Non-CascadeSpeed and Current Control of IPMSM for Electrical Vehicles based on Model Predictive Control

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Abstract. In this paper, the speed tracking problem of the interior permanent magnet synchronous machines (IPMSM) of electric vehicle is studied. A non-cascadespeed and currentcontrol strategy based on model predictive control (MPC) is proposed, which combines the speed and current control together compared with traditional cascade control. The design of the non-cascade controller takes into account the effects of load torque and d-q axis current coupling properties. Furthermore,the controller enforces both the current and the voltage limits.Finally, the simulation results show its validity and superiority of the proposed method.

Keywords: *Non-cascade, Model Predictive Control, Speed and Current Control, Interior Permanent Magnet Synchronous Motor.*

1. INTRODUCTION

With the continuous increase of car ownership, environmental pollution and lack of oil resources have increased. The clean, efficient and safe electric vehicle has become more importantin the development of automobiles. No matter what kind of electric vehicle, the dynamic performance and the electric-only range depend greatly on the drive motor. At present, the permanent magnet synchronous motor has become the mainstream driving motor of electric vehicle owing to high efficiency, high power density and high reliability [1], especially the built-in permanent magnet synchronous motor (IPMSM). IPMSM has become the ideal driving motor of electric vehicle, which has wide-range smooth speed regulation, light weight and small volume. Since the operation condition of electric vehicle is complicated, it demands high speed regulation range, dynamic response and robustness. The traditional PI control method cannot meet the requirement of control performance. To get better performance, many methods have been studied, such as backstepping control [2], adaptive control [3], robust control [4], sliding model control [5],fuzzy control [6], etc.All of these methods improve the control performance of the motor from different aspects.

In other hand, there are many research results of MPC in the PMSM servo system because of its robustnessand advantage in constraint processing ability, and the precise linear model of driving motor has also promoted the application of MPC in PMSM [7-9]. In [7] the PMSM control method based on explicit MPC is used, which adopts a novel linearization and constraint processing method. In [8], an improved model predictive current control strategy is proposed, which makes the future state of stator current dependent on the estimation of the back electromotive force rather than the system model. In [9], the PMSM speed loop and the current loop model prediction controller are designed, and the interference model to suppress current measurement error is added in the speed loop to improve the control accuracy. Up to now, many MPC methods for PMSM current loop has been researched, but few for the combined speed-current loop.

This paper presents a non-cascadespeed and current MPC method for IPMSM, which combines the speed and current controller in one controller to simplify the control structure. In this way, the constraints of the system, such as the current limitation on the quadrature-axis, can be enforced during the control volume solution process.

This paper is organized as follows. The Section 2 introduces the mathematical model of IPMSM. The Section 3 presents the design details of MPC method in IPMSM. The simulation result is presented in Section 4. A conclusion is given in Section 5.

2. MATHEMATIC MODEL OF IPMSM

For the electrical subsystem of the drive, a synchronous reference frame (d, q), with the d-axis fixed to the stator IPMSM flux linkage vector, is considered, as it lets all the electrical variables equal a constant value at steady state.Assuming the IPMSM model without considering the motor core saturation, hysteresis, eddy current and other losses, the rotor without windings, and permanent magnets without damping e□ect, the induced electromotive force waveform of the phase winding is sinusoidal waveform.The mathematic model of the IPMSM can be described by the following equation:

$$\begin{aligned} \frac{di_d}{dt} &= -\frac{R}{L_d} i_d + \frac{L_q}{L_d} \omega i_q + \frac{u_d}{L_d} \\ \frac{di_q}{dt} &= -\frac{L_d}{L_q} \omega i_d - \frac{R}{L_q} i_q - \frac{\psi_f}{L_q} \omega + \frac{u_q}{L_q} \end{aligned} \quad (1)$$

where variables $u_d, u_q, i_d, i_q, L_d, L_q$ are the d-axis voltage, q-axis voltage, d-axis current, q-axis current, d-axisinductance and q-axis inductance, respectively;variables ω, R, ψ_f are the electrical angular velocity, stator resistance, and rotor flux, respectively.

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The mechanical dynamics is derived from the torque balance, which can be described as:

$$\frac{d\omega}{dt}=\frac{3}{2}\frac{p_n^2}{J}(\psi_f+(L_d-L_q)i_d)i_q-\frac{B}{J}\omega-\frac{p_n}{J}T_L \qquad (2)$$

where, p_n is the number of pole pairs, J is the moment of inertia, B is the viscous coefficient of the load, and T_L is the disturbance torque.

