

Three-phase PMSM Comparison between DTC and MPTC

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Abstract: This paper compares the control performance, average switching frequency, and parameter robustness of a Direct Torque Control (DTC) system and a Predictive Torque Control (MPTC) system based on the stator magnetic flux coordinate system of a permanent magnet synchronous motor (PMSM). The DTC system has a simpler architecture and a lower average switching frequency, but its magnetic flux and torque ripple are larger than those of the MPTC system. The MPTC system outperforms the DTC system in terms of performance.

Keywords: PMSM; MPTC; Three-phase; Inverter Model.

1. Introduction

Permanent magnet synchronous motors (PMSMs) are widely used in new energy vehicles, high-speed rail traction, and other fields due to their advantages, such as high efficiency, high power density, and high-power factor [1]. Vector control, as a classic control theory for AC motors, is relatively mature in the PMSM field, but it requires continuous rotor position information and rotational coordinate transformation [2]. DTC technology, based on a stationary coordinate system, uses a hysteresis comparator to determine the voltage vector through a switching table. It requires no coordinate transformation, has a simple structure, is easy to implement, and has also been widely used in the PMSM field [3]. In recent years, with the improvement of microprocessor computing power, finite state set model predictive control, which uses a cost function as an evaluation index and traverses all switching states of the inverter into the motor predictive model to select the switching state with the best control effect, has attracted attention in the PMSM control field [4]. PMSM model predictive control can be implemented based on either the rotor rotating coordinate system or the stator coordinate system. The former is similar to vector control, requiring coordinate transformation and rotor position, while the latter requires real-time torque angle information. The controlled object can be the stator current component, flux linkage, and torque. The cost function of the former does not require weighting coefficients, while the latter requires the design and adjustment of weighting coefficients [5, 6].

2. Materials and Methods

2. Mathematical Model of PMSM

Given the nonlinear characteristics and parameter coupling of the PMSM, the following assumptions are required for its modeling:

- 1) The three-phase stator windings and stator currents are 120° out of phase and connected in a star configuration.
- 2) The motor flux linkage is linear, and eddy current losses and hysteresis losses are not considered.

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3) Higher harmonics are ignored, and the permanent magnet magnetomotive force is a standard sine wave.

The stator voltage, flux linkage equations, torque, and motion equations of the motor are derived as shown in equations (1) to (4).

$$\begin{aligned} u_d &= R_s i_d + p\psi_d - \omega_e \psi_q \\ u_q &= R_s i_q + p\psi_q + \omega_e \psi_d \end{aligned} \quad (1)$$

$$\begin{aligned} \psi_d &= L_s i_d + \psi_f \\ \psi_q &= L_s i_q \end{aligned} \quad (2)$$

$$T_e = \frac{3}{2} n_p (\psi_d i_q - \psi_q i_d) \quad (3)$$

$$T_e - T_m = \frac{J}{n_p} \frac{d\omega_m}{dt} + B\omega_m \quad (4)$$

In the formula: u_d, u_q , is the stator voltage d and q axis components (V); i_d, i_q , are the stator current d and q axis components (A); R_s , is the stator winding phase resistance (Ω); ω_e , is the rotor electrical angle (rad/s); ψ_d, ψ_q , are the d and q axis flux linkage components (Wb); $p=d/dt$ is the differential operator; ψ_f , is the permanent magnet flux linkage (Wb); T_e , is the electromagnetic torque (N·m); P is the number of pole pairs; T_m , is the load torque referred to the shaft end (N·m); J is the moment of inertia of the mechanical load referred to the shaft end ($\text{kg}\cdot\text{m}^2$); m is the rotor mechanical angular velocity (rad/s); B is the viscous friction coefficient, $B>0$.

2.1 Two-Level Voltage Source Inverter Model

Taking the most commonly used 2L-VSI in a three-phase PMSM system as an example, it has a general structure and operating principle, and can be easily extended to other inverter topologies [7]. Because the inverter has discrete characteristics, its specific switching states generate eight corresponding basic voltage vectors, as shown in Figure 1. Among them, u_0 and u_7 are zero-amplitude voltage vectors, and $u_1, u_2, \dots, u_6$ are non-zero voltage vectors with different phases. These different voltage vectors correspond to different switching actions of the inverter. Figure 2 shows the inverter topology and the generation principle of all switching actions.

