



Position Control Improvement of Permanent Magnet Motor Using Model Predictive Control

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ABSTRACT

Fast and accurate transient response is the main requirement in electric machine position control. Conventional cascade control structure has sluggish response due to the limitation of inner control loop bandwidth. In this paper, in order to decrease the Permanent Magnet Synchronous Motor (PMSM) transient response time it can be used reference model using feed-forward signals. In this structure, feed-forward signals generated by simplified model of permanent magnet synchronous motor. In this paper, feed-forward signals generated are employed in model predictive control; which are combined with conventional cascade control structure. Using this approach, a fast transient response and satisfactory tracking ability will be guaranteed. The proposed method is compared with the model reference method and conventional cascade structure. Simulation results showed a good performance of proposed method related to both methods. Verification of simulation results were carried out by experimental results

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NOMENCLATURE

T_{oi}	Time constant of PMSM	V_d, V_q	d and q axis volatges
K_1, K_2	Controller coefficients	B	Damping coefficient
J	Moment of inrtia	P	Number of poles
K_i	Inverter coefficient	Greek Symbols	
T_s	time step	ω_m	Angular speed
i_d, i_q	d and q axis currents	θ_m	Position
L_d, L_q	d and q axis inductances	ψ_{pm}	Permament magnet flux

1. INTRODUCTION

Extensive literatures have been published in field of Permanent Magnet Synchronous Motor (PMSM) speed control; which is generally focussed on improvement of transient response. A new approach to estimate states and parameters of the permanent magnet synchronous motor (PMSM) in the presence of unknown load torque disturbance is presented in literature [1]. Indeed, it

highlights an auxiliary dynamics that is added to the PMSM model. The observer estimates position and motor speed as well as but it is sensitive to the mechanical parameters variation such as motor load, inertia and other noises. To overcome this difficulty some alternatives such as hybrid and robust controller [2], robust model reference adaptive control [3] and robust controller with adaptive disturbance observer were reported in literature [4, 5]. A feed-forward signal with disturbance observer based on transient response is discussed in literature [6]. However, the nonlinear behavior characteristics of power converter has not been

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included in linearization model therefore the estimated disturbance torque can be higher than actual one. Iterative feed-forward controller combined with conventional PID is used to accurate position control. The performance of this method related to the unpredictable disturbance and torque variation is high but it may generate high oscillations.

A deadbeat load torque observer with system parameters compensator can be used to improve the performance of a PMSM position control [7]. In this method, PMSM operate by force at nominal condition. Therefore it can eliminate the steady-state and transient errors which are caused by distortion signals such as friction and load torque. A robust controller with variable structure control (VSC) and linear quadratic (LQ) method has been introduced for accurate position control [8]. It is used for obtaining precise control when the variation of motor parameters is considered. Usually the electric motor can be expressed as a second-order state-space model with mechanical speed and rotor position as states. Based on this concept, LQ method is an appropriate solution to overcome the control system requirements. The control drawback of this technique when an external distortion or parameter uncertainty exists, is poor [8]. Other methods for PMSM position control have been presented based on principle of maximum torque per ampere (MTPA) and Port Controlled Hamiltonian (PCH) systems theory which have been studied [9] or artificial neural network (ANN) which is discussed in literature [10, 11]. PI controller with automatic adjustment strategy utilizes the adaptive recurrent Chebyshev neural network control was employed in literature [12].

Controller design with high efficiency and fast transient response for position control of PMSM is interesting for engineers. With development of microprocessors, implementation of complicated control strategy has been simplified in recent years. One of these control methods that has been highly used is Model Predictive Control (MPC). This control method offers several advantages in motor drive application. The some advantages are stated as follows:

- Understandable and simple concept
- Multiple systems operation capability
- Limitation and nonlinear characteristics can be considered easily.
- Multivariable systems can be considered easily.
- The implementation of this method is simple [13].

MPC requires high calculation resources related to the classical control schemes. MPC is a relatively old approach that first idea was published more than 20 years ago [14]. This strategy based on an explicit model of identifiable system to predict system behavior in the future and selection of the optimal control instructions. In recent years, this method for control of electrical drives was considered because:

- Linear models explicitly of electrical drive which is derived by computational tools and identification techniques are available [15].
 - Electric drive limitation can be used in MPC easily.
- MPC is employed as design of PMSM current controller [15]. MPC have been employed to design a speed controller [16, 17]. In addition, the MPC algorithm is applied to the speed control based on cascade structure [18]. In this paper, we used MPC to position control of PMSM for obtaining a fast and accurate transient response.

