

New Eighteen-sector Direct Torque Control Based on Duty Ratio Modulation

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Abstract. In the traditional direct torque control (DTC) of permanent magnet synchronous motor (PMSM) system, the ripple of stator flux linkage amplitude and electromagnetic torque at the steady state is large. The unbalanced effect of active voltage vectors on stator flux linkage and torque control is analysed. Based on the idea of sector subdivision, combined with the six new active voltage vectors added by the three-level inverter, a new eighteen-sector DTC method is proposed to improve the control effect of voltage vectors. For the overcompensation problem caused by the voltage vector acting in a whole sampling period in DTC, the duty ratio modulation (DRM) method is used to reduce the torque ripple. Compared with the traditional DTC, the effectiveness of the proposed new control strategy for reducing the ripple of stator flux linkage and electromagnetic torque is verified.

1. Introduction

The normal operation of a high-performance PMSM system requires the support of a complete control strategy. Vector Control (VC) and Direct Torque Control (DTC) are the most widely used and most well-controlled strategies [1]. Compared with VC, DTC does not require a current regulator or a rotating coordinate conversion module [2], it directly uses the eight spatial voltage vectors generated by the two-level DC voltage source inverter at 180° conduction angle to compensate the flux linkage and torque error [3]. So it has better dynamic response performance. However, since the voltage vector selection of DTC is limited and only one voltage vector is applied in one sampling period, this will cause overcompensation.[4]

This paper analyzes the imbalanced effect of the voltage vector in the flux linkage and torque control, and proposes a method of combining the multiple voltage vectors generated by the three-level inverter with the eighteen-sector DTC. Combined with duty ratio modulation (DRM), the purpose of improving flux linkage and torque ripple is achieved.

2. Analysis of the effect of voltage vectors in DTC

In traditional DTC, the entire motor space is divided into six sectors from the axial direction. Depending on the sector in which the stator flux linkage is located, a suitable voltage vector is selected to compensate for the flux linkage and torque error. However, since there is only one voltage vector for increasing the flux linkage and torque within one sector, the control effect varies with the change of the stator flux linkage angle.



2.1. Flux linkage control effect analysis

In the case of ignoring the stator resistance, the relationship between the stator flux linkage φ_s and the stator voltage u_s is

$$\varphi_s = \int u_s dt \quad (1)$$

By differentiating Equation (1), we can get Equation (2).

$$\varphi_s(n) = u_s(n-1)T_s + \varphi_s(n-1) \quad (2)$$

In the Equation (2), T_s is time of the sampling period. The flux change is completely determined by the effective voltage vector. Figure 1 is a vector form representation of Equation (2).

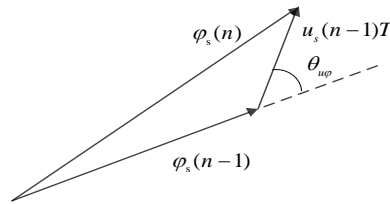


Figure 1. Effective Voltage Vector Control of Stator Flux

As shown in Figure 1, the stator flux amplitude increment $|\Delta\varphi_s|$ is related to the voltage vector magnitude $|u_s|$ and the angle $\theta_{u\varphi}$ between the voltage vector and the flux linkage. The relationship between them is:

$$|\Delta\varphi_s| = |u_s|T_s \cos \theta_{u\varphi} \quad (3)$$

Since the six effective voltage vectors have the same amplitude and the same sampling period, then:

$$\Delta\varphi = \frac{|\Delta\varphi_s|}{|u_s|T_s} = \cos \theta_{u\varphi} \quad (4)$$

$\Delta\varphi$ is the relative change of the magnitude of the flux linkage, only related to the angle $\theta_{u\varphi}$. According to the Equation (4), when the stator flux linkages are at different positions in the same sector, the angles are also different, and therefore the effect of the voltage vector is also different. As shown in Figure 2 and Figure 3, the difference in control effect is especially noticeable at the edge of the sector. At the meantime, the difference between the increase and the decrease is also significant.

