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Voltage Vector Selection Strategy of the DTC for SPMSM used in Electrical Vehicle Based on Predictive Control

Yaohua Li, Sen Jiao, Ying Wang

School of Automotive, Chang'an University, Xi'an China 710064

nuaaliyaohua@126.com

Abstract

In this paper, voltage vector selection area of the direct torque control (DTC) for surface permanent magnetsynchronous motor (SPMSM) is studied. And voltage vector selection strategy based on predictive controlis given which aims to minimize cost function of stator flux and torque's error. Space vector modulation(SVM) is used to generate the selected voltage vector. Simulation and experimental results show theproposed controlstrategy can minimize stator flux and torque's error and fix switching frequency, which isan ideal control strategy for electric vehicle.

Keywords: Voltage vector; Prediction; DTC; SPMSM

1 Introduction

The DTC for the PMSM possesses many advantages: simple control configuration, low parameter dependency, fast dynamic response, lack of coordinate transformation and rotor position except for the initial position. But it also suffers from some disadvantages: high torque and flux ripple and variable switching frequency. The DTC selects voltage vectors to control stator flux and torque. Studies showed switching table can't always satisfy the control of torque. Thus to select voltage vector properly is critical to improve the control performance of the PMSM DTC drive. In this paper, voltage vector selection area of the DTC for SPMSM is studied. And voltage vector selection strategy based on predictive control is given which aims to minimize cost function of stator flux and torque's error. SVM is used to generate the selected voltage vector. Simulation and experimental results show the proposed control strategy can minimize stator flux and torque's error and fix switching frequency, is an ideal control strategy for electric vehicle.

2 Voltage vector selection area

Because of the lack of reluctance torque, the torque of SPMSM is exciting torque, which is proportional to the cross product of stator and rotor flux vector. In the discrete system, it can be presented in (1) where l is a constant. And after applying the voltage vector for Δt, the torque can be presented in (2).

$$T_e(k) = l \cdot \vec{\psi}_s(k) \times \vec{\psi}_f(k) \tag{1}$$

$$T_e(k+1) = l \cdot \vec{\psi}_s(k+1) \times \vec{\psi}_f(k+1) \tag{2}$$

As rotor flux is excited by permanent magnet, its amplitude is constant. And the sampling period is short, the move of rotor flux can be neglected. Thus (3) holds true.

$$\vec{\psi}_f(k+1) \approx \vec{\psi}_f(k) \tag{3}$$

Neglecting the voltage drop on stator resistance, stator flux vector can be shown in (4).

$$\vec{\psi}_s(k+1) \approx \vec{\psi}_s(k) + V_s(k) \cdot \Delta t \tag{4}$$

And we can get:

$$\begin{aligned} T_e(k+1) &\approx l \cdot \vec{\psi}_s(k) \cdot \vec{\psi}_f(k) + l \cdot V_s(k) \cdot \Delta t \times \vec{\psi}_f(k) \\ &= T_e(k) + l \cdot V_s(k) \cdot \Delta t \times \vec{\psi}_f(k) \end{aligned} \tag{5}$$

Thus after applying the voltage vector for Δt, the change of torque can be presented in (6), whereβis the angle between rotor flux vector and the applying voltage vector. And it means whether the applying voltage vector increases or decreases torque is dependent on the angle between rotor flux vector and the applying voltage

$$\begin{aligned} \Delta T &= T_e(k+1) - T_e(k) = l \cdot V_s(k) \cdot \Delta t \times \vec{\psi}_f(k) \\ &= l \cdot \Delta t \cdot \widehat{V}_s(k) \cdot \widehat{\psi}_f(k) \cdot \sin\beta \end{aligned} \tag{6}$$

Considering effects of the applying voltage vector on the amplitude of stator flux and torque, voltage vector selection area in terms of the angle between stator flux and the applying voltage vector (α) is shown as followings: if α is within (0°, 90°), the applying voltage vector increases stator flux and torque; if α is within (90°, 180°-δ), the applying voltage vector decreases stator flux and increases torque; if α is within (180°, 270°), the applying voltage vector decreases stator flux and torque; if α is within (270°, 360°-δ), the applying voltage vector increases stator flux and decreases torque, where θ is torque angle, the angle between rotor flux vector and stator flux vector.