Equation (1) and (2) are the state equations of the IPMSM. From the equations of the state, it's obvious that IPMSM is a typical nonlinear, multivariable and strong coupling system. The nonlinear and coupling terms are reflected in ωi_d,ωi_q.It's necessary to linearize the nonlinear equation above to solve MPC optimization problems.

The control strategy in this paper is the $i_d = 0$ rotor flux-oriented control. This control method ensures that there is only the excitation torque and no reluctance torque in the electromagnetic torque of the IPMSM, so that the output torque of the motor is proportional to the q-axis current, which is convenient to design the control algorithms. If i_d is kept null, the term ωi_d has generally little or no affect. But the effect of the term ωi_q cannot be ignored. The rotor speed ω is assumed to be a constant in one sampling period.Then the equations of state can be reduced as:

$$\begin{aligned}
\frac{di_d}{dt}&=-\frac{R}{L_d}i_d+\frac{L_q}{L_d}\omega i_q+\frac{u_d}{L_d}\\
\frac{di_q}{dt}&=-\frac{R}{L_q}i_q-\frac{\psi_f}{L_q}\omega+\frac{u_q}{L_q}\\
\frac{d\omega}{dt}&=\frac{3}{2}\frac{p_n^2}{J}\psi_f i_q-\frac{B}{J}\omega-\frac{p_n}{J}T_L
\end{aligned} \qquad (3)$$

As both ωand i_q can be available for measurement in the drive, the term ωi_q will then be considered as a measured disturbance and is included in the model. Define the state vector of the system as:

$$x=[i_d \;\; i_q \;\; \omega i_q \;\; \omega]^T \qquad (4)$$

Define the control vector as $u = [u_d, u_q]^T$, the disturbance as $d = T_L$. Then the state equation (3) is transformed into the following standard form:

$$\dot{x} = A_c x + B_c u + B_{dc} d \qquad (5)$$

where,

$$A_c=\begin{bmatrix}-\frac{R}{L_d} & 0 & \frac{L_q}{L_d} & 0\\ 0 & -\frac{R}{L_q} & 0 & -\frac{\psi_f}{L_q}\\ 0 & 0 & 0 & 0\\ 0 & \frac{3p_n^2}{2J}\psi_f & 0 & -\frac{B}{J}\end{bmatrix}$$

$$B_c=\begin{bmatrix}\frac{1}{L_d} & 0 & 0 & 0\\ 0 & \frac{1}{L_q} & 0 & 0\end{bmatrix}^T, B_{dc}=\begin{bmatrix}0 & 0 & 0 & -\frac{p_n}{J}\end{bmatrix}^T$$

3. DESIGN OF NON-CASCADE SPEED AND CURRENT CONTROLLER BASED ON MPC

3.1. Structure of Control System

The system structure diagram is shown in Fig 1, which consists of an IPMSM, space vector pulse width modulation (SVPWM), three-phase voltage inverter, coordinate transformation, and non-cascadespeed and current controller based on MPC.

The input voltages of the IPMSM are limited by the direct-current(DC) bus voltage V_{dc} of the inverter. The control output u_d,u_q is limited at an appropriate value to filter out unreasonable large control variable.

3.2. Discrete-time Model

The continuous state equation (5) are discretized according to sampling time T_s . Define $A_k = e^{A_c T_s}$, $B_k =$

