

An Improved Cost Function Based on Model Predictive Current Control for Five-Phase PMSM

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Abstract: In the model predictive control of a five-phase permanent magnet synchronous motor (PMSM), obtaining weight coefficients through cumbersome calculations is problematic to achieve optimal system control performance. To address this issue, this paper proposes a cascade model predictive current control method for a 5-phase PMSM, employing the concept of cascade model predictive control. First, the mechanism by which the suggested scheme chooses the best voltage vector is analyzed. Then, by setting the mechanism precedence of the regulated chargeables based on the characteristics of the 5-phase PMSM, objective function design schemes without weight coefficients are proposed: a fundamental current optimization scheme employs a high-amplitude voltage vector to improve DC bus voltage utilization and dynamic response capability; and a harmonic current optimization scheme reduces stator current harmonics to reduce scheme noise and vibration. Simulation results demonstrate that the offered technique ensures the optimality of the applied voltage vector, enabling the 5-phase PMSM to achieve excellent performance with a short torque wave, rapid dynamic reaction, and little harmonic current under different operating situations.

Keywords: five-PMSM; model predictive current control; weight coefficient; voltage vector

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1. Introduction

PMSM They are widely used in industrial manufacturing due to their great power density, small size, and great efficiency [1]. In the context of vigorously developing novel energy request technologies, the electric drive system collected of 5-phase PMSM and a power converter contributes to the tendency of novel energy progress [2].

As the number of phases grows, the reliability and fault tolerance of 5-phase PMSM are enhanced. Even if a two-phase bridge arm fails, it can still work normally, and it has the characteristics of low voltage, high power, and short torque pulsation. Therefore, 5-phase PMSM can light the requirements of great concert AC transmission power and protection and dependability, and has broad demand prospects in novel energy electric cars and electric momentum airplanes [3]. Model predictive control (MPC) is an enhanced mechanism technique that has been hotly studied recently. A great number of research results show that MPC is the third great control mechanism technique for AC motors after vector control (VC) and direct torque control (DTC), and its comprehensive performance

is better than VC and DTC [4]. Rendering to different optimization methods, MPC is separated into MPC and constant set MPC [5]. MPC is a control algorithm built on the disconnected numerical type of the inverter. It can choose the finest switching state from a restricted number of switching states by inventory. Consequently, it does not require a modulator to create a pulse width modulation (PWM) drive signal, and can also effectively solve the nonlinear delinquent of the inverter [6]. MPC is simple to implement and has fast dynamic response, making it suitable for controlling multi-variable, nonlinear PMSM [7].

MPC for PMSMs is primarily divided into two categories: model-predictive torque control and MPCC, which control flux, torque, and stator dq-axis currents, individually. MPC uses the current scheme state to calculate the next state and then uses an objective function to choose the best voltage vector that balances the cost of each controlled variable. Therefore, state prediction and best voltage vector choice are key technologies for MPC implementation. In the MPC cost function, due to the different dimensions of the controlled variables, reasonable weight coefficients must be matched to achieve system stability.

However, current research still struggles to create a numerical relationship between the weight coefficients and the regulated variables. Therefore, the weight coefficients cannot be obtained analytically and are primarily determined through trial-and-error adjustments in simulations or experiments [8]. The main drawbacks of this trial-and-error method are its complexity and limited versatility. The weight coefficients must be readjusted when system parameters and operating conditions change. Therefore, the adjustment of weight coefficients is a research difficulty in model predictive control, which limits the request and expansion of MPCC in the arena of motor regulator [9].

2. Materials and Methods

2.1 Model of a 5-Phase PMSM

The 5-phase PMSM drive circuit is displayed in Figure 1. The inverter's DC source voltage is U_{dc} . By regulating the switching of the inverter's 5-phase link legs, the inverter's AC output side generates 5-phase AC power with a phase shift of 72° , creating a round revolving magnetic field in the planetary to drive the 5-phase PMSM.

