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Performance Improvement of Servo Control System Driven by Novel PMSM-DTC Based On Fixed Sector Division Criterion

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Abstract: In order to improve the performance of the servo control system driven by a permanent magnet synchronous motor (PMSM) under novel direct torque control (NDTC), which, utilizing composite active vectors, fixed sector division criterion, is proposed in this paper. The precondition of the accurate compensations of torque and flux errors is that the sector where the stator flux linkage is located can be determined accurately. Consequently, the adaptive sector division criterion is adopted in NDTC. However, the computation burden is inevitably increased with the using of the adaptive part. On the other hand, the main errors can be compensated through SV-DTC (DTC-utilizing single active vector), while another active vector applied in NDTC can only supply the auxiliary error compensation. The relationships of the two active vectors' characteristics in NDTC are analyzed in this paper based on the active factor. Furthermore, the fixed sector division criterion is proposed for NDTC (FS-NDTC), which can classify the complexity of the control system. Additionally, the switching table for the selections of the two active vectors is designed. The effectiveness of the proposed FS-NDTC is verified through the experimental results on a 100-W PMSM drive system.

Keywords: servo control system; direct torque control (DTC); permanent magnet synchronous motor (PMSM); fixed sector division criterion; active factors

1. Introduction

A permanent magnet synchronous motor (PMSM) driven by direct torque control (DTC) has a lot of merits, including high reliability and good control performance. Therefore, it has been applied in industrial application widely [1–7]. Field-oriented control (FOC) and direct torque control are two widely applied high-performance control strategies for the PMSM [8–13]. Unlike the decoupled-analyzing method in FOC, torque and flux linkage are controlled directly in DTC, therefore, the quickest dynamic response can be obtained in the PMSM driven by DTC [14–16]. However, as only six active vectors can be selected to compensate the errors of flux linkage and torque in conventional DTC, the PMSM suffers from some drawbacks, such as large torque and flux linkage ripples [17–20].

The errors of torque and flux in the conventional PMSM-DTC system are compensated by a single active vector comprehensively, thus, the torque error and the flux error cannot be compensated accurately [1]. In this case, the error compensational strategy used in a conventional PMSM-DTC system can be called single vector error compensational strategy (SV-DTC). Furthermore, the torque vector and the flux vector are introduced into the PMSM-DTC system, and the novel direct torque control (NDTC) scheme is proposed [2], which can improve the steady-state performance of the PMSM

effectively. Despite that a better performance of the PMSM driven by NDTC can be obtained, the computation burden is inevitably increased, due to the complexity of the control system.

The aim of this paper is to simplify the complexity of the servo control system by using a fixed sector division criterion. The relationships between the two active vectors' characteristics in NDTC are analyzed in this paper based on the active factor firstly. It should be noted that the main errors can be compensated by SV-DTC, and another active vector applied in NDTC can only supply the auxiliary error compensation. Therefore, the two active vectors applied in NDTC can be defined as master vector and slave vector, respectively.

Because the master vector can be selected based on SV-DTC, the precision of the slave vector selection is the key to determining the error compensational results. Therefore, the three-dimensional (3-D) diagram and the two-dimensional (2-D) contour map of the active factor are introduced to determine the suitable slave vector with the variation of the error rate and the sector location of the stator flux linkage. Furthermore, the fixed sector division criterion, including master sector and slave sector, is proposed for NDTC (FS-NDTC), which can classify the complexity of the control system effectively. Additionally, the switching table for the selections of the two active vectors is designed in this paper.

The rest of this paper comprises the following sections: The characteristics of the active factors are analyzed in Section 2. The suitable slave vectors with the variation of the error rate and the sector location of the stator flux linkage are described in Section 3. The characteristics of master vector and slave vector are also illustrated in Section 3. The fixed sector division criterion and the design of the switching table for master and slave vectors are given in Section 4. The description of the experimental setup and discussions on experimental results are given in Section 5. The conclusion is analyzed in Section 6.

2. Analysis of the Active Factors

2.1. Design of the Novel Switching Table Considering the Error Rate State

In the proposed novel direct torque control (NDTC) scheme in [2], torque active vector and flux active vector are applied in one control period, as shown in Figure 1. It is also shown in Figure 1 that the proposed fixed sector division criterion is used to replace the adaptive sector division criterion.