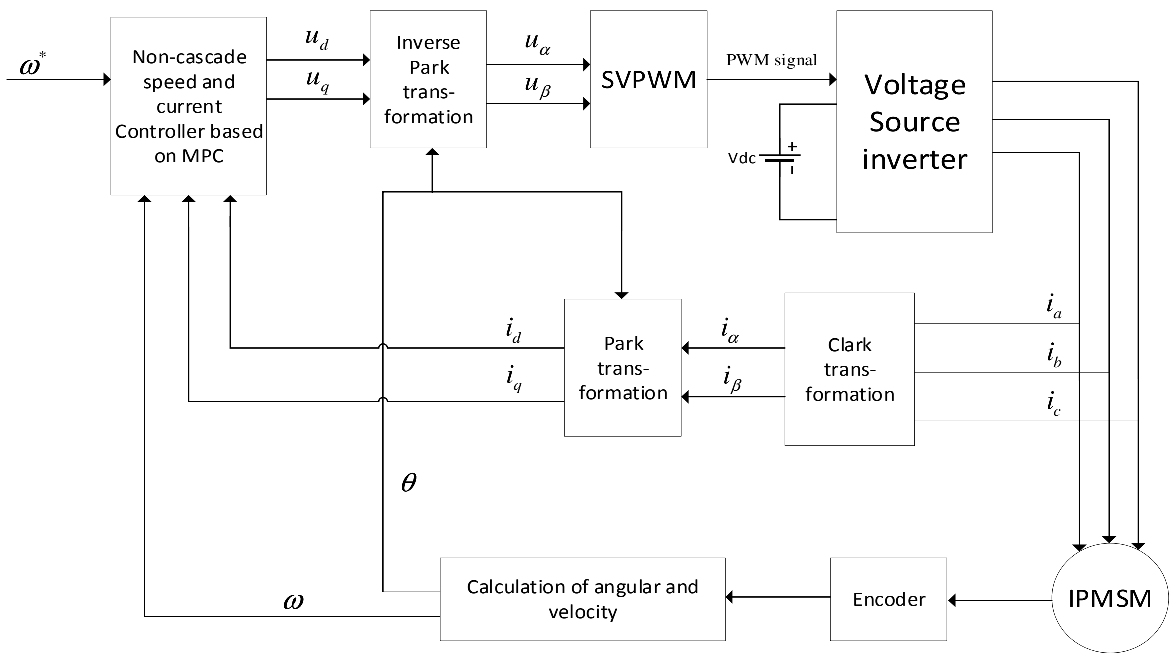

Fig.1Block diagram of IPMSM control system based on MPC

$\int_0^{T_s} e^{A_c t} dt \cdot B_c$, $B_{dk} = \int_0^{T_s} e^{A_c t} dt \cdot B_{dc}$,where T_s is the sampling period. The discretized equation can be expressed as:

$$x(k+1) = A_k x(k) + B_k u(k) + B_{dk} d(k) \quad (6)$$

3.3. State Augmentation

Load torque is generally considered as a constant during a sampling period. In order to eliminate the constant interference d(k) in the equation (6), consider using the increment model, define

$$\Delta x(k+1) = x(k+1) - x(k) \quad (7)$$

then the equation (6) can be expressed as:

$$\Delta x(k+1) = A_k \Delta x(k) + B_k \Delta u(k) \quad (8)$$

The main goal of the IPMSM speed control system for electric vehicles is to achieve dynamic tracking of the speed under the constraints.There are two constraints for the current. D-axis current $i_d$is excepted to be zero, and q-axis current $i_q$must be less than the maximum value of the motor armature current. Butequation (8) does not contain $i_q$and ω terms. In order to add the above constraints to the optimization objective, consider resetting the state vector as:

$$\hat{x} = [\Delta i_d \ \Delta i_q \ \Delta \omega i_q \ \Delta \omega \ i_d \ i_q \ \omega i_q \ \omega]^T \quad (9)$$

Then the new state equation can be expressed as:

$$\hat{x}(k+1) = \begin{bmatrix} A_k & 0 \\ A_k & I \end{bmatrix} \hat{x}(k) + \begin{bmatrix} B_k \\ B_k \end{bmatrix} \Delta u(k) = \hat{A}\hat{x}(k) + \hat{B}\Delta u(k) \quad (10)$$

3.4. Definition of the Cost Function

Define the output equation as:

$$y(k) = C_d \hat{x}(k) \quad (11)$$

where $C_d = [0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 1]$. So $y(k)$ is the speed at time k.

The purpose of the control is to ensure that the actual speed follows the setpoint and that the rate of change of the control variable is as small as possible.The performance index function is considered to set as:

$$\begin{aligned} \min J &= \sum_{k=1}^{N} (r(k) - y(k))^T Q_k (r(k) - y(k)) \\ &+ \Delta u^T (k-1) P_{k-1} \Delta u(k-1) \quad (12) \\ &= (R-Y)^T Q (R-Y) + \Delta U^T P \Delta U \end{aligned}$$

where, $r(k)$ is the given value of the speed, $Q = Q^T \geq 0$ weighs the error vector, $P = P^T \geq 0$ weighs the control vector.

In order to improve the closed-loop dynamic performance of the system, the reference trajectory of the transition from the current output $y(k)$ to the setting value c is given as:

$$r(k+1) = \alpha r(k) + (1-\alpha) c \quad (13)$$

where, $r(k+1)$ is the expected output of the speed at time $k+1$, $r(k)$ is the actual speed at time k , and c is the desired stable speed, $0 \leq \alpha < 1$. Choosing larger α can enhance the robustness of the system, but the rapidity of control will be worse.