2. REFERENCE MODEL CONTROLLER

The transient response performance of PMSM position control based on cascade structure is low because of high number of inner control loops. In order to decrease the PMSM transient response time it can be used reference model using feed-forward signals. Therefore using position, speed and current as feed-forward signals the output transient response time would be improved. Producing these signals is carried out by reference model of PMSM which is illustrated in Figure 1.

In Figure 1 the “R” is the mechanical angle as output signal, T_{oi} is time constant of PMSM and K_1 , K_2 , J , K_i are controller coefficients, moment of inertia and inverter coefficient, respectively. In reference model structure fast transient response is important therefore, we use the proportional controller in this structure instead of PI or PID. The transfer function of the reference model which has been illustrated in Figure 1 is expressed in Equation (1):

$$\frac{R}{\theta_{ref}} = \frac{1}{1 + K_2 s + \frac{JK_i}{K_1} s^2 + \frac{JK_i T_{oi}}{K_1} s^3} \quad (1)$$

In position control application the rotor position should not have any overshoot; therefore the transfer function of Equation (1) should not be have any conjugate poles. Then using pole placement method the controllers coefficients are obtained where in transfer function there are third order repeated real poles which is expressed in Equation (2):

$$\begin{aligned} (\alpha s + 1)^3 &= \alpha^3 s^3 + 3\alpha^2 s^2 + 3\alpha s + 1 \\ \alpha^3 s^3 + 3\alpha^2 s^2 + 3\alpha s + 1 &= \frac{JK_i}{K_1} T_{oi} s^3 + \frac{JK_i}{K_1} s^2 + K_2 s + 1 \\ \rightarrow \alpha &= \frac{-1}{3T_{oi}} \end{aligned} \quad (2)$$

By combination of Equations (1) and (2) the controller coefficients are calculated in Equation (3):

$$\begin{aligned} K_1 &= \frac{JK_i}{27T_{oi}^2} \\ K_2 &= 9T_{oi} \end{aligned} \quad (3)$$

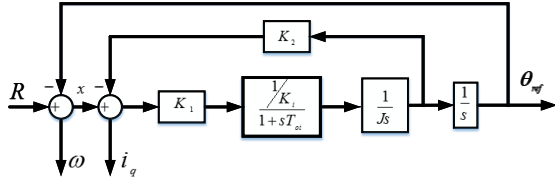


Figure 1. Reference model of PMSM

Consequently the transfer function of PMSM reference model is obtained in Equation (4):

$$\frac{\theta_{mech}}{\theta_{ref}} = \frac{1}{1 + 9T_{oi}s + 27T_{oi}^2s^2 + 27T_{oi}^3s^3} \quad (4)$$

3. PREDICTIVE MODELING OF PMSM

Dynamic equations of PMSM in rotor reference frame are expressed in Equation (5):

$$\frac{d}{dt} \begin{bmatrix} i_d \\ i_q \\ \omega_m \\ \theta_m \end{bmatrix} = \begin{bmatrix} \frac{-R_s}{L_d} & \frac{P\omega_m L_q}{L_d} & 0 & 0 \\ \frac{-P\omega_m L_d}{L_q} & \frac{-R_s}{L_q} & \frac{-P\psi_{pm}}{L_q} & 0 \\ 0 & \frac{3P}{2J}\psi_{pm} & \frac{-B}{J} & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ \omega_m \\ \theta_m \end{bmatrix} + \begin{bmatrix} \frac{1}{L_d} & 0 \\ 0 & \frac{1}{L_q} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} v_d \\ v_q \end{bmatrix} \quad (5)$$

where, ω_m , i_d , i_q , θ_m , L_d , L_q , V_d , V_q , P , ψ_{pm} , B , J are rotor speed, d and q axis current, d and q axis inductance, d and q axis stator voltage, poles, PM flux, friction coefficient and moment of inertia respectively. According to the goal of control, the rotor position is defined as output variable in Equation (6):

$$y = \begin{bmatrix} 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ \omega_m \\ \theta_m \end{bmatrix} \quad (6)$$