Assume that the stator winding comprises only the basic and 3rd harmonics, disregarding the effects of additional greater-order harmonics. Based on the organized conversion, the 5-phase currents i_a, i_b, i_c, i_d, i_e can be equal to the currents $i_{d1}, i_{q1}, i_{d3}, i_{q3}$. In the revolving organizational scheme. Their dynamic equations can be expressed as follows:

$$\frac{di_{d1}}{dt} = -\frac{R_s}{L_d} i_{d1} + \frac{L_q}{L_d} \omega_e i_{q1} + \frac{1}{L_d} u_{d1} \quad (1)$$

$$\frac{di_{q1}}{dt} = -\frac{R_s}{L_q} i_{q1} - \frac{L_d}{L_q} \omega_e i_{d1} + \frac{1}{L_q} u_{q1} - \frac{\psi_f}{L_q} \omega_e \quad (2)$$

$$\frac{di_{d3}}{dt} = -\frac{R_s}{L_{ls}} i_{d3} + \frac{1}{L_{ls}} u_{d3} \quad (3)$$

$$\frac{di_{q3}}{dt} = -\frac{R_s}{L_{ls}} i_{q3} + \frac{1}{L_{ls}} u_{q3} \quad (4)$$

Where: $i_{d1}, i_{q1}, u_{d1}, u_{q1}$ Are the d-axis and q-axis mechanisms of the stator current and voltage in the important frequency space; $i_{d3}, i_{q3}, u_{d3}, u_{q3}$ Are the dq-axis mechanisms of the stator current and voltage in the 3rd harmonic frequency space; R_s is the stator resistance; L_d and L_q are the dq-axis stator inductances, correspondingly; L_{ls} is the stator leakage inductance; ω_e is the rotor electrical angular velocity; ψ_f Is the flux linkage of the permanent magnet.

2.2 Space voltage vector of a 2-level 5-phase inverter

The two-level 5-phase inverter can provide 32 spatial voltage vectors, counting 30 effective voltage vectors and 2 zero voltage vectors [10]. Define (Sa, Sb, Sc, Sd, Se) (S

represents the state of each bridge arm, $S \odot 1$ when on and $S \odot 0$ when off). Figures 2 show the distribution of these spatial voltage vectors in the d_1 - q_1 (two-phase stationary coordinate system when the rotation speed is zero) and d_3 - q_3 coordinate systems. According to the magnitude of the voltage vector in the d_1 - q_1 coordinate system, it is divided into four categories, as shown in Table 1. The large vector and small vector in the d_1 - q_1 coordinate system are mapped to the small vector and large vector in the d_3 - q_3 coordinate system, respectively [11]. The rich voltage vectors in the five-phase inverter provide more options for the selection of the control set in the FCS-MPTC algorithm.