3.5. Optimal Problem for Speed Tracking

The complete formulation of the optimal control problem for setpoint tracking can be expressed as:

$$\min J = \frac{1}{2} \sum_{k=1}^{N} e^T(k) Q_k e(k) + \Delta u^T (k-1) P_{k-1} \Delta u(k-1) \quad (14)$$

subject to,

$$\begin{aligned} &\hat{x}(k+1) = \hat{A}\hat{x}(k) + B\Delta u(k) \\ &y(k) = C_d \hat{x}(k) \\ &e(k) = r(k) - y(k) \quad (15) \\ &i_d = 0 \end{aligned}$$

the state variable boundis:

$$\begin{aligned} &| i_d | \leq i_{dm} \\ &| i_q | \leq i_{qm} \quad (16) \\ &| \Delta i_q | \leq i_{qm} \end{aligned}$$

The subscript m represents the maximum value. This constraint means that the q-axis current and its rate of the change are limited. $i_{dm}$is a coefficient positivenumber. As i_d is excepted to be zero, this limitation is somehow acceptable.

The above linear quadratic optimization control problemeq.(14) to eq.(16) can be expressed in the form of a standard quadratic programming. Then the control variable ΔUcan be obtained.

4. SIMULATION RESULT

The parameters of IPMSM are selected from Toyota Prius Hybrid vehicles, as shown in table 1.

In the sinusoidal modulation, the maximum effective value of line voltage fundamental wave output by SVPWM inverter is $\sqrt{2}U_{dc}/2$, and the modulation ratio can reach 1. Therefore, the DC-bus voltage of the inverter can be selected according to the peak value of the rated voltage of the motor, that is, $U_{dc} = \sqrt{2}U_N K_0$, where k_0 is the safety factor given in consideration of the loss of switching elements, generally $k_0 = 1.1$. Thus, the DC-bus voltage is selected as 778V, the PWM switching period is 0.0001s.

Table.1 IPMSM parameters.

Description	Values	Units
ψ_f(Rotor flux)	0.035	Wb
L_d	0.169	mH
L_q	0.331	mH
R_s(Resistance of stator)	0.07	Ω
J(Moment of inertia)	0.1312	$kg \cdot m^2$
p_n(Poles)	4	
U_N	500	V
I_N	250	A

The parameters of MPC method are chosen as: the prediction horizon is $N = 5$, the weighting matrices are $P_1 = P_2 = P_3 = \cdots = P_N = diag[50 \ 0.1]$, $Q_1 = Q_2 = Q_3 = \cdots = Q_N = 30000$,the constraints are, $\Delta i_{qm} = 70$, i_{qm}=250. The sampling time is $T_s = 1\mathrm{e} - 4$.

The initial speed is given as 1000r/min, and it drops to 500r/min at 0.4s. The initial load torque is 0, and the load torque of 50N.m is suddenly applied at 0.3s and keeps invariant. The response curves are shown with Fig. 2 to Fig. 5.