3 Voltage vector selection strategy based on predictive control

Any voltage vector in the selection area can be used to satisfy the control of stator flux and torque in theDTC system theoretically. In this paper, a voltage vector selection strategy based on predictive control isproposed, which aims to minimize cost function of stator flux and torque's error.The move of stator flux due to the application of voltage vector is shown in Fig. 1.

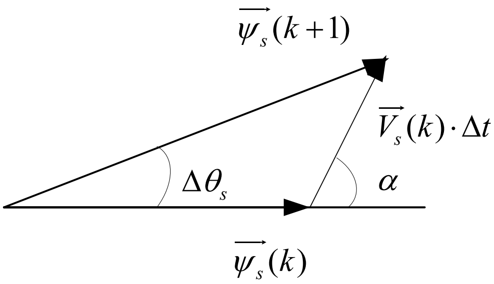

Figure 1: The move of stator flux vector

According the law of cosine and Fig. 1, after applying the voltage vector for Δt the amplitude of stator fluxcan be expressed in (7). And neglecting the move of stator flux, torque angle can be presented in (8). Andthe torque of SPMSM can be presented in (9).

$$\widehat{\psi}_s(k+1) = \widehat{\psi}_s(k)\sqrt{1+q^2+2q\cos\alpha}, \quad q = \widehat{V}_s \cdot \Delta t / \widehat{\psi}_s(k) \tag{7}$$

$$\delta(k+1) \approx \delta(k)+\Delta\delta=\delta(k)+\arcsin\frac{q\sin\alpha}{\sqrt{1+q^2+2q\cos\alpha}} \tag{8}$$

$$\begin{aligned} T_e(k+1) &= \frac{3p\psi_f}{2L_d}\widehat{\psi}_s(k+1)\sin(\delta(k+1)) \\ &= \frac{3p\psi_f}{2L_d}\widehat{\psi}_s(k)\sqrt{1+q^2+2q\cos\alpha}\cdot \\ &\quad \sin[\delta(k)+\arcsin\frac{q\sin\alpha}{\sqrt{1+q^2+2q\cos\alpha}}] \end{aligned} \tag{9}$$

According to (7) and (9), we can define cost function of statorflux and torque's error shown in (10).

$$g=\sqrt{[T_e^*\text{-}T_e(k+1)]^2+[\widehat{\psi}_s^{\,*}-\widehat{\psi}_s(k+1)]^2} \tag{10}$$

From (10), the cost function is about the angle between the voltage vector and stator flux. Thus g values at different angles can be predicted.

In this paper, an optimal voltage vector selection strategy for direct torque control of surface permanent magnet synchronous motor is proposed.The specific process is as follows.

(1) Determine the appropriate voltage vector selection interval based on the torque and flux hysteresis comparator output and the stator flux position and torque angle.

(2) The selected interval is divided equally to n and get the n angles of the voltage vector are applied at the next moment $\alpha_1-\alpha_n$ .In the space vector modulation linear modulation range, the amplitude of the applied voltage vector is fixed to $\widehat{V}_s$. In theory, when the interval is divided more, the calculation accuracyis higher, but the computational complexity is also increased and the real-time is difficult to guarantee. In this article, select n = 10.

(3) According to the current moment of the stator flux amplitude $\widehat{\psi}_s(\mathrm{k})$ and torque angle $\delta(\mathrm{k})$, predict the amplitudes of torqueand the stator flux at the next moment for different α .

(4) The amplitudes of torqueand the stator flux at the next moment and the reference amplitudes of torqueand the stator flux are substituted into equation (12). The cost function for the voltage vector at different anglesapplied at the next momentis predicted.

(5) Select the α value that minimizes the cost function. The applied voltage vector angle is determined by α and stator flux position information.