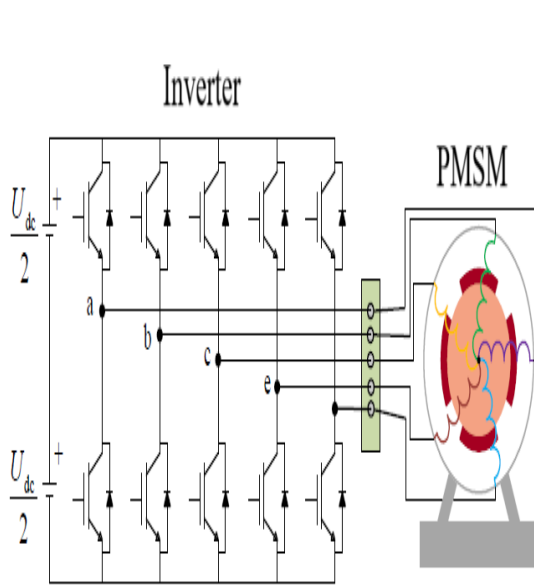


Figure 1. 5-phase PMSM system

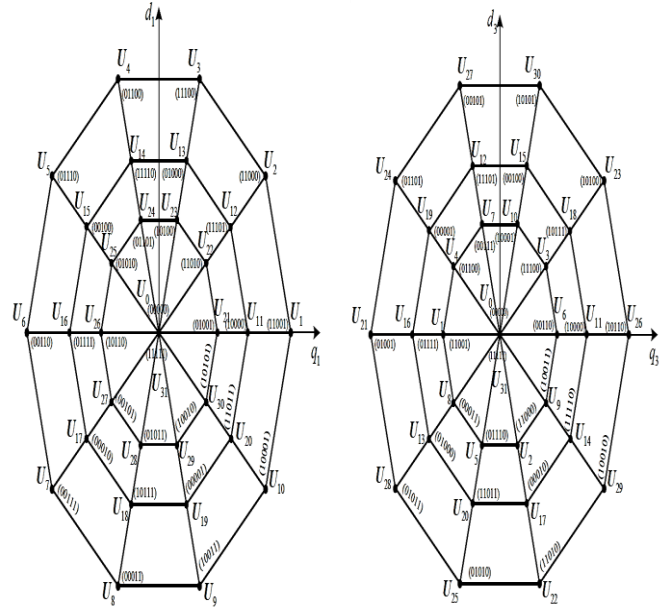


Figure 2. Voltage vector of a 5-phase inverter

2.3 Traditional MPCC of 5-Phase PMSM

The block illustration of the MPCC architecture for a 5-phase PMSM is illustrated in Figure 3. The regulated adjustable comprises speed, basic currents i_{d1} and i_{q1} , and 3rd sympathetic currents i_{d3} , i_{q3} . Speed is controlled via a PI regulator, while the basic and sympathetic currents are optimized, consuming an objective function. Model-predictive current control periodically monitors stator current, predicts system states, and selects the optimal voltage vector, achieving online progressive optimization [12]. First, the current speed mistake is calculated, and the speed regulator converts the error signal into a stator q-axis current reference command i_{q1}^* . Second, the current stator current is measured, and the basic and 3rd harmonic currents for the subsequent instant are intended based on the current forecast model [13]. Third, the forecast current and its reference command are fed into the objective function to choose the best voltage vector that balances the current of the stator basic and 3rd sympathetic currents. Lastly, the best voltage vector is transformed into the regulator indication for the heavy 5-phase PMSM.

Based on the Euler method, the constant typical of the 5-phase PMSM is discretized. The differential of the stator current can be articulated using a discrete-time model: where T_s , k , are the mechanism period, the current time, and the earlier time, correspondingly [14]. Moving the current time k forward by one time, the stator current prediction model at time $k+1$ is attained:

$$i_{d1p} = \left(1 - \frac{R_s T_s}{L_d}\right) i_{d1}(k) + T_s \omega_e(k) i_{q1}(k) + \frac{T_s}{L_d} u_{d1}(k) \quad (5)$$

$$i_{q1p} = \left(1 - \frac{R_s T_s}{L_q}\right) i_{q1}(k) - T_s \omega_e(k) i_{d1}(k) + \frac{T_s}{L_q} u_{q1}(k) - \frac{T_s \psi_f}{L_q} \omega_e(k) \quad (6)$$

$$i_{d3p} = \left(1 - \frac{R_s T_s}{L_{ls}}\right) i_{d3}(k) + \frac{T_s}{L_{ls}} u_{d3}(k) \quad (7)$$

$$i_{q3}p = \left(1 - \frac{R_s T_s}{L_{ls}}\right) i_{q3}(k) + \frac{T_s}{L_{ls}} u_{q3}(k) \quad (8)$$

Where $i_{d1}p, i_{q1}p, i_{d3}p, i_{q3}p$ Are the forecast currents in the fundamental and 3rd harmonic spaces, correspondingly. $u_{d1}(k), u_{q1}(k), u_{d3}(k), u_{q3}(k)$ Are the output voltages of the 5-phase inverter.

Objective Function: After completing the predictions for a piece regulated variable, the cost function combines the forecast and orientation values of all regulated adjustable into a function to quantify the difference between the system's next state and the desired state, thereby selecting the optimal state and its corresponding voltage vector [15]. The objective function g is constructed by subtracting $i_{d1}p, i_{q1}p, i_{d3}p, i_{q3}p$ from their respective reference commands and match them with the corresponding weight coefficients:

$$g = |i_{d1}^* - i_{d1}p| + |i_{q1}^* - i_{q1}p| + \lambda[|i_{d3}^* - i_{d3}p| + |i_{q3}^* - i_{q3}p|] \quad (9)$$

Where: λ is the weight coefficient of the 3rd sympathetic current; $i_{d1}^*, i_{q1}^*, i_{d3}^*, i_{q3}^*$ these are the reference values of the basic current and the 3rd sympathetic current, respectively. Since the harmonic space of the surface-mounted 5-phase PMSM does not participate in the electromechanical energy conversion, to suppress the 3rd harmonic current, $i_{d1}^* = i_{d3}^* = i_{q3}^* = 0$. The objective function value for a piecewise voltage vector is intended spending Equation (8). The lesser the objective function value, the lesser the sum of the stator current mistakes and the healthier the mechanism concert of the scheme. So, the voltage vector with the least objective function value is the best voltage vector for the scheme.

