Dead-time Compensation Method Based on Field Oriented Control Strategy

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Abstract. This paper analyzed a dead-time effect and zero-current clamping phenomenon in FOC control strategy, and then proposed corresponding compensation measures. The Field Oriented Control (FOC) strategy of brushless motor is improved according to this Dead-time Compensation measure. On the basis of the existing FOC control theory, a dead-time hysteresis loop is added near the current zero-crossing point to prevent current fluctuation and zero-point clamping from causing errors. The dead-time compensation is carried out in each PWM cycle according to the principle that the actual volt-second area is equal. Finally, the feasibility of the method was verified by experiments, the results showed that the compensation method effectively improves the current waveform and improves the stability of the motor operation, and it proved to be of good use value.

1. Introduction
With the development of modern power electronics technology and power semiconductor technology, the control mode of brushless motor is gradually diversified. Field Oriented Control (FOC) is more conducive to reducing electromagnetic torque ripple than traditional square wave drive. In the PWM inverter circuit, the switching transistor needs to be turned on and off for a certain period of time, and the turn-on time is less than the turn-off time. If one of the same bridge arm is not fully turned off and the other switch is turned on, a through short circuit occurs and the inverter circuit is damaged. Therefore, a dead-time should be added in the control strategy for the turn-on and turn-off time of the switching device. The dead-time effect generated will cause the inverter output current waveform distortion, increase the harmonic component, and affect the control accuracy.

The dead-time compensation method is mainly divided into two aspects: voltage compensation and time compensation. The voltage compensation is to offset the error voltage with a compensation voltage of opposite polarity and the same magnitude. The time compensation method calculates the loss PWM pulse width according to the polarity of the current, and corrects the actual switching time of the switch tube by using the principle of equal second square area. N. Urasaki set the d-axis voltage threshold, corrected the current polarity when it exceeds the threshold, and performed Dead-time Compensation[1]. Artur Cichowski proposed to set current threshold and compensate linearly within the threshold range, but did not consider the effect of switching device on-off delay and continuation process[2]. Wang Gaolin proposed to estimate the zero-crossing time of current in stationary coordinate system and compensate it directly in stationary coordinate system. The algorithm is complex and the estimation accuracy needs to be considered[3].
Based on the existing FOC control theory, this paper focuses on the dead-time effect and zero current clamp problem, adding dead zone hysteresis near the current zero crossing to prevent current fluctuation and zero clamp error. Dead-time compensation is performed in each PWM cycle according to the principle of equal volt-second area equalization. And through the establishment of the experimental platform to verify the feasibility of the method, paving the way for subsequent research.

2. Improved FOC Control Model For Brushless Motor

2.1. Analysis of FOC Control Model

The core idea of FOC control is to simplify the control model of brushless motor. A brushless motor requiring commutation is abstracted into a control model of a DC motor by various algorithms. It only needs to control two simple DC components to control the brushless motor. $U_q$ is abstracted as the voltage at both ends of DC motor, and $U_d$ can adjust the motor torque. This model needs a real-time calculation of motor shaft angle $\theta$. In order to realize this control model, two mathematical transformations, Clarke transformation and park transformation, as well as classical PID control model, are needed. Finally, the on-time sequence of six power devices is controlled by means of SVPWM driving mode, so as to achieve the goal of controlling the motor to run efficiently. Based on the classical FOC control model, a dead-time hysteresis loop is added near the current zero-crossing point to prevent current fluctuation and zero-point clamping from causing error compensation. According to the principle of equal area of actual volts and seconds, dead-time compensation is carried out in each PWM cycle. The control model is shown in the Figure 1.

\[ \text{Figure 1. Improved control model} \]

$I_{q, \text{ref}}$ is the current setting value of q axis (quadrature axis), $I_{d, \text{ref}}$ is the current setting value of d axis (straight axis), $I_a$, $I_b$ and $I_c$ are the sampling currents of A phase, B phase and C phase, respectively. It can be directly sampled by AD. Usually, two phases can be sampled directly, and the third phase can be calculated by formula $I_a + I_b + I_c = 0$. Electrical angle theta can be calculated by reading the value of magnetic encoder in real time. Electrical angle $\theta$ can be calculated by reading the value of magnetic encoder in real time. After obtaining three-phase current and electric angle, the current loop can be executed: three-phase current $I_a$, $I_b$ and $I_c$ are obtained by Clark transformation;
then $I_q$ and $I_d$ are obtained by Park transformation; then the errors are calculated with their set values $I_{q\_ref}$ and $I_{d\_ref}$ respectively; and then the errors of q-axis current are substituted for those of q-axis current PI ring to calculate $U_q$ respectively. The error value of d-axis current is substituted into the PI loop of d-axis current to calculate the $U_d$. Then $U_q$ and $U_d$ are inversely Park transformed to get $U_\alpha$ and $U_\beta$. Then the output value of three-phase voltage is obtained by SVPWM algorithm, and finally input to the three-phase motor. In this way, the control of primary current inner loop is completed.