As the angle of selected voltage vector is arbitrary,which depends on the stator flux vector angular position and the torque angle, in theory, it is an arbitrary value in the[0°,360°].Voltage source inverter can only generate 6 non-zero voltage vector, can only corresponding to the 6 different phase angles: 0°, 60°,120°,180°,240° and 360°. Therefore, the six voltage vectors generated by the inverter can’t meet the requirements of the phase angle of the voltage vector selection strategy, and the technology of space vector modulation (SVM) is used to generate the selection voltage vector and the amplitude of selected voltage vector is kept constant.

Take the desired voltage vector V_s between V_1 and V_2 as an example, the space vector modulation technique is shown in Figure 1,Where γ is the angle between V_s and V_1 , the amplitude of V_1 and V_2 is $2U_{dc}/3$, the amplitude of V_s is $\sqrt{3}U_{dc}/3$, U_{dc} is DC bus voltage.

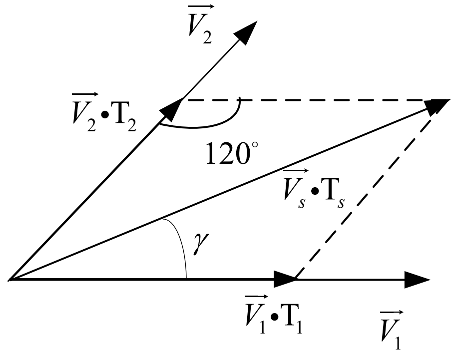

Figure 2: Space vector modulation

As can be seen from Fig.2, we choose T_s as a calculation cycle, the action time of the voltage vector V_1, V_2 and V_0 in a calculation cycle as shown in equation (11).

$$\begin{cases} T_1 = \sin(60^\circ - \gamma) * T_s \\ T_2 = \sin\gamma * T_s \\ T_3 = T_s - T_1 - T_2 \end{cases} \tag{11}$$

The diagram of the DTC for SPMSM using voltage vector selection strategy based on predictive control is shown in Fig. 3.

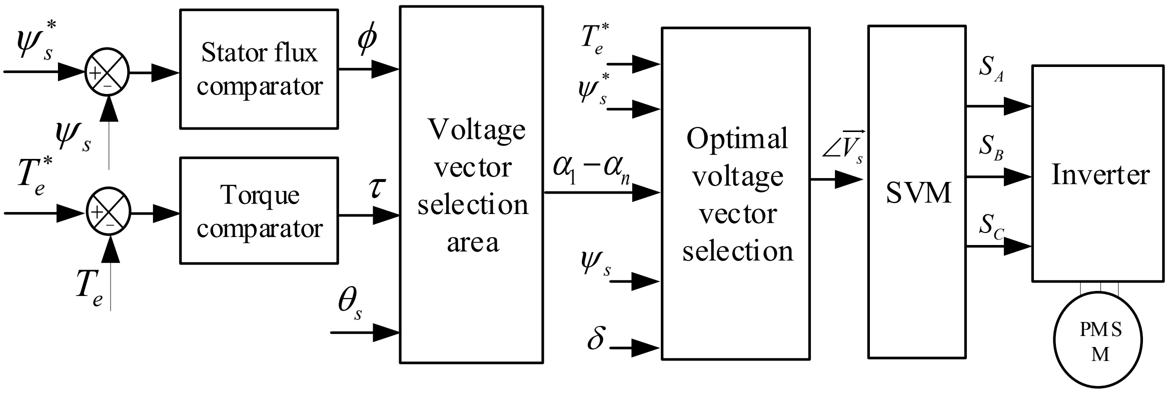

Figure 3: The DTC for SPMSM using voltage vector selection strategy based on predictive control

4 Simulation and analysis

The DTC system of the optimal voltage vector selection strategy is modeled and simulated: the simulation cycle is 2*10-5s; the reference motor speed is 60rpm; the reference torque is 10N·m with a step change to 30N·m at 0.5s; thereference stator flux amplitude is 0.3Wb;the torque hysteresis width is 0.01N·m; the flux hysteresis width is 0.001Wb.The motor parameters are shown in Table 1.

