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Direct Torque Control Technology of Permanent Magnet Synchronous Motor Based on Pan-Boolean Algebra and SVPWM

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Abstract

AS far as the traditional Direct Torque Control (DTC) of PMSM be concerned, it has some disadvantages, such as speed fluctuation, large torque ripple, inconstant switch frequency, etc. By analyzing and researching the control algorithm of Pan-Boolean algebra, this paper believed that the Pan-Boolean algebra PID control can replace the traditional rotative speed regulator; And aiming at the disadvantage of the inconstant switch frequency, this paper argues that the original look-up table module can be substituted in SVPWM module. In addition, an improved scheme of Direct Torque Control method of PMSM is presented in this thesis. The results of the corresponding simulation model built in MATLAB/Simulink show that the system can effectively reduce the torque ripple and improve the system stability of rotation speed, and has a better dynamic response ability..

Keywords

PMSM; Pan-Boolean algebra PID control; SVPWM; DTC.

1. Introduction

For traditional DTC, through the calculation of the amplitude of torque and flux linkage, the comparison of the given value, the differences between them were used to control the amplitude of the angle and stator flux linkage between the flux linkage and vector, and to output the required space voltage vector directly by the flux and torque regulator, so as to achieve the purpose of direct control of torque and flux linkage [1].

Since then, many scholars have carried out a lot of research, and the role of zero voltage vector in direct torque control has been studied in literature [2]. Based on the principle of minimum switching times, a new switching table with zero voltage vector is proposed. The results show that it can effectively reduce the switching times of DTC system, and then reduce the switching loss. In literature [3], aiming at the problem of large torque ripple in DTC system, the traditional third-order hysteresis comparator is extended to the seventh-order hysteresis comparator by taking advantage of the fact that six-phase inverters can provide abundant voltage vectors, and the hierarchical control of torque error is realized. The results show that the torque ripple can be reduced by reasonably distributing the action time of effective vector and zero voltage vector. In literature [4], an improved model of method used to predict direct torque control is proposed. According to deadbeat control theory, the expected voltage vector of stator flux and electromagnetic torque reaching the given value in the next cycle is calculated. The results show that the method can effectively suppress the torque ripple and flux linkage ripple, reduce the stator current distortion rate, and improve the robustness of the system.

In this study, Pan-Boolean algebra PID control strategy and SVPWM technology are combined with DTC technology. According to the strong robustness of Pan Boolean control algorithm, the stability of DTC of PMSM in dynamic situation is improved, the torque ripple is reduced, and modeling and simulation are carried out. It provides a theoretical reference for further improvement of traditional DTC control.

2. Mathematical Model of PMSM

The PMSM is controlled in d-q axis system without considering the saturation of motor core, eddy current and hysteresis loss in motor. The equations of voltage, flux linkage and torque are as follows:

The voltage equation is as follows:

$$\begin{cases} \mathrm{u}_d = R_s i_d + \dfrac{d\psi_d}{dt} - \omega_r \psi_q \\ \mathrm{u}_q = R_s i_q + \dfrac{d\psi_q}{dt} + \omega_r \psi_d \end{cases} \tag{1}$$

The flux linkage equation is as follows:

$$\begin{cases} \psi_\mathrm{d} = L_d i_d + \psi_f \\ \psi_q = L_\mathrm{q} i_q \end{cases} \tag{2}$$

Where L_d is synchronous inductance of stator direct axis; L_q is synchronous inductance of stator quadrature axis.

The torque equation is as follows:

$$\begin{aligned} T_e &= \frac{3}{2} P_n (\psi_\mathrm{d} i_q - \psi_\mathrm{q} i_d) \\ &= \frac{3}{2} P_\mathrm{n} (\psi_\mathrm{f} i_q + (L_d - L_q) i_d i_q) \end{aligned} \tag{3}$$

Where P_n is the number of poles of the motor.

3. Improved direct torque control system

3.1 Pan-Boolean algebra PID control strategy

In the control system of Pan-Boolean algebra, each factor has several state variables composed of two types of logic states 0 and 1. If you take X_1, X_2…as the factors in the system, and the possible states of any one of the factors X_i are called "number of states" of X_i which is recorded as n_i, and X_i^j is a state variable, where j represents the number of states and i represents the factors which X belongs. In Pan Boolean algebra, each factor X_i represents only one of N states in a certain situation [6]. This is determined by the division rules of concepts.

