Performance Improvement for PMSM Driven by DTC Based on Discrete Duty Ratio Determination Method

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Abstract: In order to improve the performance of the servo control system, which is composed of the permanent magnet synchronous motor (PMSM) driven by novel direct torque control based on the fixed sector division criterion (FS-DTC) utilizing the composite active vectors, a discrete duty ratio determination method (FS-DDTC) is proposed in this paper. The determination of the accurate duty ratio is the key to obtain the desired error compensational results for PMSM, which is related to the performance of the servo system directly. As the applied master vector and slave vector during each control period are the adjacent vectors, therefore, the direction of the synthetic vector is between the directions of the two applied active vectors. Additionally, the analytical relationship between the sector angle of the synthetic vector and the error rate, which can realize the determination of the discrete duty ratio value without complicated calculations is deduced first. Furthermore, the duty ratio values of the two applied active vectors in FS-DTC are obtained through the selections of the duty ratio scale in the novel discrete duty ratio determination method directly, which can simplify the calculation process of the accurate duty ratio values effectively. The effectiveness of the proposed discrete duty ratio determination method is verified through the experimental results on a 100-W PMSM drive system.

Keywords: direct torque control (DTC); permanent magnet synchronous motor (PMSM); synthetic vector; discrete duty ratio

1. Introduction

The performances of the servo motor and the motor control strategy determine the quality of the servo system. Permanent magnet synchronous motor (PMSM) has lots of merits, including high reliability and good control performance. Additionally, it has been applied in industrial robot application widely [1–7]. Field-oriented control (FOC) and direct torque control (DTC) are the two widely applied high-performance control strategies for the PMSM [8–13]. Torque is the variable in DTC that is controlled directly, so the quickest dynamic response can be obtained in the PMSM driven by DTC [14–16]. Therefore, the servo system that is composed by the permanent magnet synchronous motor (PMSM) driven by direct torque control owns many merits than other servo systems.

The torque error and the flux error are compensated by a single active vector comprehensively in single vector error compensational strategy (SV-DTC). Therefore, the PMSM driven by SV-DTC suffers from some drawbacks, such as large torque and flux linkage ripples as the errors of flux linkage and torque in conventional DTC (CDTC) are compensated by only one active vector [17–20]. On the other hand, in order to improve the steady-state performance of the PMSM, the novel direct torque control

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Additionally, the fixed sector division criterion is proposed for NDTC (FS-DTC), which can classify the complexity of the control system [3]. Despite the better steady-state and dynamic-state performance of the PMSM system can be obtained, the computation burden is inevitably increased with the using of the adaptive sector division criterion, therefore, the fixed sector division criterion is proposed for the control system (FS-DTC) in [3].

In order to simplify the complexity of the control system, the determination method of the duty ratio value is studied in this paper. The analytical relationship between the sector angle of the synthetic vector and the error rate is deduced first. It should be noted that the applied master vector and slave vector during each control period in FS-DTC are the adjacent vectors, therefore, the direction of the equivalentsynthetic vector is between from the directions of the two active vectors. The precondition of the accurate duty ratio value determination is the selection of the suitable discrete duty ratio value. The complexity of the control system will be increased while the discrete duty ratio value is much accurate, on the other hand, the required error compensation results cannot be obtained while the discrete duty ratio value is inaccurate. The proposed discrete duty ratio determination method can solve the existing problems in FS-DTC effectively.

The rest of this paper comprises the following sections. The calculations of the accurate active factors are described in Section 2. The scheme diagram of the discrete duty ratio determination method is illustrated in Section 3. The calculation for the synthetic vector, the discrete sector angle, the discrete error angle, and the duty ratio scale are also described in this Section, which are the indispensable integral parts of the discrete duty ratio determination method. The description of experimental setup and discussions on experimental results are given in Section 4. The conclusion is analyzed in Section 5.

2. Calculating the Accurate Active Factors

In the proposed novel direct torque control (NDTC) scheme in [2], two active vectors are applied in one control period, which can improve the steady-state performance of the control system effectively. Additionally, the fixed sector division criterion is proposed for NDTC (FS-DTC), which can classify the complexity of the control system [3], as shown in Figure 1. It is also shown in Figure 1 that the proposed discrete duty ratio determination method in this paper is used to replace the traditional duty ratio determination method in FS-DTC.

![Figure 1. Schematic diagram of the discrete duty ratio determination method for novel direct torque control based on the fixed sector division criterion (FS-DDTC) for a permanent magnet synchronous motor (PMSM).](image-url)
As the main errors can be compensated by the applied active vector in SV-DTC [2], the applied two active vectors in FS-DTC are classified as master vector and slave vector [3]. Consequently, the active angle of the master vector and the slave active vector in FS-DTC are defined as $\theta_{sm}$ and $\theta_{ss}$, respectively, as shown in Figure 2.