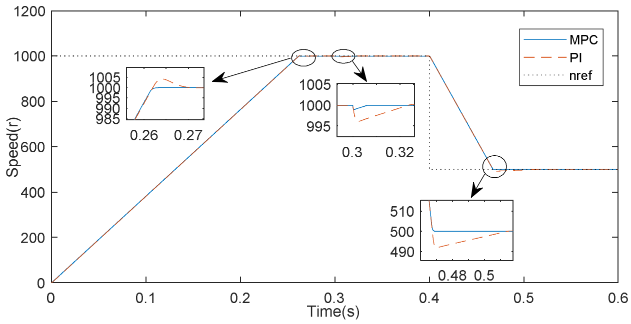

Fig.2Speed response

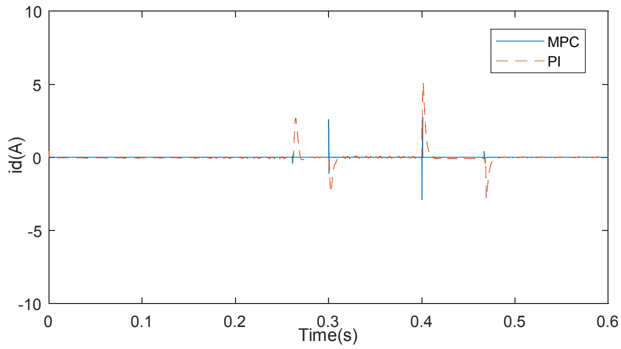

Fig.3 Direct axis current response

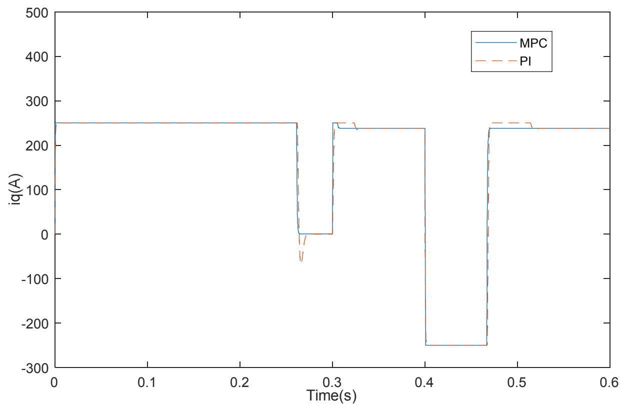

Fig.4Quadrature axis current response

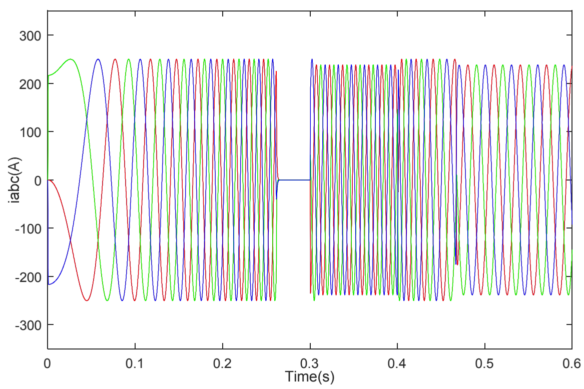

Fig. 5 Stator three-phase current waveforms of MPC

Fig.2 shows speed response of IPMSM under the conditions of starting, abrupt change of load and decelerate to half the original speed.The label *nref* refers toexcepted speed.The first enlarged portion is under the condition that the motor reached the rated speed 1000r/min with no load torque. The second enlarged portion is under the condition that the load torque of 50N.m is suddenly applied and the speed keep invariant. The third enlarged portion is under the condition that the speed reduce to 500r/min with 50N.m load torque. This paper compares the simulation results of the MPC method with the traditional PI controller. From the Fig.2, it can be seen that there is no overshoot if the motor using the MPC method when the speed reaches the given value. When the load torque of 50N.m is suddenly applied, the speed of the system using MPC has only a very small drop and it resumes the setpoint operation in a very short time. When the speed is decreased at $0.4s$, the curve using MPC can quickly follow the given value, and there is no overshoot when reaching the given speed. It's obviously that the traditional PI method has poorer performance than the MPC method.

Fig. 3 and Fig. 4 are the responseof the d-axis current and the q-axis current, respectively. In Fig. 3, i_d only oscillates slightly near the 0 value when the system reaches a steady state, and its average value is 0. Compared to PI, MPC has a smaller peak value. In Fig. 4, i_q quickly reaches the maximum value of $250A$ during the start-up phase, which maximizes the electromagnetic torque to rapidly increase the motor speed. When the speed reaches the given value, i_q decreases to zero rapidly. Then the motor is under the steady state. When the load torque is suddenly applied, i_q increases rapidly to resist load disturbance. The motor recoveries to the given speed. When the speed decreases, i_q rapidly reaches the reverse maximum value and the maximum reverse electromagnetic torque is obtained. The motor is quickly braked and resumes steady state when the speed is equal to a new given value. From the comparison of the two method, it can be seen that the curve using MPC is almostno overshoot and has shorter setting time than PI. From Fig.3 and Fig.4, we can see that the constraints $i_d = 0, |i_q| \le 250A$ are satisfied well, and the system using MPC method have better performance than PI.

Fig. 5shows the three-phase AC current waveform of the stator using MPC method. From the figure, its value is zero when there is no load torque. When the load torque is added, the steady-state frequency is determined by the set-point of speed, and the value in steady-state is determined by the load torque. The dynamic adjustment process is similar to thatof q-axis current, which further verifies the effectiveness of the proposed control strategy.

5. CONCLUSION

This paper presents the application of non-cascadespeed and current control strategy based on MPC in IPMSM speed tracking problem. The designed controllerintegrates combines the traditional speed control and the current control. The controller has a simple structure, fast dynamic response, and good robustness. By comparing with traditional PI control, the effectiveness and superiority of the designed controller based on MPC are verified.

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