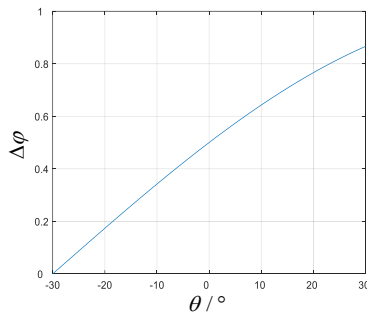


Figure 2. Relative increase in flux linkage

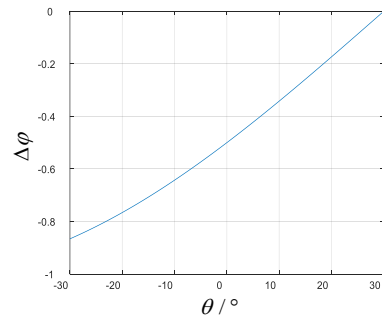


Figure 3. Relative decrease in flux linkage.

2.2. Torque control effect analysis

For the hidden pole PMSM, the electromagnetic torque equation is:

$$T_e = \frac{3n_p |\varphi_s|}{2L_d L_q} \varphi_f L_q \sin \delta \quad (5)$$

In the Equation(5), T_e is the electromagnetic torque, n_p is the magnetic pole pair, L_d and L_q are the straight axis inductance and the cross-axis inductance, φ_f is the rotor flux linkage and δ is the angle between the stator and rotor flux linkage. In steady-state operation, the stator flux linkage amplitude remains essentially constant, and torque control can be achieved by simply controlling the angle of the stator and rotor flux linkages.

Equation (6) is the differential of Equation (5).

$$dT_e = \frac{3n_p |\varphi_s|}{2L_d L_q} \varphi_f L_q \cos \delta d\delta \quad (6)$$

Since $|\Delta\varphi_s|$ is basically unchanged during steady-state operation, so we can get:

$$\Delta T_e = \frac{3n_p |\varphi_s|}{2L_d L_q} \varphi_f L_q \cos \delta \Delta\delta \quad (7)$$

Since the change of the angle between the stator and rotor flux linkage is extremely small, then:

$$\Delta\delta \approx \sin \Delta\delta = \frac{|u_s| T_s \sin \theta_{u\varphi}}{|\varphi_s|} \quad (8)$$

Substituting Equation (8) into Equation (7):

$$\Delta T_e = K |u_s| T_s \sin \theta_{u\varphi}, \quad K = \frac{3n_p \varphi_f L_q \cos \delta}{2L_d L_q} \quad (9)$$

Since the voltage vectors have the same amplitude and sampling period, K remains the same, then:

$$\Delta T = \frac{\Delta T_e}{K |u_s| T_s} = \sin \theta_{u\varphi} \quad (10)$$

ΔT is the relative change in torque, only relevant to $\theta_{u\varphi}$. According to the Equation (11), when the stator flux linkages are at different positions in the same sector, the angles are also different, and therefore the effect of the voltage vector is also different. As shown in Figure 4 and Figure 5, the difference in control effect is especially noticeable at the edge of the sector. At the meantime, the difference between the increase and the decrease at the edge of the sector is also significant.

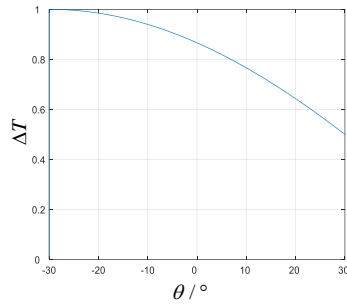


Figure 4. Relative increase in torque

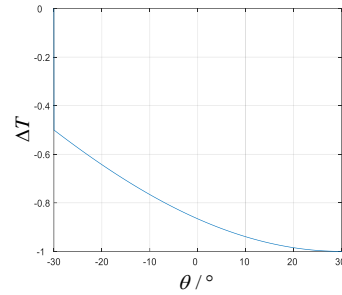


Figure 5. Relative decrease in torque.

3. New eighteen-sector DTC based on DRM

It can be seen from the above analysis that the imbalance of the effect of the voltage vector is mainly concentrated on the edge of the sector. Therefore, each sector of the conventional DTC is divided into three small sectors by 20 degrees, for a total of 18 sectors. As shown in Figure 6, the new sector is named by S_{kn} , k is the traditional DTC sector number, n is the small sector number. At the same time, because the traditional two-level inverter has fewer voltage vectors, another six voltage vectors can be added by the three-level inverter. The newly added 6 effective voltage vectors and the original 8 voltage vectors form a combination of 12 effective voltage vectors and 2 zero vectors.