As the main errors can be compensated by the applied active vector in SV-DTC [1], the two applied active vectors in NDTC can be classified as master vector (the applied active vector in SV-DTC) and slave vector (another applied active vector in NDTC).

The error rate state of the control system can be defined as

$$\tau_i = \begin{cases} \tau_0 < \tau < \frac{1}{\tau_0}, & i = A \\ \tau < \tau_0, & i = B \\ \tau > \frac{1}{\tau_0}, & i = C \end{cases} \quad (1)$$

where τ_0 is the reference value of error rate state.

The value of the error rate state is calculated as

$$\tau = \frac{r_T}{r_F} \quad (2)$$

where r_T and r_F are torque error rate and flux error rate, respectively, which can be obtained by

$$\begin{bmatrix} r_T \\ r_F \end{bmatrix} = \begin{bmatrix} \frac{1}{C_T} & \\ & \frac{1}{C_F} \end{bmatrix} \begin{bmatrix} e_T \\ e_F \end{bmatrix} \quad (3)$$

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

Figure 1. Schematic diagram of the novel direct torque control (NDTC) strategy for a permanent magnet synchronous motor (PMSM). Reproduced/Adapted with permission from [2], T, Q, Yuan, IEEE Access, T, Q, Yuan, 2019.

Therefore, the switching table of the active vectors in SV-DTC can be modified based on the value of the error rate state, as shown in Table 1.

Table 1. Vector switching table.

Sector	Error Rate State	Error Property	V_n	Error Property	V_n
S_{2+}	$\tau_{A/C}$	a	V_{N+1}	b	V_{N+3}
		c	V_N	d	V_{N+4}
	τ_B	a	V_{N+2}	b	V_{N+2}
		c	V_{N+5}	d	V_{N+5}
S_{1+}	$\tau_{A/B/C}$		V_{N+1}	b	V_{N+3}
			V_N	d	V_{N+4}
S_0	$\tau_{A/B}$	a	V_{N+1}	b	V_{N+2}
		c	V_{N+5}	d	V_{N+4}
	τ_C	a	V_N	b	V_{N+3}
		c	V_N	d	V_{N+3}
S_{1-}	$\tau_{A/B/C}$		V_N	b	V_{N+2}
			V_{N+5}	d	V_{N+3}
S_{2-}	$\tau_{A/C}$	a	V_N	b	V_{N+2}
		c	V_{N+5}	d	V_{N+3}
	τ_B	a	V_{N+1}	b	V_{N+1}
		c	V_{N+4}	d	V_{N+4}

The error property in Table 1 is defined according to the values of torque error property and flux error property, as shown in Table 2.

Table 2. Error property compound modes.

Error Property	Torque Error Property	Flux Error Property
a	1	1
b	1	−1
c	−1	1
d	−1	−1

2.2. Analysis of the Characteristics for the Active Vectors

The active angle and the impact angle of the one applied active vector in NDTC are θ_s and δ_s , respectively, as shown in Figure 2.

Figure 2. Relationships of the variables in the control system.

The active factors of torque error and flux error supplied by the applied active vector in Figure 1 can be calculated as

$$\mu_T = \sin \theta_s \quad (4)$$

$$\mu_F = \cos \theta_s \quad (5)$$

In NDTC, the adaptive sector division criterion is adopted. Therefore, the active factors of the torque error and the flux error within different error rate states and different small sectors are shown in Table 3.

Table 3. Relationships among active factors and motor variables.

Error Rate State	τ_A		τ_B		τ_C	
	μ_T	μ_F	μ_T	μ_F	μ_T	μ_F
S_{2+}	0.5	0.9	1	0	0.5	0.9
S_{1+}	(0.9, 0.5)	(0.5, 0.9)	(0.9, 0.5)	(0.5, 0.9)	(0.9, 0.5)	(0.5, 0.9)
S_0	0.9	0.5	0.9	0.5	0	1
S_{1-}	(0.5, 0)	(0.9, 1)	(0.5, 0)	(0.9, 1)	(0.5, 0)	(0.9, 1)
S_{2-}	0.5	0.9	1	0	0.5	0.9

With the using of different active vectors, the active factors, active angle, and the impact angle are binary periodic functions. In order to obtain the variation character of the active factors, the vector angle θ_v that is between the applied active vector and the sector vector is introduced to replace the active angle. Therefore, the three-dimensional (3-D) diagram of μ_T and μ_F can be obtained, as shown

in Figures 3a and 4a. Furthermore, the two-dimensional contour map of the torque active factor and flux active factor are obtained by describing the third dimension, as shown in Figures 3b and 4b.