After discretization of Equation (5) using suitable time step T_s the motor equation is to be rearrangement in Equation (7):

$$\begin{bmatrix} i_d(k+1) \\ i_q(k+1) \\ \omega_m(k+1) \\ \theta_m(k+1) \end{bmatrix} = \begin{bmatrix} 1 - \frac{R_s T_s}{L_d} & \frac{P\omega_m L_q T_s}{L_d} & 0 & 0 \\ \frac{-P\omega_m L_d T_s}{L_q} & 1 - \frac{R_s T_s}{L_q} & \frac{-PT_s \psi_{pm}}{L_q} & 0 \\ 0 & \frac{3T_s P}{2J} \psi_{pm} & \frac{-BT_s}{J} & 0 \\ 0 & 0 & T_s & 1 \end{bmatrix} \begin{bmatrix} i_d(k) \\ i_q(k) \\ \omega_m(k) \\ \theta_m(k) \end{bmatrix} + \begin{bmatrix} \frac{T_s}{L_d} & 0 \\ 0 & \frac{T_s}{L_q} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} v_d(k) \\ v_q(k) \end{bmatrix} \quad (7)$$

where, k is the time step index. The Equation (7) shows clearly that PMSM drive system has been characterized by a series of non-linear equations, even if electrical and mechanical parameters of the motor are considered constant. To solve this problem, several methods are introduced in many articles. For example, Shan et al.

[19], have defined term " $\omega_m i_q$ " as an additional state. Although, this approach eliminates computation complexity but by adding a new state, calculation resources will increase. Other solution is system linearization around a given operating point. Linearization error of this method, while it works only around a given operating point is negligible. To overcome this difficulty, in this paper, a simplified model for PMSM is suggested. Figure 2 shows a transfer function of simplified model of PMSM which the d-axis current set to zero therefore the only q-axis current developed the output torque. In Figure 2 $u(t)$ is input of the motor (stator voltage) and n_p is the pole pairs. In simplified model which is illustrated in Figure 2 the states are considered as $x_1=i_q$, $x_2=\omega_m$, $x_3=\theta_m$. Therefore, system discrete state space equation is defined in Equation (8). Future outputs can be derived from Equation (8) that is expressed in Equation (9):

$$\begin{bmatrix} x_1(k+1) \\ x_2(k+1) \\ x_3(k+1) \end{bmatrix} = \underbrace{\begin{bmatrix} 1 - \frac{T_s}{T_{oi}} & 0 & 0 \\ \frac{3N_p \psi_{pm} T_s}{2J} & 1 & 0 \\ 0 & T_s & 1 \end{bmatrix}}_A \begin{bmatrix} x_1(k) \\ x_2(k) \\ x_3(k) \end{bmatrix} + \underbrace{\begin{bmatrix} \frac{T_s K_i}{T_{oi}} \\ 0 \\ 0 \end{bmatrix}}_B [u(k)] \quad (8)$$

$$y(k) = \underbrace{\begin{bmatrix} 0 & 0 & 1 \end{bmatrix}}_C \begin{bmatrix} x_1(k) \\ x_2(k) \\ x_3(k) \end{bmatrix}$$

$$\begin{aligned} y(k) &= x_3(k) \\ y(k+1) &= x_3(k+1) = T_s x_2(k) + x_3(k) \\ y(k+2) &= x_3(k+2) = \frac{3N_p \psi_{pm} T_s^2}{2J} x_1(k) + 2T_s x_2(k) + x_3(k) \\ y(k+3) &= x_3(k+3) = \frac{3N_p \psi_{pm} T_s^2}{2J} (3 + \frac{T_s}{T_{oi}}) x_1(k) + 3T_s x_2(k) + x_3(k) + \frac{3N_p \psi_{pm} T_s^2}{2T_{oi} J} u(k) \end{aligned} \quad (9)$$