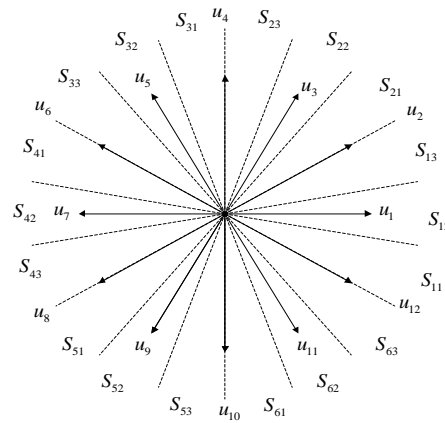


Figure 6. New eighteen-sector DTC voltage vector distribution

3.1. Determination of the new voltage vector selection table

Since more sectors are divided and new voltage vectors are added, the voltage vector selection table needs to be re-determined. In the determination of the new voltage vector selection table, a voltage vector near the stator flux linkage position of 45 degrees is selected to achieve the best control effect. The new voltage vector selection table is shown in Table 1. $\tau = 1$ indicates that the torque needs to be increased, $\tau = 0$ indicates that the torque needs to be reduced; $\varphi = 1$ indicates that the flux linkage needs to be increased, $\varphi = 0$ indicates that the flux linkage needs to be reduced. k represents the number of original sectors, and if the number of selected vectors after calculation is greater than 12, it is decremented by 12.

Table 1. new voltage vector selection table

τ	φ	S_{k1}	S_{k2}	S_{k3}
1	1	u_{2k}	u_{2k+1}	u_{2k+1}
	0	u_{2k+3}	u_{2k+3}	u_{2k+4}
0	1	u_{2k+9}	u_{2k+9}	u_{2k+10}
	0	u_{2k+6}	u_{2k+7}	u_{2k+7}

3.2. Duty ratio modulation

By adding a three-level inverter, the optional voltage vector is increased. However, the selected voltage vector acts on an entire sampling period, and the problem of overcompensation still exists, and the resulting flux linkage and torque ripple are still obvious. Adding the duty ratio modulation can effectively reduce the torque ripple. The basic idea is to calculate the effective voltage vector in the sampling period after selecting the appropriate voltage vector based on the error between the torque and the reference torque. The proportion is the duty ratio, and the zero vector is applied for the rest of the time. Ideally, after the duty ratio is introduced, the amount of change in the electromagnetic torque can exactly offset the torque error of the previous moment in one sampling period. The block diagram of the new eighteen-sector DTC based on DRM is shown in Figure 7.

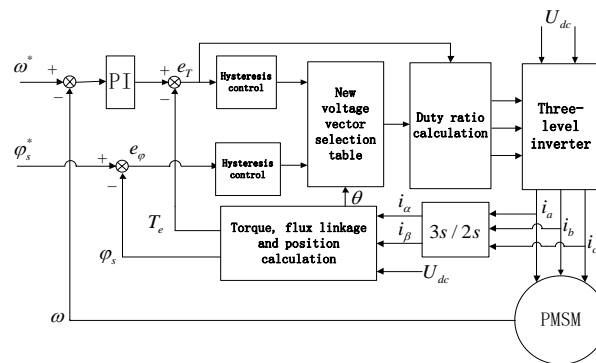


Figure 7. Block diagram of the new eighteen-sector DTC based on DRM

4. Simulation analysis

In order to verify the feasibility and effectiveness of the proposed new DTC, a simulation model was built with MATLAB, and PMSM was used as the control object.

Figure 8 and Figure 9 are the waveform diagrams of the steady-state magnetic flux trace of the conventional DTC and the new eighteen-sector DTC. As shown in the figures, the traditional DTC has a unbalanced control effect on the flux linkage, so that the flux trace has a significant distortion at the intersection of the sectors. After adding the voltage vectors and subdividing the sectors, the flux distortion is basically eliminated, and the flux linkage fluctuation is also reduced.

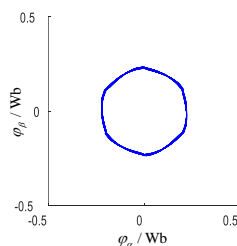


Figure 8. Flux trace of traditional DTC

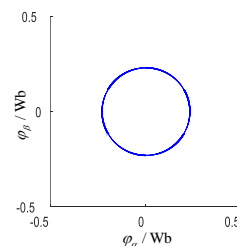


Figure 9. Flux trace of new eighteen-sector DTC

Figures 10 to 12 show the flux linkage and torque waveforms of the conventional DTC, the new eighteen-sector DTC, and the new eighteen-sector DTC based on DRM.

