ_e	Direction of a, b and c-phase current	Compensation time of a-phase	Compensation time of b-phase	Compensation time of c-phase
(0,30°)	a-,b+,c-	Ter/2	-Ter/2	Ter/2
(30°,60°)	a-,b+,c+	Ter/2	-Ter/2	-Ter/2
(60°,120°)	a-,b-,c+	Ter/2	Ter/2	-Ter/2
(120°,180°)	a+,b-,c+	-Ter/2	Ter/2	-Ter/2
(180°,240°)	a+,b-,c-	-Ter/2	Ter/2	Ter/2
(240°,300°)	a+,b+,c-	-Ter/2	-Ter/2	Ter/2

Simulation results and analysis

The simulation model of AC servo based on voltage feed forward decoupling method is established as Fig. 7. Set the modulation period of SVPWM to be 0k HZ and the dead-zone time to be 5us.

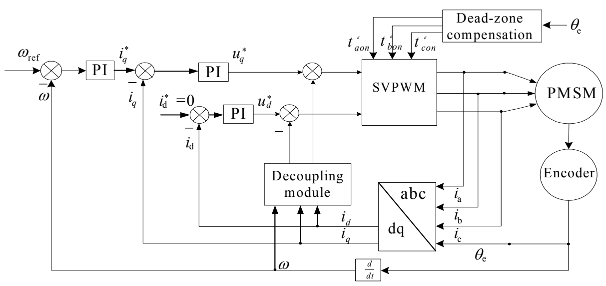

Fig.7 Block diagram of AC servo system based on voltage feed forward decoupling

Simulation results and analysis are following:

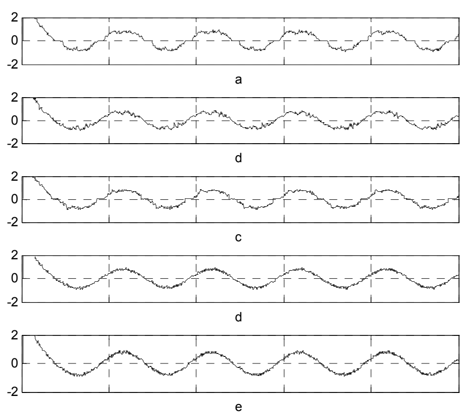

Fig.8 Wave of a-phase current

The wave of a-phase current is shown in Fig.8. In Fig. 8(a) dead-zone is added to PWM impulse but without compensation. From Fig. 8(a),it can been seen that because of the existence of dead-zone time, there exists obvious zero-current clamping and crest reduction phenomenon in a-phase current and the current is significantly distorted. In Fig.8(b) dead-zone is compensated by direct current detection method. In Fig. 8(c) dead-zone is compensated by typical electrical angle prediction method. In Fig. 8(d) dead-zone is compensated by the electrical angle method which is completely decoupled. In Fig. 8(d) there is no dead-zone. Compared Fig. 8(d) to Fig.8(e), it is known that the electrical angle method which is completely decoupled can better recover the ideal given current.

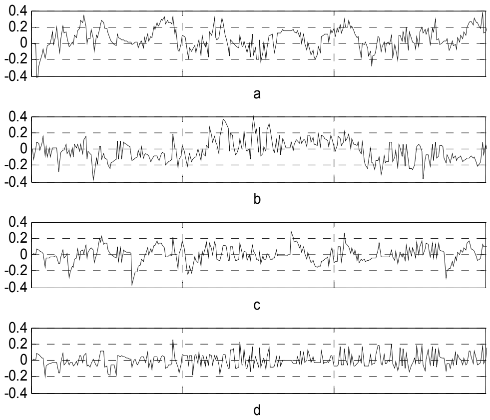

Fig. 9 Difference between the a-phase output current and the ideal output current

Fig.9 shows the difference between the output wave of a-phase current and the ideal wave without dead-zone. Fig. 9(c) shows the difference between the incomplete decoupling a-phase current and the ideal a-phase current. Fig. 9(d) shows the difference between the a-phase current compensated by the proposed method in this paper and the ideal a-phase current. Compared each sub figure in Fig.9, it is known that the completely decoupling method can obviously improve the wave of a-phase current.

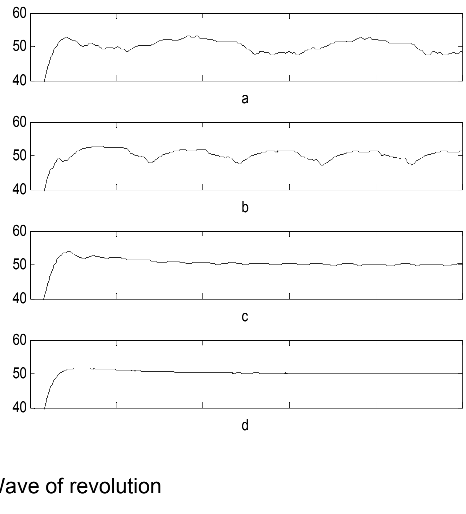

Fig.10 Wave of revolution

Set the speed to be 50 r/min and the load to be 0.2 Nm, then the speed wave is shown in Fig. 10. In Fig. 10(a) there is no dead-zone compensation. In Fig. 10(b) the method which detects the current direction directly is employed. In Fig. 10(c) the method employed is incompletely decoupled. In Fig. 10(d) the proposed method in this paper is used. From the sub figures, it can be seen that dead-zone effect at low speed can be well overcome by the proposed method.

Conclusions

In this paper, voltage feed forward decoupling method is employed. The current in d and q axis of FOC are completely decoupled, the corresponding relationship between the electrical angle and the three-phase current is established, and the time compensation method is used to compensate for the dead-zone.

The simulation model of AC servo based on voltage feed forward decoupling method is established, which show that the good performance of the proposed method is verified by comparing a- phase current and the revolution at low speed. The result shows that using the proposed method can ideally recover the given signal wave.

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