Figure 3. Torque active factor variation character. (a) three-dimensional image; (b) two-dimensional image.

Figure 4. Flux active factor variation character. (a) three-dimensional image; (b) two-dimensional image.

3. Analysis of the Suitable Slave Vectors with the Variation of the Variables

3.1. Slave Vectors Selection in Main Sector

In SV-DTC, the suitable active vectors are V_2 or V_1 , which can be applied to compensate the errors, while the stator flux linkage is located in S_{1+} or S_{1-} small sector. The vector angles of V_2 and V_1 are 60° and 0° , respectively, as shown in Figure 5.

Figure 5. Two-dimensional contour map of torque error active factors.

(1) error rate state is τ_B

(a) S_{1+} sector

Torque error is larger than flux error in the error rate state of τ_B . From Figure 5, it can be observed that the max value of torque active factor supplied by the master vector V_2 is 0.9 with the impact changing from -30° and 0° .

In order to compensate the large torque error effectively, the active vector V_3 , which supplied the best torque active factor, should be selected as the slave vector, and its vector angle is 120° .

(b) S_{1-} sector

It is also shown in Figure 5 that the max value of torque active factor of the master vector V_1 is only 0.5, with the impact changing from 0° and 30° . Therefore, the active vector V_2 , which supplied the best torque active factor, should be selected as the slave vector to compensate the large torque error effectively, and its vector angle is 60° .

(2) error rate state is τ_C

(a) S_{1+} sector

The flux error is larger than the torque error in the error rate state of τ_C . From Figure 6, it can be observed that the wanted flux active factor cannot be supplied by the master vector V_2 with the impact changing from -30° and 0° .

In order to meet the required large flux error compensations, the active vector V_1 , which supplied the best flux active factor, should be selected as the slave vector to compensate the large flux error effectively, and its vector angle is 0° .

(b) S_{1-} sector

It is also shown in Figure 6 that master vector V_1 can supply larger flux error compensations. To avoid the offset of the error compensations, the active vector V_6 , which supplied the positive flux active factor, should be selected as the slave vector, and its vector angle is 300° .

(3) error rate state is τ_A

(a) S_{1+} sector

The stator flux linkage is located in S_{1+} , and the torque active factor and the flux active factor are equal, so the relationships of the variables can be described as

$$\mu_T = \sin \theta_{s2} = \mu_F = \cos \theta_{s2} \quad (6)$$

The impact angle can be obtained as

$$\delta_{s2} = \theta_{s2} - 60^\circ = -15^\circ \quad (7)$$

Figure 7 shows that the value of the torque active factor supplied by the master vector V_2 is the balance value of 0.7, while the impact angle is -15° . In addition, the torque error compensation will become smaller with the impact angle changing from -15° to -30° . Therefore, the active vector V_3 should be selected as the slave vector, which can supply the decreased torque error compensation supplied by the master vector V_2 .

Figure 6. Two-dimensional contour map of flux error active factors.

Figure 7. Two-dimensional contour map of torque error active factors.

According to the two-dimensional contour map of the torque active factor in Figure 7, it can be observed that the value of the torque active factor supplied by the master vector V_2 is the balance value of 0.7, while the impact angle is -15° . In addition, the torque error compensation will become smaller

with the impact angle changing from -15° to -30° . Therefore, the active vector V_3 should be selected as the slave vector, which can supply the decreased torque error compensation supplied by the master vector V_2 .

According to the two-dimensional contour map of the flux active factor in Figure 8, it can be observed that the value of flux active factor supplied by the master vector V_2 is the balance value of 0.7, while the impact angle is -15° . Consequently, the flux error compensation will become smaller with the impact angle changing from -15° to 0° . In this case, the active vector V_1 should be selected as the slave vector, which can supply the decreased flux error compensation supplied by the master vector V_2 .