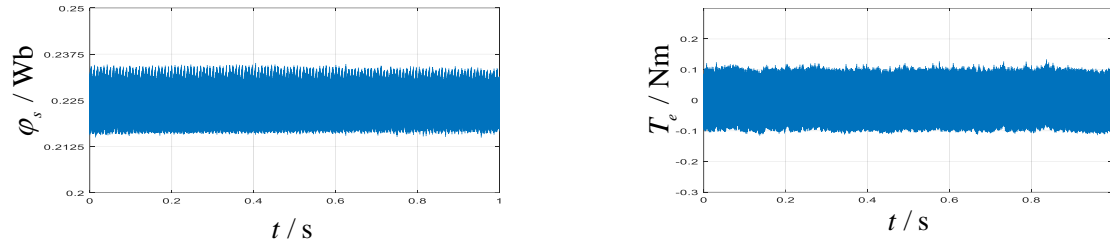


Figure 10. Flux linkage and torque waveforms of the conventional DTC

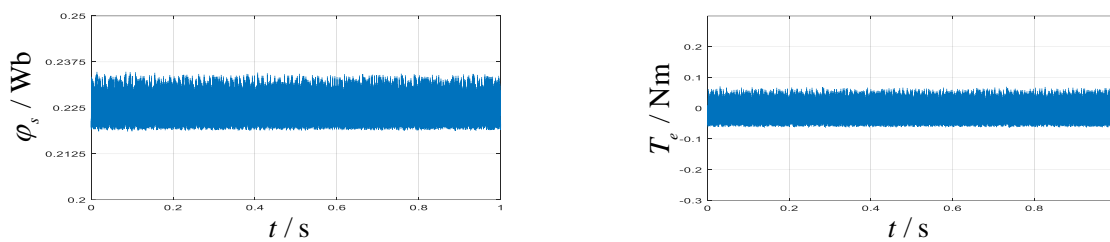


Figure 11. Flux linkage and torque waveforms of the new eighteen-sector DTC

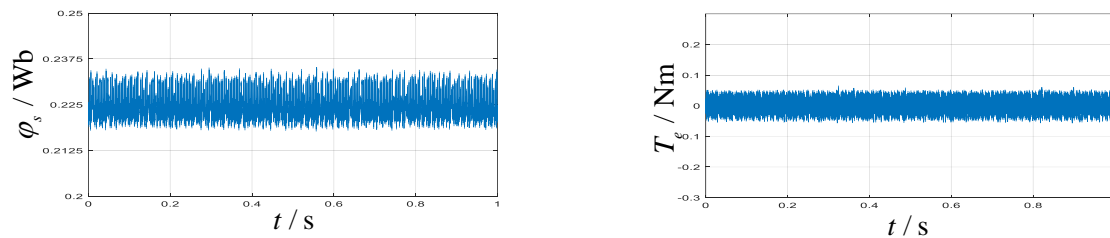


Figure 12. Flux linkage and torque waveforms of the new eighteen-sector DTC based on DRM

The simulation test shows that the maximum value of the PMSM stator flux amplitude fluctuation is basically the same under the three control modes, both of which are 0.008 Wb . In terms of torque control, the traditional DTC torque ripple is $0.1 \text{ N} \cdot \text{m}$, and the new eighteen-sector DTC is about $0.05 \text{ N} \cdot \text{m}$. After the DRM is added, the torque ripple is about $0.03 \text{ N} \cdot \text{m}$. The experimental results show that the new eighteen-sector DTC can effectively reduce the flux linkage and torque ripple. After combining the DRM, the improvement effect is more obvious.

5. Conclusion

In this paper, a new eighteen-sector DTC based on DRM is proposed. By using six new voltage vectors combined with eighteen sector DTC, the control effect of stator flux linkage and torque is effectively improved. Simulation results show that the proposed method can effectively improve the distortion of the stator flux at the edge of the sectors, reduce the flux fluctuation, reduce the torque ripple, and effectively improve the steady-state performance of DTC.

Acknowledgments

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