The logic switch is used to force switching into different control laws to improve the performance index of the system. Using the fuzzy control idea of error and error change, the motion trajectory of the object on the response curve is analyzed through the phase plane, and the error zero band (allowable range of error), error integral zero band (accumulated error range) and error variation zero band (allowable range of error variation), these three types of control indexes are introduced. It can increase the number of adjustable parameters of the controller and weaken the interaction between the control parameters [7]. The specific control rules are as follows:

As shown in Table 1: when $e(t) < -\varepsilon$, $de(t)/dt > \delta$, and $\int \mathrm{e(t)}dt < -e(\infty)$, at present, the system error is located at outside the allowable range of error (lower than the lower limit of allowable error), the integral value of deviation is lower than the lower limit of allowable value, but the differential value of deviation is greater than the allowable value, which indicates that its movement trend is "fast" approaching to the reference value. In order to avoid excessive acceleration of the system, the output Y_1^8（Y_1^i indicates nine control rules from strong to weak）is given, that is a weak negative control effect, which can give the system a "deceleration" effect and avoid a large overshoot.

Tab.1 Pan-Boolean Algebra Controller

Y1 / e（t）	$\frac{de(t)}{dt}$ / $\int e(t)dt$	$\frac{de(t)}{dt} > \delta$	$\left\|\frac{de(t)}{dt}\right\| \le \delta$	$\frac{de(t)}{dt} < \delta$
$e(t) > \varepsilon$	$\int e(t)dt > e(\infty)$	Y_1^3	Y_1^3	Y_1^2
	$\left\|\int e(t)dt\right\| \le e(\infty)$	Y_1^1	Y_1^2	Y_1^3
	$\int e(t)dt < -e(\infty)$	Y_1^2	Y_1^1	Y_1^1
$\|e(t)\| \le \varepsilon$	$\int e(t)dt > e(\infty)$	Y_1^7	Y_1^6	Y_1^6
	$\left\|\int e(t)dt\right\| \le e(\infty)$	Y_1^4	Y_1^5	Y_1^6
	$\int e(t)dt < -e(\infty)$	Y_1^4	Y_1^4	Y_1^3
$e(t) < -\varepsilon$	$\int e(t)dt > e(\infty)$	Y_1^9	Y_1^9	Y_1^8
	$\left\|\int e(t)dt\right\| \le e(\infty)$	Y_1^7	Y_1^8	Y_1^9
	$\int e(t)dt < -e(\infty)$	Y_1^8	Y_1^7	Y_1^7

3.2 SVPWM control strategy

The SVPWM control strategy is combined with DTC technology. In SVPWM technology, the voltage vector of any position can be synthesized by combining the action time of zero voltage vector and non-zero voltage vector. Based on this, instead of the look-up table module in traditional DTC control, the most reasonable voltage vector is selected to compensate the error of flux linkage and torque in one cycle, so as to achieve the ideal flux circle as far as possible and to realize the precise control of torque [9].

For the generation of reference voltage vector, the reference torque generated by Pan Boolean PID control can be obtained by PI control, and the position deviation $d\theta$ can be obtained.

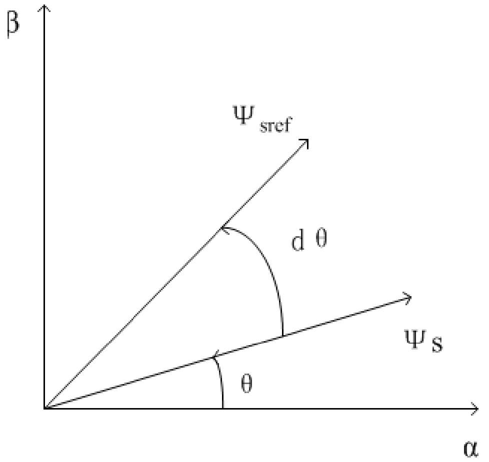


Fig.1 reference flux vectors

In the α-β coordinate system, the stator voltage equation is as follows:

$$\begin{cases} u_\alpha = R_s i_\alpha + \dfrac{d\psi_a}{dt} \\ u_\beta = R_s i_\beta + \dfrac{d\psi_\beta}{dt} \end{cases} \tag{4}$$

Reference voltage u_α^*, u_β^* is the voltage component of the expected voltage u_{sref}, according to Fig. 1, it can be obtained that:

$$\begin{cases} u_\alpha^* = R_s i_\alpha + \dfrac{|\psi_{sref}|\cos(\theta+d\theta) - |\psi_s|\cos\theta}{T_s} \\ u_\beta^* = R_s i_\beta + \dfrac{|\psi_{sref}|\sin(\theta+d\theta) - |\psi_s|\sin\theta}{T_s} \end{cases} \tag{5}$$

Where T_s is a single control cycle; R_s is the stator resistance.