Table 1: Parameters of tested motor

Parameters	Value
Stator resistance (Ω)	0.02
dq-axis inductance (H)	[8.5e-3 8.5e-3]
Rotor flux amplitude (Wb)	0.175
The number of poles	4

The simulation results speed, torque, stator flux and current are shown in Fig.4-9.

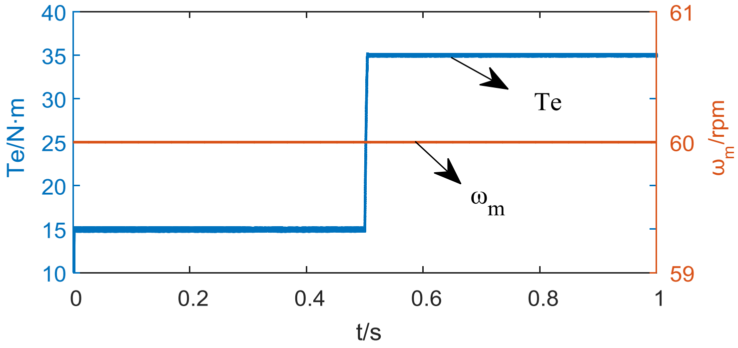

Figure 4: Motor speed and torque

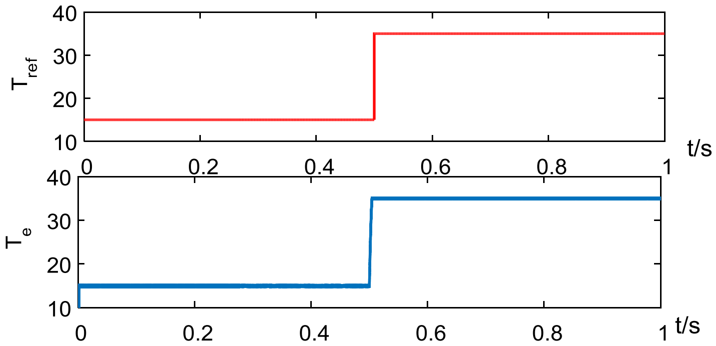

Figure 5: Motor reference torque and actual torque

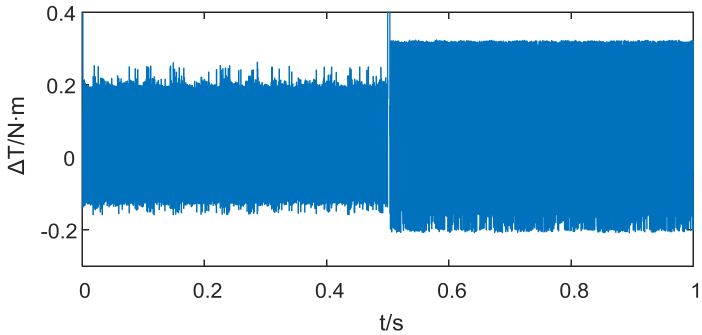

Figure 6: Motor torque error

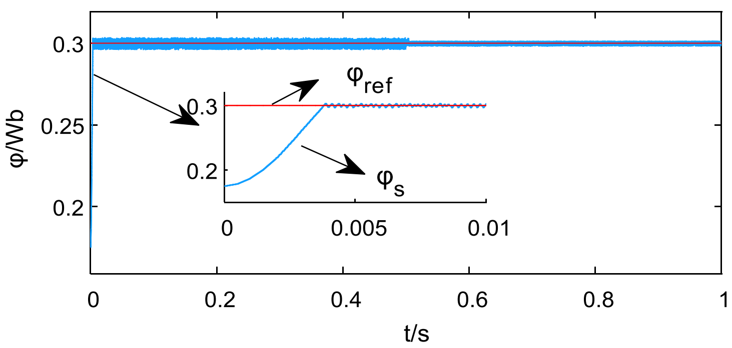

Figure 7: Variation of stator flux amplitude