$W_{\text{ref}}$ is the speed setting value and $W_{\text{speed}}$ is the speed feedback of the motor. It can be calculated by the encoder of the motor. The calculated motor speed and Speed_Ref are used to calculate the error value and are substituted into the speed PI loop. Taking the calculated results as the input of the current loop, since the d-axis current does not produce output force for the rotation of the driving motor, the d-axis current is usually set to zero (but not always to zero); when $I_{d\_ref} = 0$, $I_{q\_ref}$ equals the output of the speed loop; combined with the current loop above, the double closed-loop control of the speed current is realized.

2.2. Dead-time Effect Analysis

The turn-on and turn-off of the power device can be completed after a certain switching time. When it gets the shutdown signal, it has to go through the off time to enter the steady state cutoff; when the device is turned on, it must also pass the turn-on time to fully turn on. The turn-on time is often less than the turn-off time\(^5\)\(^7\). If the power devices of the upper and lower arms of the inverter are operated at the same time, it is easy to turn on at the same time. In order to avoid such a straight-through failure, it is usually necessary to set a certain size of dead-time. The magnitude of the value is determined according to the characteristics of the switching device.

In terms of dead-time effect, Figure 2 is a main circuit structural diagram of a three-phase voltage source type PWM inverter motor load\(^4\). Taking the A-phase bridge arm as an example, the influence of dead-time on the output voltage is analyzed, and the current polarity is defined as positive when the inverter flows to the load. As shown in Figure 3, the current $i_a > 0$ in Figure 3 (a), the current $i_a < 0$ in Figure3 (b).

![Figure 2. Main circuit structure diagram of inverter](image1)

(a) $i_a > 0$

(b) $i_a < 0$

![Figure 3. Dead-time impact analysis diagram](image2)

The following specifically analyzes the impact of dead-time on the output voltage:

1) When $i_a > 0$, as shown in Figure 3 (a): When $V_1$ is turned off, due to the dead-time effect, $V_4$ fails to turn on immediately, and the current continues to flow through the freewheeling diode $D_4$, at the on-time and dead. During the on-time and dead-time, current flows to the motor, causing a deviation in the output voltage. When $V_1$ is turned on, the current continues to flow through the freewheeling diode $D_4$ during the turn-off delay time.

2) When $i_a < 0$, as shown in Figure 3(b): When $V_4$ is turned off, $V_1$ is not turned on immediately due to the dead-time effect, and the current continues to flow through the freewheeling diode $D_4$, during the turn-off delay time.
during the on-time and dead-time. The current flows to the inverter, causing a deviation in the output voltage. When \( \text{V4} \) is turned on, the current continues to flow through the freewheeling diode \( \text{D1} \) during the off time delay.

When \( \text{i_a} < 0 \), as shown in Figure 3(b): When \( \text{V4} \) is turned off, \( \text{V1} \) is not turned on immediately due to the dead-time effect, and the current continues to flow through the freewheeling diode \( \text{D1} \), during the on-time and dead-time. The current flows to the inverter, causing a deviation in the output voltage. When \( \text{V4} \) is turned on, the current continues to flow through the freewheeling diode \( \text{D1} \) during the off time delay.

![Diagram showing the effect of dead-time on the output of the inverter.](image)

**Figure 4. The effect of dead-time on the output of the inverter**

### 2.3. Zero Current Clamping Phenomenon

Taking a pair of bridges in a three-phase bridge rectifier circuit as an example, when the phase a current changes from negative to positive, at the moment of its zero crossing: since the upper and lower tubes of the bridge arm are both closed and the freewheeling diode is blocked, the output voltage at this moment is equal to the induced electromotive voltage \( e \) of the motor coil [8-10]. At the same time, the phase A current cannot be clamped to the zero point in the opposite direction. This phenomenon is called zero current clamping phenomenon, which will increase the distortion of the current at the zero point, as shown in the Figure 5.

![Diagram showing zero current clamping phenomenon.](image)

**Figure 5. Zero current clamping phenomenon**

### 3. Dead-Time And Zero Clamp Error Compensation Algorithms

#### 3.1. Dead-time Compensation Algorithms

In a PWM cycle, the dead-time error voltage is calculated by using the principle that the ideal area is equal to the actual volt-second area:
$$\Delta U = \frac{t_{err}}{T} U_{dc} \text{sign}(i_x)$$  \hspace{1cm} (1)$$

$t_{err}$ is the error time of the dead-time effect:

$$t_{err} = \text{sign}(i)(t_{on} - t_{off} + \frac{U_{dev}}{U_{dc}} T_s)$$  \hspace{1cm} (2)$$

Among them:

$$\text{sign}(i_x) = \begin{cases} 1, & i_x > 0 \\ -1, & i_x < 0 \end{cases}$$  \hspace{1cm} (3)$$

$$U_{dev} = \begin{cases} \frac{t_{on}}{T} U_s + \frac{t_{off}}{T} U_d, & i_x > 0 \\ \frac{t_{off}}{T} U_s + \frac{t_{on}}{T} U_d, & i_x < 0 \end{cases}$$  \hspace{1cm} (4)$$