Combined with SVPWM control and Pan Boolean PID control, the improved DTC control block diagram of PMSM is shown in Fig. 2

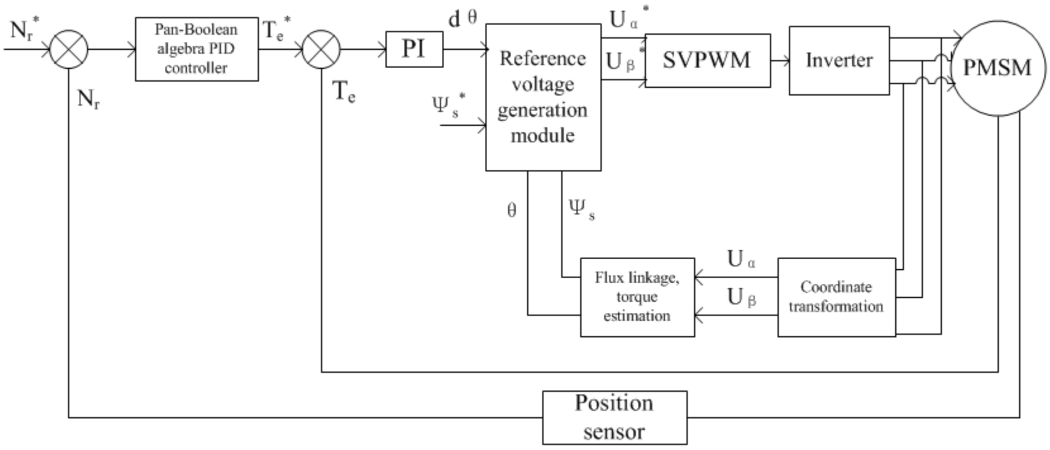


Fig.2 Improved DTC control block diagram of PMSM

4. System Simulation Modeling

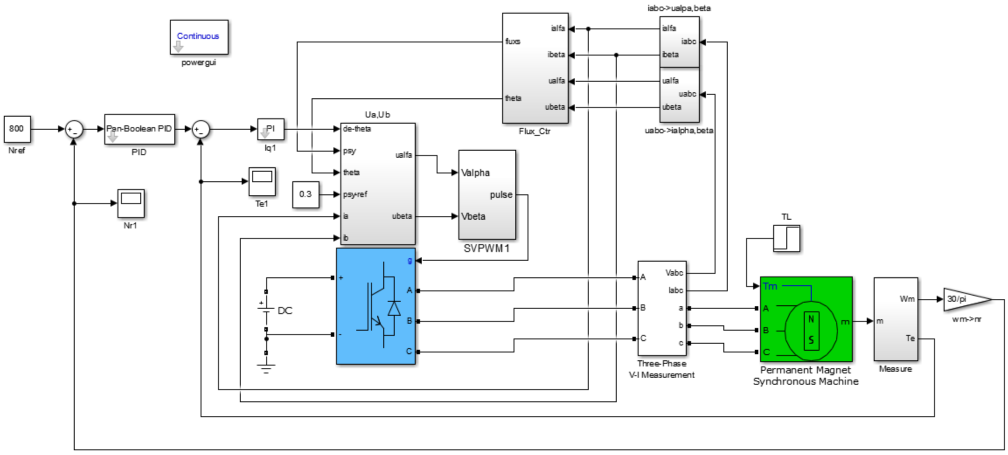


Fig.3 DTC simulation model of PMSM based on Pan-Boolean Algebra and SVPWM

In the MATLAB / Simulink simulation environment, the simulation model of the improved PMSM DTC system as shown in Figure 3 is established. It mainly includes Pan Boolean algebra PID control module, reference voltage vector calculation module, SVPWM control module, flux linkage and torque calculation module. The motor parameters are set as follows: pole number P_n=4, stator inductance L_s=8.5mH, stator resistance R=1.2Ω, flux linkage ψ_f =0.175Wb, moment of inertia J=0.0008 $Kg \bullet m^2$.

In the Pan Boolean algebra control module, set the symbol $K_i \pm$ (i=0,1,2,3,4) stands for nine control functions of Y_1^1, Y_1^2, Y_1^3, Y_1^4, Y_1^5, Y_1^6, Y_1^7, Y_1^8, Y_1^9, specific parameter are : K_{4+}=800000, K_{3+}=100, K_{2+}=10, K_{1+}=0.003, K_0=0, K_{1-}=-0.003, K_{2-}=-30, K_{3-}=-150, K_{4-}=-200.