2.4 Improved MPCC of 5-Phase PMSM

The MPCC algorithm, based on an improved cost function, eliminates third-harmonic voltages during virtual voltage vector synthesis. For a 5-phase PMSM with a sinusoidal stator winding distribution and no third-harmonic permanent magnets, no third-harmonic current is generated. This simplifies the prediction equation and evaluation function:

$$i_{d1}p1 = \left(1 - \frac{R_s T_s}{L_d}\right) i_{d1}p + T_s \omega_e(k) i_{q1}p + \frac{T_s}{L_d} u_{d1}p \quad (10)$$

$$i_{q1}p1 = \left(1 - \frac{R_s T_s}{L_q}\right) i_{q1}p - T_s \omega_e(k) i_{d1}p + \frac{T_s}{L_q} u_{q1}p - \frac{T_s \psi_f}{L_q} \omega_e p \quad (11)$$

$$g = |i_{d1}^* - i_{d1}p1| + |i_{q1}^* - i_{q1}p1| \quad (12)$$

3. Results and Discussion

A 5-phase PMSM simulation platform was built in MATLAB/Simulink to confirm the precision of the projected technique. The factors of the 5-phase PMSM are in Table 1. To address the relevant issues in the above research, this paper proposes an MPCC method to improve the performance of a five-phase PMSM driven by a two-level voltage source inverter (VSI). First, a five-phase PMSM operating model is established under natural operation.

Non-zero switching states that generate large voltage vectors in the d-q subspace are selected as candidate states. Based on the selected voltage vectors, an SVM method is proposed. Finally, a simulation platform is built to verify the effectiveness of the proposed method.

By selecting the value function vector and performing non-analytical optimization, MPCC was achieved over a wide speed range, thereby ensuring that the motor operates stably in a predetermined manner within different speed ranges and improving the steady-state performance of the system. However, the duty cycle control or MPCC control strategy in the above studies cannot eliminate the voltage vector error.

Figures 4 and 5 show that both conventional MPCC and improved MPCC have good dynamic performance, but improved MPCC has lower torque ripple and stator current

harmonic content. The torque ripple for conventional MPCC is 9.66%, while that for improved MPCC is 1.96%. Improved MPCC on the torque ripple discount.

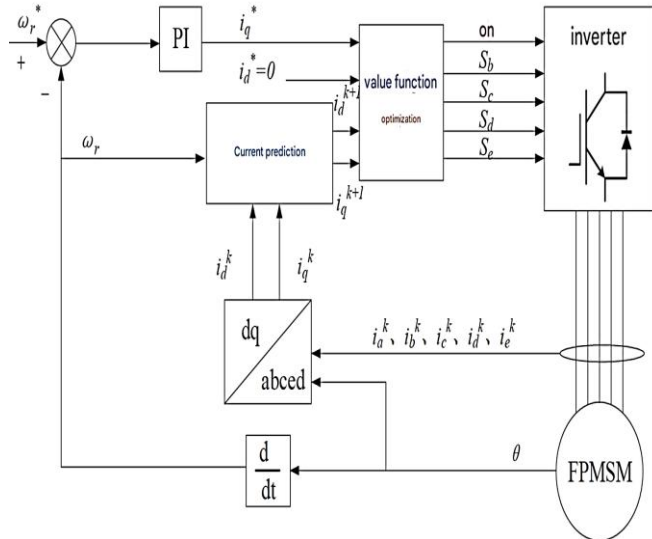


Figure 3. Block illustration of the MPCC of the 5-phase PMSM.

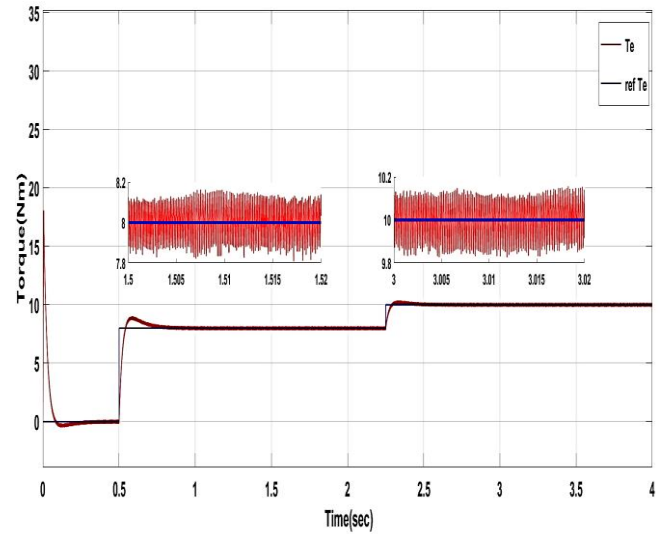
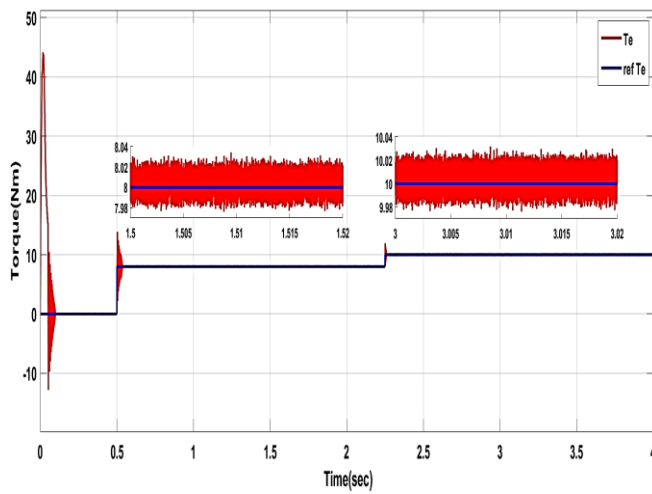