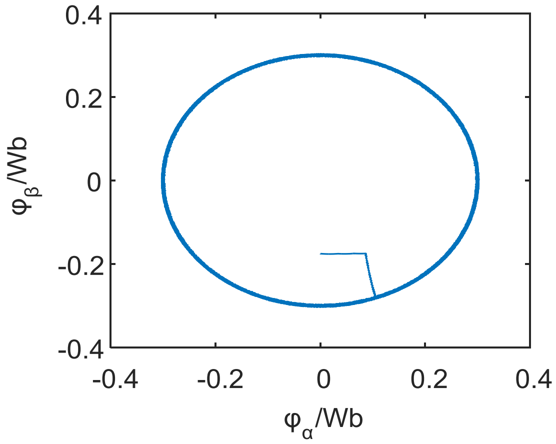

Figure 8: Flux chain

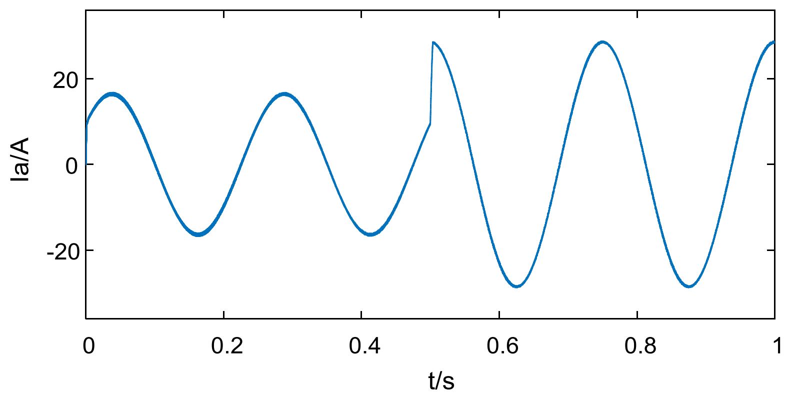

Figure 9: A-phase current waveform

From Figure 4-9 that the motor speed, torque, stator flux and current meet the expected results. The simulation results show the feasibility of the model and the optimal voltage vector selection strategy.

The relationship between the torque and the time and flux angle of the direct torque control achieved by the voltage vector selection strategy and the space vector modulation are shown in Fig.10 and Fig.11. The unreasonable torque ripple can be suppressed.