Dead-time Compensation time: \( t_{conv} = -t_{err} \); Converted to compensatory duty cycle: \( D_{err} = \frac{t_{conv}}{T_s} \)

### 3.2. Zero Clamp Error Compensation

In this study, the current threshold is set in the current zero-crossing area, and a fixed duty cycle is used to compensate outside the threshold, and linear duty compensation is used in the threshold.

$$D_{conv} = \begin{cases} +D_{err}, & i \leq -\Delta i \\ \frac{i}{2\Delta i}[D_{err} - (-D_{err})], & -\Delta i < i \leq \Delta i \\ -D_{err}, & i \geq \Delta i \end{cases}$$  \hspace{1cm} (5)$$

$+D_{err}$ is the interval duty compensation value of \( i \leq -\Delta i \);

$-D_{err}$ is the interval duty compensation value of \( i \geq \Delta i \);

$D_{conv}$ is the duty cycle compensation value in one cycle.

### 4. RESULTS AND ANALYSIS

The simulation construction and results have been analyzed in detail in the previously written literature. On this basis, verification was carried out through the test platform. The three-phase brushless motor test platform control drive block diagram and physical diagram are shown in the figure 6, divided into four functional modules: rectifier module, IPM module, DSP module and interface circuit. The rectifier module rectifies the AC220V power supply to provide DC 310V bus voltage for the IPM module. The IPM module controls the three-phase brushless motor by controlling the six IGBT power switches to generate a UVW three-phase voltage with variable frequency amplitude according to the PWM signal of the DSP. The DSP module uses a TMS320F28335 with a 150MHz clock speed and 32-bit floating point arithmetic. The experimental parameters are as follows:

700W Brushless motor, pole pair \( p = 4 \), phase resistance \( R = 3.15\Omega \), cross-axis inductance \( L_d = L_q = 0.012H \), moment of inertia \( J = 0.000245kg\cdot m^2 \), rated torque \( T = 2.38N\cdot m \), flux \( \varphi_f = 0.12Wb \), PWM switching frequency \( f = 5kHz \)
When the motor runs at low speed, the influence of dead-time effect on the motor operation is particularly obvious. In order to verify the dead zone compensation effect, the test given speed is set to 100 rpm, and the motor AB two-phase current curve and speed curve are respectively collected. The test results are shown in Figure 7 and Figure 8.

The purpose of adding dead-zone hysteresis near the zero-crossing point of current is to reduce the error compensation caused by current polarity misjudgement caused by zero-current clamp and interference signal.
The test results show that the motor current waveform after Dead-time Compensation is significantly improved, the speed fluctuation is reduced, and the stability of the system operation is greatly improved.

5. CONCLUSION
In order to compensate for the influence of dead time on control accuracy, this paper proposes an improved Dead-time compensation method based on FOC control strategy. This method prevents current fluctuation and zero clamping from causing error compensation, and adds dead-zone hysteresis near current zero-crossing. The dead-time compensation is carried out in each PWM cycle according to the principle that the actual volt-second area is equal. Moreover, the feasibility of the method was verified by experiments, the results showed that the compensation method effectively improves the current waveform and improves the stability of the motor operation, and it proved to be of good use value.

References
[1] Naomitsu Urasaki, Tomonobu Senjyu, Katsumi Uezato, et al. (2007) Adaptive dead-time compensation strategy for permanent magnet synchronous motor drive. IEEE Transactions on Energy Conversion, 271-279.
[2] Aetur Cichowski, Janusz Nieznanski. (2005) Self-tuning dead-time compensation method for voltage-source inverters. IEEE Power Electronics Letters, 72-76
[3] Wang Gaolin, Yu Yong, Yang Yongfeng, et al. (2008) Dead-time effect compensation of space vector PWM control inverters for induction motors. Journal of Electrical Engineering of China, 79-82
[4] C.Attai anese, G.Tomasso. (2001) Predictive compensation of dead-time effects in VSI feeding induction motors[J]. IEEE Transactions on Industry Applications, 37(3): 856-863.
[5] Munoz A R, Lipo T A. (1999) on-line dead-time compensation technique for open-loop PWM-VSI drives. IEEE Transactions on Power Electronics, 638-639
[6] Summers T J, Betz R E. (2004) Dead-time issues in predictive current control. IEEE Transactions on Industry Applications, 835-844
[7] Limori K, Shinohara K, Yamamoto K. (2006) Study of dead time of PWM rectifier of voltage-source inverter without operating characteristics of induction motor. IEEE Transactions on Industry Applications, 518-525
[8] Urasaki N, Senjyu T, Kinjo T, er al. (2005) Dead-time compensation strategy for permanent magnet synchronous motor drive taking zero-current clamp and parasitic capacitance effects into account. Electrical Power Applications, 845-853

[9] Choi JongWoo, Sul SeungKi. (1995) A new compensation strategy reducing voltage/current distortion in PWM VSI system operation with low output voltages. IEEE Transactions on Industrial Electronics, 1001-1007

[10] Lazhar Benbrahim. (2004) On the compensation of dead time and zero current crossing for a PWM-inverter-controlled ac servo drive. IEEE Transactions on Industrial Electronics, 1113-1117