Figure 2. Relationships of the variables in the control system driven by fixed sector division criterion (FS-DTC).

Therefore, the active factors of torque error and flux error supplied by the master vector in Figure 1 can be calculated as:

\[
\mu_{Tm} = \sin \theta_{sm} \quad (1)
\]

\[
\mu_{Fm} = \cos \theta_{sm} \quad (2)
\]

Consequently, the active factors of torque error and flux error supplied by the slave vector can be calculated as:

\[
\mu_{Ts} = \sin \theta_{ss} \quad (3)
\]

\[
\mu_{Fs} = \cos \theta_{ss} \quad (4)
\]

The relationships among the active vectors and the variables of the PMSM can be described as

\[
\begin{bmatrix}
    r_T \\
    r_F 
\end{bmatrix}
= \begin{bmatrix}
    \mu_{Tm} & \mu_{Ts} \\
    \mu_{Fm} & \mu_{Fs} 
\end{bmatrix}
\begin{bmatrix}
    d_m \\
    d_s 
\end{bmatrix} \quad (5)
\]

where $d_m$ and $d_s$ are the duty ratio values of the master vector and the slave vector, respectively. $r_T$ and $r_F$ are the torque error rate and the flux error rate, respectively, which can be obtained by

\[
\begin{bmatrix}
    r_T \\
    r_F 
\end{bmatrix}
= \begin{bmatrix}
    \frac{1}{C_T} \\
    \frac{1}{C_F} 
\end{bmatrix}
\begin{bmatrix}
    e_T \\
    e_F 
\end{bmatrix} \quad (6)
\]

where $C_T$ and $C_F$ are the max compensations of torque error and flux error supplied by the active vector, respectively.

From the aforementioned analyses, it can be observed that Equation (5) is the binary system of linear Equations, which will inevitably increase the computation burden of the control system.

3. Analysis of the Analytical Relationships of the Synthetic Vector

3.1. Analysis of the Synthetic Vector

The stator flux linkage $\varphi_s$ is located in sector 1, and the impact angle is $\delta_s$, as shown in Figure 3.
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Figure 3. Relationships of variables in the control system.

The master vector $V_2$ and the slave vector $V_1$ will be selected to compensate the errors of the PMSM according to the selection rules of the master vector and the slave vector in FS-DTC [3]. It is worth mentioning that the selected master vector and slave vector in each control period are the adjacent vectors. Therefore, the direction of the equivalent synthetic vector is between the directions of the master vector and the slave vector.

Figure 3 shows that the principal of the accurate error compensation is that the direction of the synthetic vector is the same as that of the errors of the PMSM. Therefore, the relationship between the active angle of the synthetic vector and the error angle can be described as:

$$\theta_{sms} = \theta_{\tau}$$

where $\theta_{sms}$ is the active angle of the synthetic vector, which can be calculated as:

$$\theta_{sms} = \sigma_v + \delta_s$$

The error angle $\theta_{\tau}$ can be calculated as:

$$\theta_{\tau} = \tan^{-1} \tau$$

where $\tau$ is the state value of the error rate, which can be expressed as:

$$\tau = \frac{r_T}{r_F}$$

As the variation range of the sector angle $\sigma_v$ is $[0^\circ, 60^\circ)$, the sector angle that can be used in the whole rotation space of the stator flux linkage can be described as

$$\sigma_v = \theta_{\tau} - \delta_s - (N_N - N_s) \cdot 60^\circ$$

where $N_N$ is the sector number of the phase-lag active vector, $N_s$ is the sector number where the stator flux linkage located in.

3.2. Calculation of the Discrete Sector Angle

The suitable discrete value of the duty ratio is approximately 0.1 [9–13]. In this paper, the discrete value of the duty ratio is defined as 1/12, therefore, the discrete values including 12 synthetic vectors ($V_{msi}$) and 12 sector angle ($\sigma_v$) can be obtained. In this case, the value of $i$ varies within the range from 0 to 11, and the value of $i$ is an integer. The discrete voltage vector results are shown in Figure 4.
within the range from 0 to 11, and the value of $i$ is an integer. The discrete voltage vector results are shown in Figure 4.

The discrete values of the master vector and the slave vector are $i_m$ and $i_s$, respectively. Furthermore, the duty ratio values of the master vector and the slave vector are $d_m$ and $d_s$, respectively, and the sum of duty ratio values of the two active vectors is 1.