Figure 8. Two-dimensional contour map of flux error active factors.

(b) S_{1-} sector

When the stator flux linkage is located in S_{1-} sector, the variation range of the impact angle is from 0° to 30° . The comparison result of the torque active factor and the flux active factor supplied by the master vector V_1 can be expressed as

$$\mu_T < \mu_F \quad (8)$$

According to the two-dimensional contour maps of the torque active factor and flux active factor in Figures 7 and 8, it can be observed that the value of the torque active factor supplied by V_1 is constantly lower than the balance value 0.7, while the value of the flux active factor is constantly greater than the balance value 0.7. Thus, V_2 is the most suitable active vector to be the slave vector, considering the torque error and the flux error compensational results synthetically.

3.2. Slave Vectors Selection in Other Sectors

(1) S_0 sector

(a) The active vector V_2 will be selected as the master vector while the error rate state is τ_A . According to the two-dimensional contour map of the flux active factor in Figure 9, it can be observed that the value of the flux active factor supplied by the master vector V_2 is constantly lower than the balance value of 0.7. Therefore, in order to compensate the motor errors, the active vector V_1 should be selected as the slave vector, which can supply the flux error compensation supplied by the master vector V_2 .

Figure 9. Two-dimensional contour map of flux error active factors.

(b) The active vector V_2 will be selected as the master vector while the error rate state is τ_B . According to the two-dimensional contour map of the torque active factor in Figure 10, it can be observed that the master vector V_2 can supply the large torque error compensation. The torque error is much greater than the flux error in the error rate state of τ_B , therefore, the active vector V_3 that can supply the greatest torque error compensation should be selected as the slave vector.

Figure 10. Two-dimensional contour map of torque error active factors.

(c) The active vector V_1 will be selected as the master vector while the error rate state is τ_C . According to the two-dimensional contour map of the flux active factor in Figure 9, it can be observed that the master vector V_1 can supply the greatest flux error compensation. The flux error is much greater than the torque error in the error rate state of τ_C , therefore, the active vector V_2 that can supply the positive flux error compensation should be selected as the slave vector to avoid the offset of the flux error compensations supplied by different active vectors.

(2) S_{2+} sector

(a) The active vector V_2 will be selected as the master vector while the error rate state is τ_A . According to the two-dimensional contour map of the torque active factor in Figure 10, it can be observed that the value of the torque active factor supplied by the master vector V_2 is constantly lower than the balance value 0.7. Therefore, the active vector V_1 should be selected as the slave vector, which can supply the insatiable torque error compensation supplied by the master vector V_2 , which can compensate the motor errors effectively.

(b) The active vector V_3 will be selected as the master vector while the error rate state is τ_B . According to the two-dimensional contour map of the torque active factor in Figure 10, it can be observed that the master vector V_3 can supply the greatest torque error compensation. The torque error is much greater than the flux error in the error rate state of τ_B , therefore, the active vector V_2 that can supply the positive torque error compensation should be selected as the slave vector to avoid the offset of the torque error compensations supplied by different active vectors.

(c) The active vector V_2 will be selected as the master vector while the error rate state is τ_C . According to the two-dimensional contour map of the flux active factor in Figure 9, it can be observed that the master vector V_2 can supply a large flux error compensation. The flux error is much greater than the torque error in the error rate state of τ_C , hence, the active vector V_1 that can supply much greater flux error compensation should be selected as the slave vector.

(3) S_{2-} sector

(a) The active vector V_1 is selected as the master vector while the error rate state is τ_A . According to the two-dimensional contour map of the torque active factor in Figure 10, it can be observed that the value of torque active factor supplied by V_1 is constantly lower than the balance value 0.7. Therefore, the active vector V_2 should be selected as the slave vector, which can supply much greater torque error compensation.

(b) The active vector V_2 will be selected as the master vector while the error rate state is τ_B . According to the two-dimensional contour map of torque active factor in Figure 10, it can be observed that the master vector V_2 can supply the greatest torque error compensation. The torque error is much greater than the flux error in the error rate state of τ_B , therefore, the active vector V_1 that can supply the positive torque error compensation should be selected as the slave vector to avoid the offset of the torque error compensations supplied by different active vectors.