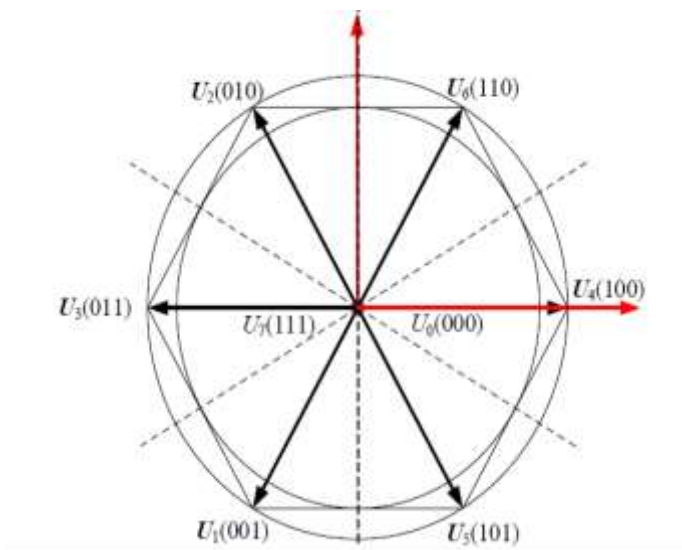


Fig. 1 Basic voltage vector distribution diagram

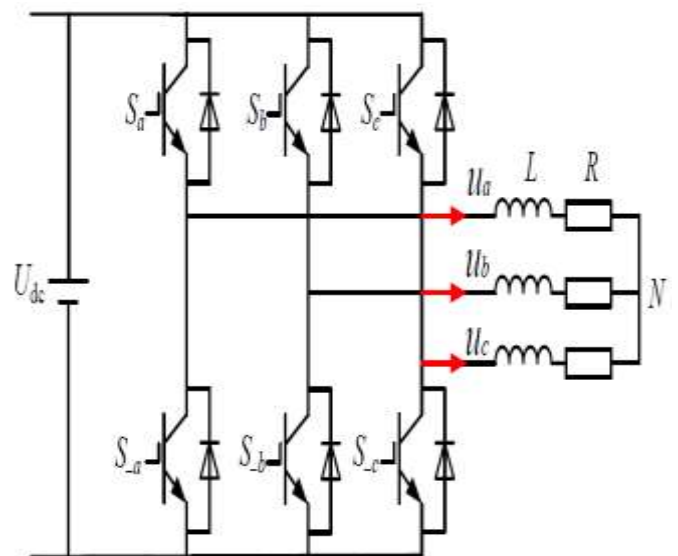


Fig. 2 Topology of 2-level voltage source inverter

Figure 2 shows a 2L-VSI topology containing three-phase branches, each with two Insulated-Gate Bipolar Transistors (IGBTs), connecting the corresponding load terminals to the positive or negative bus of the inverter [8]. The switch has three gating signals, defined as S_a , S_b , and S_c . The value of the switch signal S is either 0 or 1, representing on or off, respectively. Normal inverter operation requires that the upper and lower bridge arms S and S' cannot be on simultaneously; otherwise, a short circuit will occur on the DC side, damaging the inverter. Therefore, for a three-phase branch, when the upper bridge arm is on, the lower bridge arm must remain off. Each phase branch has two switching states: upper arm on, lower arm off, and upper arm off, lower arm on. Extending this to the entire three-phase branch generates eight switching states [9].

The switching table and corresponding basic voltage vector generated by the switching actions of the inverter are shown in Table 1.

Table 1. basic voltage vector generated by the switching actions of the inverter

Basic voltage vector	Inverter upper arm			State combination
	S_a	S_b	S_c	
u_0	0	0	0	(000)
u_7	1	1	1	(111)
u_4	1	0	0	(100)
u_6	1	1	0	(110)
u_2	0	1	0	(010)
u_3	0	1	1	(011)
u_1	0	0	1	(001)
u_5	1	0	1	(101)

Each different switching state in the inverter defines a set of phase voltages relative to the negative bus. The three-phase AC voltages generated by different switching states can be expressed as:

$$\begin{cases} u_a = -\frac{1}{3}U_{dc}(2S_a - S_b - S_c) \\ u_b = \frac{1}{3}U_{dc}(2S_b - S_a - S_c) \\ u_c = \frac{1}{3}U_{dc}(2S_c - S_b - S_a) \end{cases} \quad (5)$$

In the formula, U_{dc} is the DC bus voltage. In summary, the 2L-VSI has 8 switching states and generates 8 basic voltage vectors in a two-phase stationary coordinate system.