The discrete values of the sector angle under different duty ratio values of the master vector and the slave vector can be determined according to Figure 4, as shown in Table 1.

| Variables | Value |
|-----------|-------|
| $d_m(i_m)$ | 0 1 2 3 4 5 |
| $d_s(i_s)$ | 12 11 10 9 8 7 |
| $\sigma_v(\degree)$ | 0 4 9 14 19 25 |

| Variables | Value |
|-----------|-------|
| $d_m(i_m)$ | 6 7 8 9 10 11 |
| $d_s(i_s)$ | 6 5 4 3 2 1 |
| $\sigma_v(\degree)$ | 30 35 41 46 51 56 |

3.3. Calculation of the Discrete Error Angle

The discrete value of the sector angle of the synthetic vector is 5° approximately according to the discrete sector angle results in Table 1, therefore, the discrete value of error angle can also be set as 5° according to Equation (6). The error rate is the absolute value of torque error rate and flux error rate therefore, the variation range of the error angle is (0°, 90°). Table 2 shows the calculation results of the discrete error angle.

| Variables | Value |
|-----------|-------|
| $\theta_t(\degree)$ | 0 5 10 15 20 25 |
| $\tau_D$ | 0 0.09 0.18 0.27 0.36 0.47 |
| $\theta_t(\degree)$ | 30 35 40 45 50 55 |
| $\tau_D$ | 0.58 0.7 0.84 1 1.2 1.43 |
| $\theta_t(\degree)$ | 60 65 70 75 80 85 |
| $\tau_D$ | 1.73 2.14 2.75 3.73 5.7 11.4 |
4. Discrete Duty Ratio Determination Method

4.1. Scheme Diagram of the Discrete Duty Ratio Determination Method

In order to simplify the calculation process of the accurate duty ratio values of the master vector and the slave vector, the analytical relationship between the sector angle of the synthetic vector and the error rate is deduced in this section. Additionally, the discrete duty ratio determination method based on the discrete error angle and the duty ratio rate of the master vector and the slave vector are proposed, as shown in Figure 5. The parameters in Figure 5 are defined by:

- \(d_m\): Duty ratio value of the master vector;
- \(d_s\): Duty ratio value of the slave vector;
- \(k_{ms}\): Scale between the master vector duty ratio and the slave vector duty ratio;
- \(\theta_{sv}\): Active angle of the phase-lag active vector;
- \(r_T\): Torque error rate;
- \(\sigma_v\): Sector angle between the synthetic vector and the slave vector;
- \(\theta_\tau\): Error angle;
- \(\delta_s\): Impact angle between the sector vector and the stator flux linkage \(\phi_s\);
- \(N_N\): Sector number of the phase-lag active vector;
- \(N_s\): Sector number where the stator flux linkage located in;
- \(V_m\): Master vector;
- \(V_s\): Slave vector;
- \(\tau_D\): Discrete value of the error rate state value;
- \(\tau\): State value of the error rate.

![Figure 5. Process of duty ratio discretization.](image)

4.2. Calculation of the Duty Ratio Scale

The scale between the master vector duty ratio and the slave vector duty ratio is defined as

\[
k_{ms} = \frac{d_m}{d_s}
\]  \hspace{1cm} (12)

The calculation process of the discrete duty ratio is described as follows:

1. The relationship between the duty ratio scale and the sector angle of the synthetic vector is determined, as shown in Table 3.
(2) The duty ratio scale between the applied master vector and slave vector is selected from Table 3 according to the sector angle.

(3) The final duty ratio can be calculated based on the duty ratio scale.

Table 3. Duty ratio scale switching table.

| Variables | Value |
|-----------|-------|
| $\sigma_v^\circ$ | 0 | 5 | 10 | 15 | 20 | 25 |
| $k_{ms}$ | 0 | 0.09 | 0.2 | 0.33 | 0.5 | 0.71 |
| $\sigma_v^\circ$ | 30 | 35 | 40 | 45 | 50 | 55 |
| $k_{ms}$ | 1 | 1.4 | 2 | 3 | 5 | 11 |

As torque is the most important variable in the control system, the determination of the duty ratio values of the master vector and the slave vector should meet the prerequisites that the torque error should be compensated to the desired condition. The relationships of the variables in Equation (5) can be rewritten as

$$r_T = \mu_{Tm} \cdot d_m + \mu_{Ts} \cdot d_s = d_m \left( \mu_{Tm} + \frac{\mu_{Ts}}{k_{ms}} \right)$$

(13)

Therefore, the final duty ratio of the master vector can be calculated as

$$d_m = \frac{r_T}{\left( \frac{1}{2} + \frac{1}{k_{ms}} \right) \cdot \sin \theta_{sv} + \frac{\sqrt{3}}{2} \cos \theta_{sv}}$$

(14)

where $\theta_{sv}$ is the active angle between the phase-lag active vector and the stator flux linkage.