Figure 4. Torque traditional MPCC



(a) Figure 5. Torque with improved MPCC

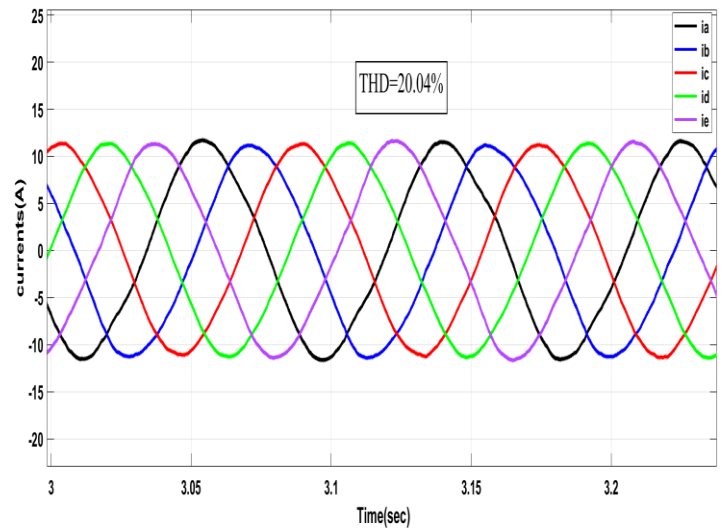


Figure 6. Measured 5-Phase PMSM Currents with traditional MPCC

Table 1. This System factors of MPCC for 5-phase PMSM

Parameter	Value	Unit
TL	12	N.m
Udc	300	V
p	3	-
Rs	0.5	Ω
Ld=Lq	12.4	mH
J	0.02	kg. m ²
flux	0.09	Wb

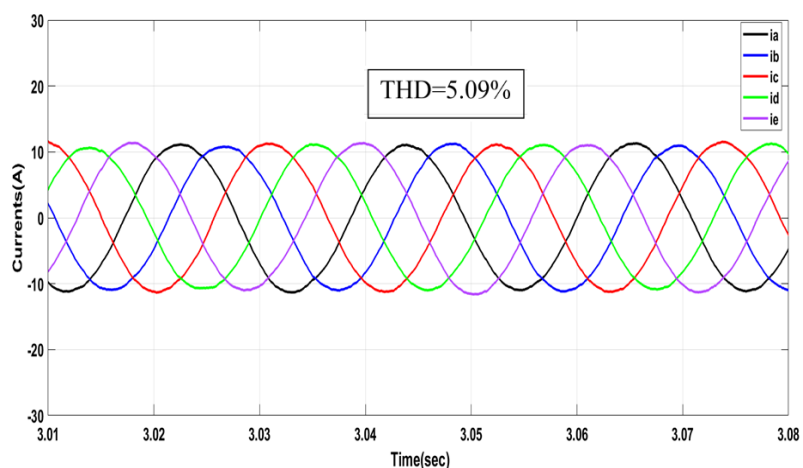


Figure 7. Measured 5-Phase PMSM Currents with improved MPCC

5. Conclusions

This paper proposes an MPC for a 5-phase PMSM, addressing the cumbersome weight coefficient tuning problem. By setting the control priority of the basic and harmonic currents, a cost function is established for the structure. This objective function selects the best voltage vector that balances fundamental and harmonic current performance without requiring weight coefficients. The cost function structure can be modified based on system performance requirements, including a fundamental current optimization scheme to improve output torque and a harmonic current optimization scheme to eliminate the third harmonic of the stator current. Simulation results demonstrate that the proposed method, which eliminates the need for weight coefficients when controlling a five-phase PMSM, achieves superior current harmonic suppression and dynamic response speed compared to traditional MPC.

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