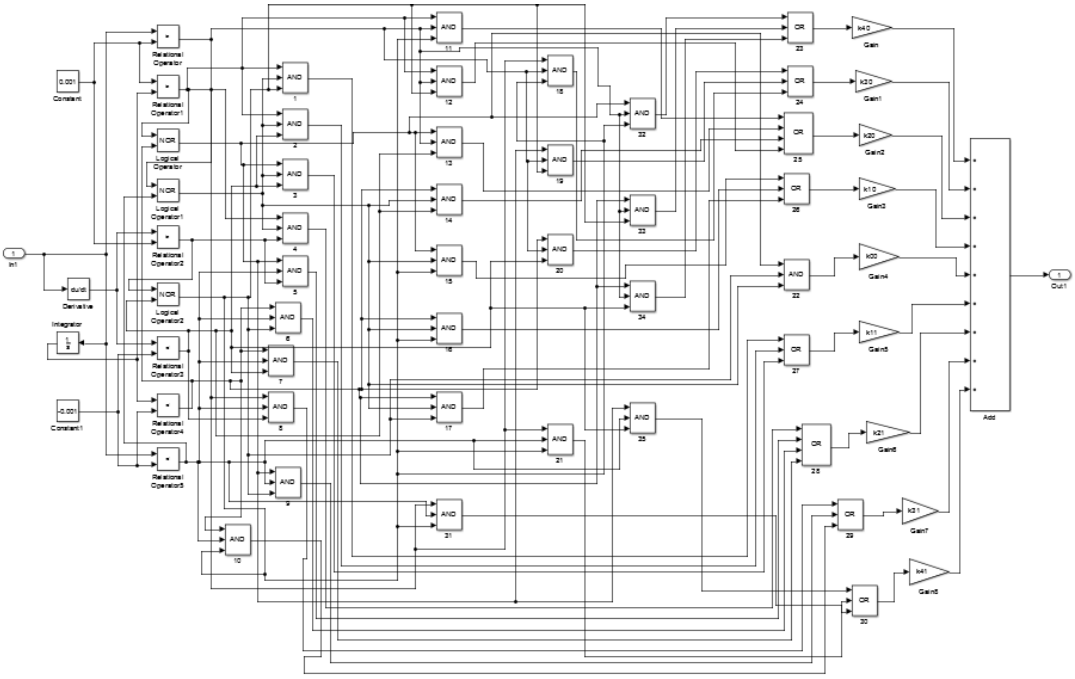
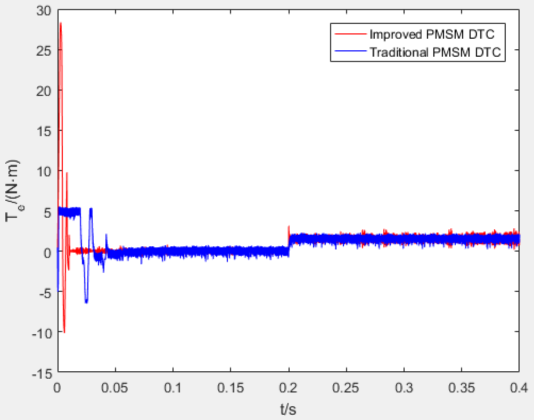


Fig.4 Pan-Boolean PID simulation module

The simulation adopts the fixed step size ode3 (Bogacki-Shampine) algorithm, and the step size and sampling time are set as follows: 1e-6, the simulation time is 0.4S, the given speed is 800r/min, the reference stator flux linkage is 0.3Wb, and the initial load torque is $T_L=0\ N \bullet \mathrm{m}$. When t=0.2S, the load torque suddenly changes to 1.5 $N \bullet \mathrm{m}$. The simulation results are shown in Fig. 5-10.