2.3 Direct Torque Control

The control block diagram of the direct torque system is shown in Figure 3, which includes a PI regulator, a switching meter, an inverter, coordinate transformation, flux linkage, and torque hysteresis, PMSM, etc. [10]. The principle of Figure 3 is as follows: the given motor speed is compared with the detected speed, and the difference between the two speeds is used as an error signal. After passing through the PI speed regulator, the output is the reference torque signal T_e^* , which is compared with the torque signal T_e calculated by the q-axis current in the control system. The difference between the two enters the torque hysteresis controller. The principle of flux linkage hysteresis control is to compare the given flux linkage with the flux linkage ψ calculated by the d-axis voltage and current in the control system. The difference between the two enters the flux linkage hysteresis controller. Finally, the two signals are effectively modulated in the two

hysteresis controllers and finally switched. The switch outputs the corresponding voltage vector, thereby controlling the inverter to control the permanent magnet synchronous motor and achieve the purpose of speed regulation [11].

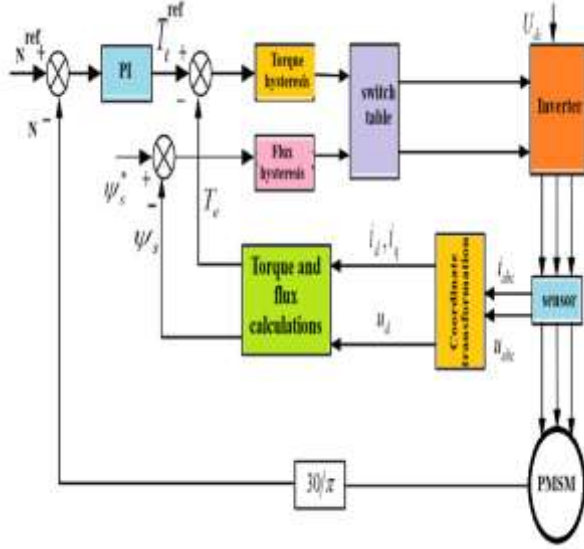


Fig. 3 block diagram of the direct torque control

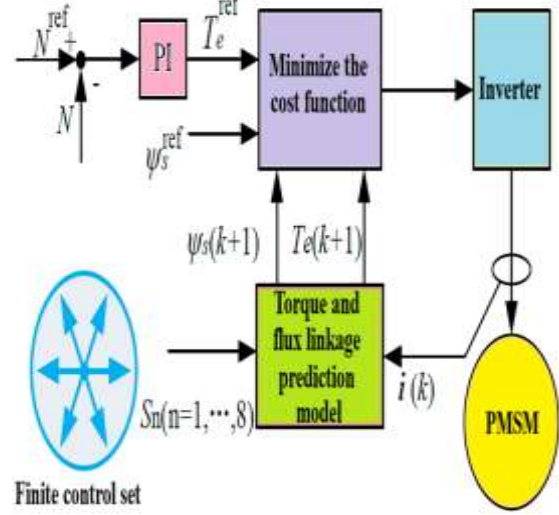


Fig. 4 Block diagram of FCS-MPTC strategy for PMSM system

2.4 Model Predictive Torque Control

The MPTC strategy for the PMSM system uses torque and flux linkage as the main controlled objects. Its cost function includes both torque error tracking and flux linkage error tracking [12]. The MPTC strategy uses cost function optimization to replace the torque hysteresis, flux linkage hysteresis, and offline lookup table in traditional DTC, thus enabling the selection of a more accurate voltage vector. Based on equations (6), (7), and (8), the torque and flux linkage prediction model of the MPTC strategy is established in a two-phase rotating coordinate system:

$$\begin{bmatrix} \psi_d(k+1) \\ \psi_q(k+1) \end{bmatrix} = \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} \begin{bmatrix} i_d(k+1) \\ i_q(k+1) \end{bmatrix} + \begin{bmatrix} \psi_f \\ 0 \end{bmatrix} \quad (6)$$