(c) The active vector V_1 will be selected as the master vector while the error rate state is τ_C . According to the two-dimensional contour map of the flux active factor in Figure 9, it can be observed that the master vector V_1 can supply the large flux error compensation. The flux error is much greater than the torque error in the error rate state of τ_C , hence, the active vector V_6 that can also supply the large flux error compensation should be selected as the slave vector.

3.3. Analysis of the Characteristics of the Master and Slave Vectors

From the aforementioned analyses, it can be observed that the suitable master vector and slave vector are different with the variation of the error rate state and the sector where the stator flux linkage is located. Table 4 shows the conclusions of the suitable master vector and slave vector for different variations of PMSM.

Table 4. Relationships among active factors and motor variables.

Error Rate State	τ_A		τ_B		τ_C	
	V_m	V_s	V_m	V_s	V_m	V_s
S_{2+}	V_2	V_3	V_3	V_2	V_2	V_1
S_{1++}	V_2	V_3	V_2	V_3	V_2	V_1
S_{1+-}	V_2	V_1	V_2	V_3	V_2	V_1
S_0	V_2	V_1	V_2	V_3	V_1	V_2
S_{1-}	V_1	V_2	V_1	V_2	V_1	V_6
S_{2-}	V_1	V_2	V_2	V_1	V_1	V_6

There exists no difference with the applied sequence variation of master vector and slave vector. Therefore, the characteristics of the suitable active vector in each small sector can be described as:

- (1) The selected master and slave vectors are the same, while the stator flux linkage is located in S_{2+} or S_{1++} sector;
- (2) The selected master and slave vectors are the same, while the stator flux linkage is located in S_0 or S_{1+-} sector;
- (3) The selected master and slave vectors are the same, while the stator flux linkage is located in S_{2-} or S_{1-} sector.

In short, the small sectors S_{2+} , S_0 and S_{2-} are not necessary. Furthermore, the adaptive sector division criterion is not suitable for NDTC.

4. Design of Master and Slave Vectors' Switching Table

4.1. Devision of Master and Slave Sectors

The negative sector and the positive sector in each sector in conventional DTC are defined as master sector and slave sector, respectively. The slave sector can be divided into the positive slave sector and the negative slave sector through the median line l_{m+} , according to the Equation (7).

The location of the master sector and the slave sector will exchange equally, therefore, the master sector should also be divided into the positive master sector and the negative master sector through the median line l_{m-} . The analysis results of the sector characteristic for sector 1 is shown in Figure 11.

Figure 11. Relationships of the variables in the control system.

According to the analysis results in Figure 10, the division criterion for the master and slave sector, which is suitable for NDTC, can be obtained in terms of the active vector that is closest to the error, as shown in Figure 12.

Figure 12. Fixed sector division results.

4.2. Master and Slave Vectors Switching Table

The slave vector is applied to compensate the errors that the master vector cannot compensate, therefore, the master vector switching table is the same in SV-DTC, and the slave vector switching table that considers the error rate state is shown in Table 5.

Table 5. Slave vector switching table.

τ_i	Sector	Error Property	V_s	Error Property	V_s
τ_A	S_{s+}	a	V_{N+2}	b	V_{N+2}
		c	V_{N+5}	d	V_{N+5}
	S_{s-}	a	V_N	b	V_{N+2}
		c	V_{N+5}	d	V_{N+5}
	S_{m+}	a	V_{N+1}	b	V_{N+1}
		c	V_N	d	V_{N+4}
τ_B	S_{m-}	a	V_{N+1}	b	V_{N+1}
		c	V_{N+4}	d	V_{N+4}
	S_s	a	V_{N+2}	b	V_{N+2}
		c	V_{N+5}	d	V_{N+5}
	S_m	a	V_{N+1}	b	V_{N+1}
		c	V_{N+4}	d	V_{N+4}
τ_C	S_s	a	V_N	b	V_{N+4}
		c	V_{N+1}	d	V_{N+3}
	S_m	a	V_{N+5}	b	V_{N+3}
		c	V_N	d	V_{N+2}