Additionally, the final duty ratio of the slave vector can be calculated according to the duty ratio scale and the master vector duty ratio. It is worth mentioning that, the duty ratio of the master vector should be defined as 1, while the sum of the master vector duty ratio and the slave vector duty ratio is greater than 1, which can avoid the offset of the error compensations supplied by the two active vectors effectively.

5. Experimental Analysis

5.1. Experimental System Setup

Experimental studies are carried out on a 100-W PMSM drive system to validate effectiveness and feasibility of the discrete duty ratio determination method for FS-DTC (FS-DDTC). The experimental hardware setup is illustrated in Figure 6.

![Figure 6. Experimental setup of control system.](image-url)
The parameters of the PMSM are given as follows: \( R_s = 0.76 \, \Omega \); \( L_s = 0.00182 \, H \); the number of pole pairs \( p = 4 \). The DC voltage is 36 V. The experiments are implemented in a TMS320F28335 DSP control system with a sampling period of 100 \( \mu s \).

5.2. Steady-State Performance

The steady-state performances of FS-DTC and FS-DDTC are compared under the same operating condition. The PMSM is operated at 500 rpm and the reference values of torque and flux linkage are 0.8 N·m and 0.3 Wb, respectively. The torque and flux linkage waveforms of the PMSM driven by different control strategies are shown in Figure 7, and the stator currents of the PMSM driven by two control strategies are shown in Figure 8.

From these experimental results it can be found that, the torque ripples and the flux ripples of FS-DTC are 0.32 N·m and 0.045 Wb, respectively. The torque ripples and the flux linkage ripples of FS-DDTC are 0.35 N·m and 0.05 Wb, respectively. The total harmonic distortions of the input current \( I_{THD} \) of the PMSM driven by FS-DTC and FS-DDTC are 6.11% and 6.26%, respectively. Therefore,
although the proposed discrete duty ratio determination method simplifies the complexity of FS-DTC, the required steady-state performance in FS-DTC will not be affected.

5.3. Dynamic Performance

To validate the fast dynamic response of the proposed FS-DDTC, the responses of torque and flux in the PMSM driven by the two control are tested when the torque and the flux linkage are set as 0.4 N·m and 0.3 Wb, respectively. In these tests, a step change to 100 rpm is applied on the speed reference while the PMSM is in static state, as shown in Figure 9.

Figure 9. The torque and flux trajectory with the speed changes from 0 rpm to 100 rpm when using: (a) FS-DTC; (b) FS-DDTC.

To validate the fast dynamic response of the proposed FS-DDTC, the speed responses of the PMSM driven by the two control strategies are also tested when the torque is set as 0.5 N·m. In these tests, a step change from 200 to 400 rpm is applied on the speed reference, as shown in Figure 10.

Figure 10. The speed trajectory from 200 rpm to 400 rpm when using: (a) FS-DTC; (b) FS-DDTC.
It can be seen that the torque and the flux linkage can adjust to the settled state within the similar time, the settling time of the torque using the two different control strategies are 0.032 and 0.03 s. And the ripple of the speed is 27 rpm when using FS-DTC, while the speed ripple of the PMSM is about 28 rpm with the using of FS-DDTC. Moreover, the settling time of the rotor speed using two different control strategies are 0.015 and 0.014 s.

Therefore, the main advantage of FS-DTC, i.e., the fast dynamic response, can be maintained in the proposed FS-DDTC. The experimental results show that dynamic response owns higher priority than ripples in dynamic-state condition, hence, the accurate duty ratio determination method in FS-DTC can be abandoned.

6. Conclusions

The discrete duty ratio determination method based on the error rate is proposed in this paper. The corresponding relations between the duty ratio value of the synthetic vector and the error rate is deduced. It should be noted that the duty ratio value of the synthetic vector is the scale between the master vector duty ratio and the slave vector duty ratio. Additionally, the final duty ratio value of the master vector and the slave vector can be obtained based on the duty ratio scale value. The proposed discrete duty ratio determination method can simplify the duty ratio determination method in FS-DTC, which is the binary system of linear equations.

Experimental results clearly indicate that the FS-DDTC exhibits excellent control of torque and flux linkage with the similar steady-state ripples when compared to FS-DTC and has the same transient response performance.

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