$$T_e(k+1) = \frac{3}{2} P_n i_q(k+1) [i_d(k+1)(L_d - L_q) - \psi_f] \quad (7)$$

$$\psi_s(k+1) = \sqrt{(\psi_d(k+1) + \psi_q(k+1))^2} \quad (8)$$

In the formula, $i_d(k+1)$ and $i_q(k+1)$ are the predicted current values obtained from equation (9). Based on the prediction model of torque and flux linkage, the following cost function is designed:

$$J = \left(T_e^{ref} - T_e(k+1) \right)^2 + \lambda_\psi \left(\psi_s^{ref} - \psi_s(k+1) \right)^2 \quad (9)$$

In the formula, λ_ψ is a weighting factor in the cost function, which aims to balance the importance of torque and flux linkage. By selecting an appropriate voltage vector, either the torque tracking error or the flux linkage tracking error can be minimized;

however, these two objectives cannot be achieved simultaneously. Therefore, it is necessary to design a weighting factor to balance their priorities. Figure 4 shows the control block diagram of the FCS-MPTC strategy in the PMSM system. The implementation process of the MPTC strategy on the PMSM is basically the same as that of the MPCC strategy, also including current sampling, prediction model establishment, cost function minimization, switching sequence output, and rolling optimization [13].

3. Results

Based on simulation results, this section compares the performance of the traditional DTC strategy and the MPTC strategy. The biggest difference between these two schemes lies in the different sizes of the alternative voltage vector sets. To improve the realism and reliability of the simulation, the PMSM parameters in the simulation test are kept consistent with the PMSM parameters in the experiment. The main parameters of PMSM are shown in Table 2.

Table 2. The main parameters of PMSM

Parameter	Value	Unit	Parameter	Value	Unit
load torque	8.5	N.m	R_s	1.3	Ω
Vdc	300	V	$L_d=L_q$	9	mH
P	3	-	PMflux	0.41	Wb

As depicted in the ocular representations designated as Figures 5 and 6, it becomes progressively obvious that once the force stabilizes and achieves a constant state condition, the variation in force oscillates within an outlined range, specifically between 4Nm and 8Nm. It is positively apparent that the exercise of direct torque control methods results insignificant and evident fluctuations in turn principles, that can lead to functional incompetence's and inconstancy in structure performance; still, when engaging the more progressive technique famous as Model Predictive Torque Control (MPTC), individual can see a notable reduction in the size of these revolution vacillations, with enhancing the overall balance and efficiency of bureaucracy. This comparative reasoning of twist action under clashing control strategies underlines the significance of selecting appropriate control methods in order to advance twisted item administration and ensure the dependability of machinelike wholes in miscellaneous applications.