5. Experimental Analysis

5.1. Experimental System Setup

Experimental studies are carried out on a 100-W PMSM drive system to validate the effectiveness of the fixed sector division criterion for NDTC (FS-NDTC). The experimental hardware setup is

illustrated in Figure 13. The parameters of the PMSM are given as follows: $R_s = 0.76 \Omega$; $L_s = 0.00182 \text{ H}$; the number of pole pairs $p = 4$. The DC voltage is 36 V. The rated speed and torque are 750 rpm and 1.2 Nm, respectively. This study compares the steady-state and the dynamic response performance of the PMSM, driven by FS-NDTC and NDTC. The experiments are implemented in a TMS320F28335 DSP control system with a sampling period of 100 μs .

Figure 13. Experimental setup of control system.

5.2. Steady-State Performance

The steady-state performances of FS-NDTC and NDTC are compared under the same operating conditions. The PMSM is operated at 500 rpm and the reference values of torque and flux linkage are 0.8 Nm and 0.3 Wb, respectively. The torque and flux linkage waveforms of the PMSM driven by NDTC and FS-NDTC are shown in Figure 14a,b, respectively.

Figure 14. Experimental torque and flux linkage of the PMSM when using: (a) NDTC; (b) FS-NDTC.

From these experimental results, it can be found that the torque ripples and the flux linkage ripples of NDTC are 0.32 Nm and 0.035 Wb, respectively. The torque ripples and the flux linkage

ripples of FS-NDTC are 0.32 Nm and 0.045 Wb, respectively. Therefore, although the proposed fixed sector division criterion classify the complexity of NDTC, the ideal steady-state performance in NDTC will not be affected with the using of a fixed sector division criterion.

5.3. Dynamic Performance

To validate the fast dynamic response of the proposed FS-NDTC, the speed and torque responses of the PMSM driven by the two control strategies are tested. In the speed tests, a step change from 200 to 400 rpm is applied on the speed reference when the torque is set as 0.5 Nm. The speed waveforms of the PMSM driven by NDTC and FS-NDTC are as shown in Figure 15a,b, respectively.

Figure 15. The speed trajectory is from 200 rpm to 400 rpm when using: (a) NDTC; (b) FS-NDTC.

In the torque and flux linkage tests, a step change from 0 to 100 rpm is applied on the speed reference when the torque and the flux linkage are set as 0.5 Nm and 0.3 Wb, respectively. The torque and flux linkage waveforms of the PMSM driven by NDTC and FS-NDTC are as shown in Figure 16a,b, respectively.

Figure 16. The torque and flux linkage trajectory when using: (a) NDTC; (b) FS-NDTC.

From the above tests, it can be seen that the ripples of the rotor speed with the using of NDTC and FS-NDTC are 29 and 27 rpm, respectively. Moreover, the settling time of the rotor speed using the two different control strategies are 0.014 and 0.015 s. In the torque and flux linkage tests, it can be seen that the flux linkage can adjust to the settling value within an instant, and the settling times of the torque using the two different control strategies are 0.034 and 0.032 s.

Therefore, the main advantage of NDTC, i.e., the fast dynamic response, is maintained in FS-NDTC. The experimental results show that dynamic response owns higher priority than ripples in dynamic-state condition, hence, the adaptive sector division criterion can be abandoned.

6. Conclusions

The fixed sector division criterion is introduced to replace the adaptive sector division criterion used in NDTC in this paper. The proposed fixed sector division criterion can simplify the determination process of the sector where the stator flux linkage is located. To ensure the reasonability of the fixed sector division criterion, the active factors of the applied active vectors are used to obtain the characteristic relationships of the master vector and the slave vector in NDTC. Finally, the switching table for the slave vector is designed, which can ensure the required error compensational results, using the proposed fixed sector division criterion.

Experimental results clearly indicate that the FS-NDTC exhibits similar control performance of torque and flux linkage when compared to NDTC, and the transient response performance can also be retained in FS-NDTC. In short, the steady and dynamic performances of the PMSM driven by NDTC and FS-NDTC are similar. The proposed fixed sector division criterion can simplify the complexity of the servo control system without decreasing the operation performance of the PMSM.

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