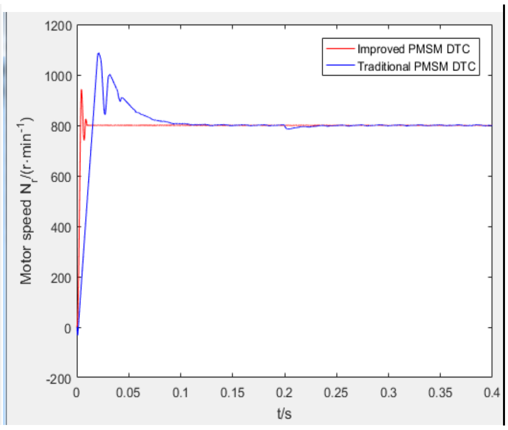
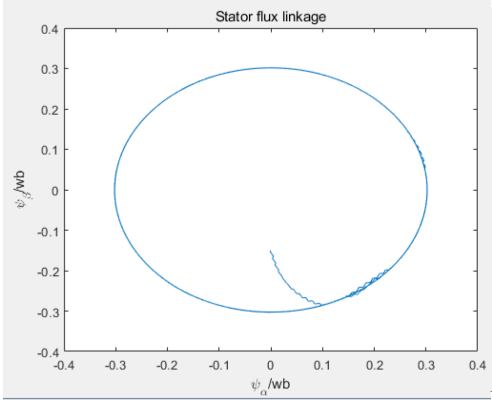


Fig.5 Electromagnetic torque waveform **Fig.6** Speed waveform



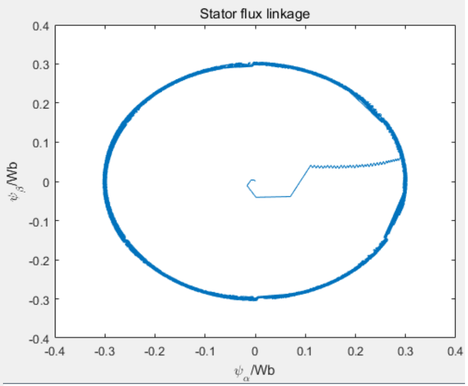
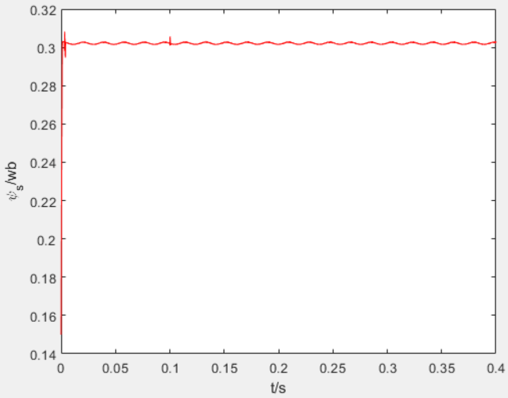


Fig.7 Improved stator flux linkage phase diagram **Fig.8** Traditional flux linkage phase diagram



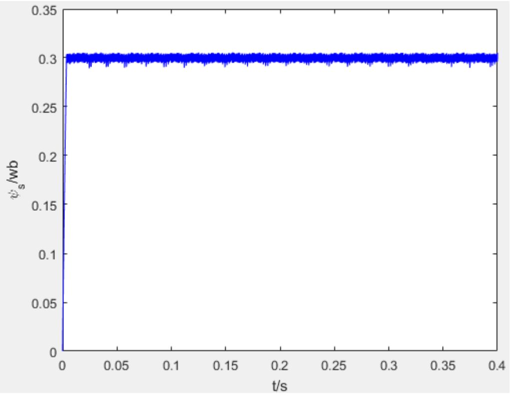


Fig.9 Improved stator flux linkage waveform **Fig.10** Traditional stator flux waveform

It can be seen from the above simulation results that the permanent magnet synchronous motor DTC technology based on Pan Boolean algebra and SVPWM is greatly improved compared with the traditional DTC technology. According to figure 5, the torque can be quickly stabilized at 0N·m, and the response time is about 30% of the traditional control. When both of the torque approaches stability, the torque ripple is smaller. It can be seen from Figure 6 that when the motor rises from standstill to the reference speed of 800r/min, the response speed of the improved control system is faster, and the overshoot is about 900r/min. The maximum speed of the traditional permanent magnet synchronous motor DTC exceeds 1000 r/min. Moreover, when t = 0.2 s, the load torque suddenly changes to 1.5 N·m, the speed of the improved system almost has no fluctuation, and the steady-state performance is better. According to figures 7-10, the flux ripple of the improved system is smaller, which is better than the traditional DTC.

5. Conclusion

Based on the analysis of direct torque control algorithm of permanent magnet synchronous motor, a direct torque control system based on Pan Boolean algebra is proposed in this paper, at the same time, the SVPWM technology is applied in the DTC system, and the SVPWM module is used to replace the original look-up table module, eliminating the original flux linkage and hysteresis comparison module. The simulation model is built for comparative analysis. The simulation results show that the scheme has a certain feasibility, which can effectively improve the stability of the speed and reduce the overshoot of the system in the case of torque mutation. It provides a theoretical basis for improving the torque and flux fluctuation in DTC technology.

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