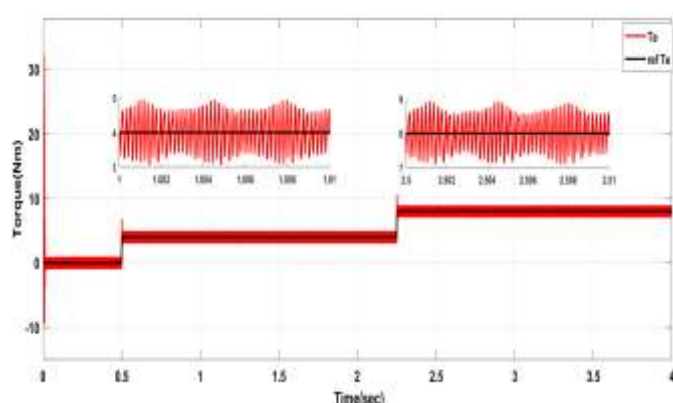


Fig. 5 torque waveform with DTC

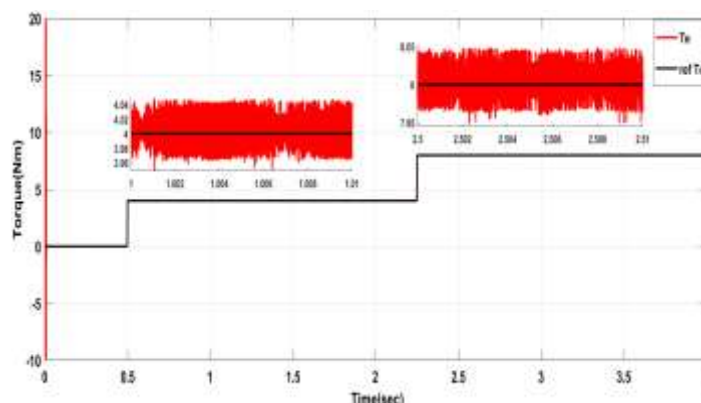


Fig. 6 torque waveform with MPTC

As depicted in Figure 7, it is apparent that the stator alteration relation exhibits a degree of vacillation, vacillating about a mean advantage of nearly 0.41 Wb, while together professed a vacillation range that spans from 0.42 Wb to 0.405 Wb, thereby happening in a vacillation worth that may be restricted as 0.015 Wb. As depicted in Figure 8,

it is apparent that the stator alteration relation exhibits a degree of vacillation, vacillating about a mean advantage of nearly 0.41 Wb, while together professed a vacillation range that spans from 0.4104 Wb to 0.4097 Wb, thereby happening in a vacillation worth that may be restricted as 0.0007Wb. When engaging the methods known as MPTC, individuals can celebrate a greatly diminished level of ripple effects distinguished from the common methods that have been historically appropriated in this field.

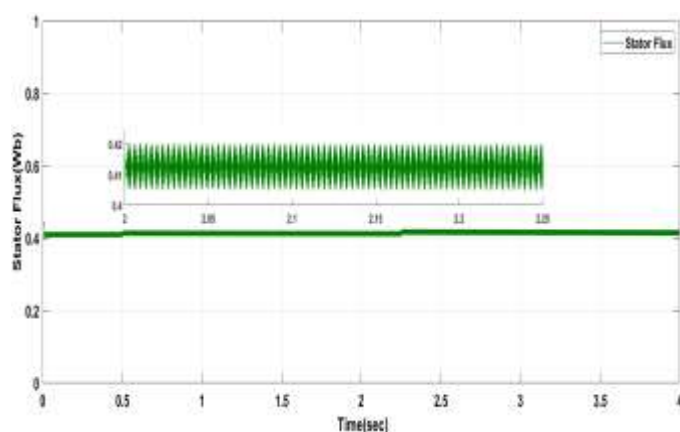


Fig.7 stator flux amplitude with DTC

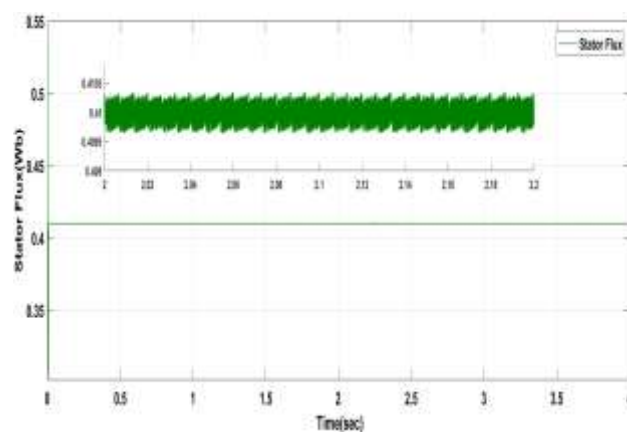


Fig.8 stator flux amplitude with MPTC

4. Conclusions

Both the method famous as direct torque control particularly planned for constant magnet simultaneous motors, usually refer to as PMSM DTC, and the methodology of predicting twist control that is to say established stator coordinates, shortened as MPTC, basically exploit magnetic fluctuation and necklace as the basic elements for control purposes, while together engaging the heading of output service caused apiece inverter as the key variable for control adaptations, and two together blueprints exhibit several joint traits that are important. This scholarly paper endeavors to conduct an inclusive, contrasting, and meticulous examination of these two distinct control actions, focusing specifically on their relative control performance, overall influence, and strength against differences in parameters that grant permission to influence their movement. In particular, the MPTC approach is recognized for its ability to considerably mitigate turn ripple, which refers to the unacceptable fluctuations in necklace manufacturing, in addition to stabilizing differences in attractive modification that can unfavorably impact the performance of the engine. Such verdicts highlight the potential advantages of the MPTC arrangement in embellishing the functional efficiency and dependability of lasting belt synchronous motors through enhanced control devices.

Conflicts of Interest: The authors declare no conflict of interest.

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