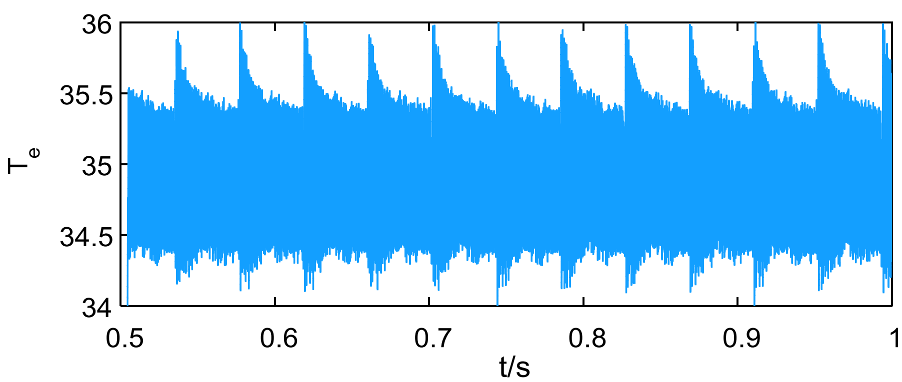

Figure 10: Variation of torque for Switch Table

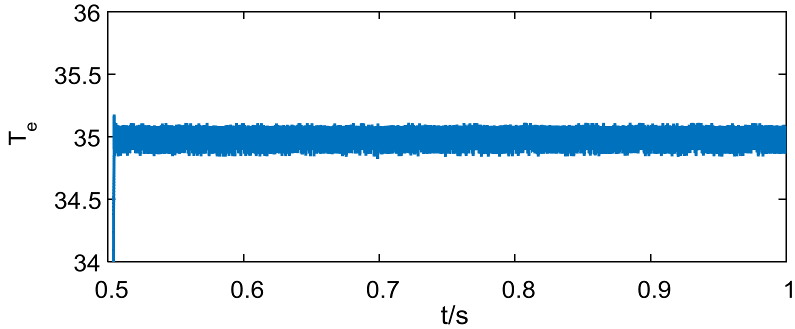

Figure 11: Variation of torque for Optimum Vector

The validity of the optimal voltage vector is verified by comparing cost function for optimal voltage vector and the voltage vector selected by the switch table. The values of g are shown as Fig.12. The average value of g for optimal voltage vector is 0.069, and the average value of g for switch table is 0.252. The average value of cost function is reduced by 72.6%.

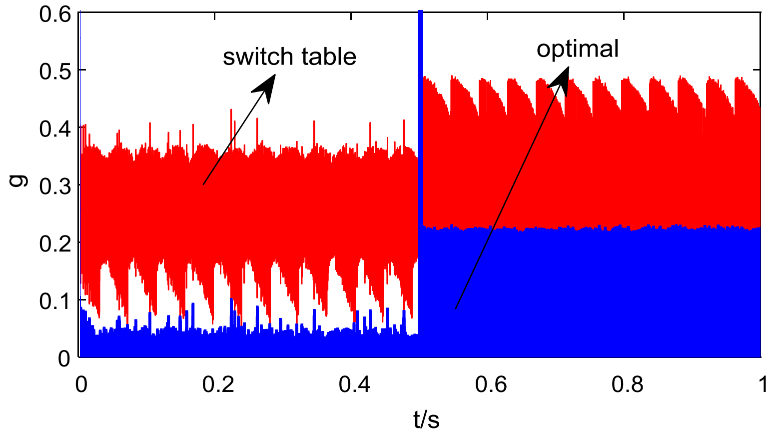

Figure 12:The comparison of g

Under the same conditions and sampling period, the mean absolute percentage error(MAPE)and the Peak-Peak value of the torque and the stator flux linkage for the switch table and the optimal voltage vector are compared, the results are shown in Table 2.The optimum voltage vector torque error is reduced by 61.9%, stator flux error is reduced by 29.3%. The torque's peak-peak valve is reduced by 83.3% during 0.6-0.9s.The flux's peak-peak valve is reduced by 67.3% during 0.6-0.9s.It is shown that the optimal voltage vector selection strategy can effectively reduce the torque and stator flux error.

Table 2: The comparison of torque and flux error

Evaluation	Switch	Optimum	Optimization rate
MAPE of torque	1.587%	0.604%	61.9%
MAPE of stator flux	0.625%	0.441%	29.3%
Peak-Peak for torque (0.6s-0.9s)	1.08N·m	0.18N·m	83.3%
Peak-Peak for flux (0.6s-0.9s)	0.0055Wb	0.0018Wb	67.3%

5 Conclusion

In this paper, an optimal voltage vector selection strategy is proposed for the problem of unreasonable torque ripple in direct torque control of surface permanent magnet synchronous motor realized by traditional switch table.According to the law of voltage vector and flux linkage, the voltage vector selection interval table is obtained, and the cost function of flux linkage and torque error is established. Based on the predictive control, the voltage vector in interval is selected optimally, and achieved by the space vector modulation technique.The simulation results show that the optimal voltage vector selection strategy proposed in this paper can eliminate the unreasonable torque ripple caused by the improper selection of the voltage vector of the switch tablecompletely, reduce the torque error more than 60%, reduce the error of the stator flux amplitude more than 29%, it can reduce the torque and flux erroreffectively, and make the switching frequency constant.Simulation and experimental results show the proposed control strategy can minimize stator flux and torque's error and fix switching frequency, which is an ideal control strategy for electric vehicle.

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Authors

Li Yaohua, Associate professor of school of automobile of Chang’an University, Xi’an, China. His research interests include electrical vehicle and automotive electronic control.