According to Equation (9) if the future outputs are not to be limited so the amount of calculation resource s will be high. Therefore, the future output must be computed in limited forecast horizon (N_p) which is expressed in Equation (10):

$$\begin{bmatrix} y(k+1) \\ y(k+2) \\ \vdots \\ y(k+N_p) \end{bmatrix} = \begin{bmatrix} CA \\ CA^2 \\ \vdots \\ CA^{N_p-1} \end{bmatrix} \begin{bmatrix} x_1(k) \\ x_2(k) \\ x_3(k) \end{bmatrix} + \begin{bmatrix} CB & 0 & \dots & 0 \\ CAB & CB & \dots & 0 \\ \vdots & \vdots & \dots & \vdots \\ CA^{N_p-1} B & \dots & \dots & 0 \end{bmatrix} \begin{bmatrix} u(k) \\ u(k+1) \\ \vdots \\ u(k+N_p) \end{bmatrix} \quad (10)$$

where, A , B and C are defined in Equation (8) previously. Second step in MPC is introducing the suitable cost function for minimization of approximation error. In this paper the cost function "J" in matrix form is shown in Equation (11):

$$J = (y - y_d)^T Q (y - y_d) + U^T R U \quad (11)$$

where, R and Q are the weight matrixes, y_d is desired

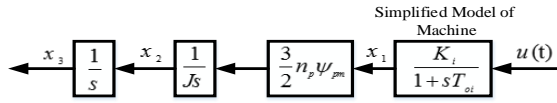


Figure 2. simplified model of PMSM transfer function

output and U is input signal. The term $U^T R U$ it may produce steady-state error at transient condition in the cost function J . Therefore, $U^T R U$ is replaced by $(u-u_{ss})^T R(u-u_{ss})$ where “ss” subscript is defined as steady-state value of the U signal. Since in the reference model U_{ss} is kept at zero value therefore there will no steady state error in the output transient response. In addition, the desired output signal y_d is achieved by applying a low pass filter with α order to the input signal is expressed in Equation (12). In this paper the low pass filter order is selected as $\alpha=0.83$ and the respective forecast horizons of the motor and control system are considered 12 and 3, respectively.

$$y_d(t+1) = \alpha y_d(t+i-1) + (1-\alpha)r(t+i) \tag{12}$$

The “i” subscript is iteration number. The motor control strategy based on MPC is illustrated in Figure 3

4. SIMULATION AND EXPERIMENTAL RESULTS

Nominal parameters of the test motor is provided in Table 1. The controller parameters of model reference is calculated in Equation (13). The reference position signal is a square waveform which is stepped from -3 to 3 radian with frequency of 0.333 Hz.

The controller parameters of model reference is calculated in Equation (13). The reference position signal is a square waveform which is stepped from -3 to 3 radian with frequency of 0.333 Hz.

$$K_i = 1, T_{oi} = 0.01s, K_1 = \frac{JK_i}{27T_{oi}^2} = 1.66 \frac{kgm^2}{s^2} \tag{13}$$

$$K_2 = 9T_{oi} = 0.09s$$

According to the Table 1 information, the load is modeled as moment of inertia which is added to the machine moment in Equation (5) where $J=J_m+J_L$. Simulation results of PMSM rotor position using cascade controller, reference model controller and MPC

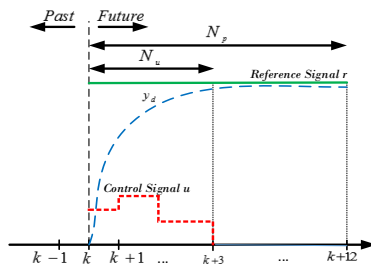


Figure 3. MPC control strategy

TABLE1: PMSM and drive parameters

Parameter	Value	Parameter	Value
Vdc	311V	poles	4
Rs	8.5Ω	Jm (motor moment)	0.001Kgm ²
Ld	35mH	JL (load moment)	0.0036Kgm ²
Lq	66 mH	Switching frequency	20 kHz
Ψ _{pm}	0.09 wb	Motor current	4.4 A

is illustrated in Figure 4. Simulation results demonstrate that the MPC has faster transient response in compare with the other techniques. According to the Figure 4 cascade structure time delay is 1 second for tracking the reference command. The reference model structure has reduced this time delay to 0.7 second and finally the MPC has reduced this time delay more i.e. 0.4 second with zero steady state error in counterclockwise direction. Durig suddenly change in the reference command at time 1.5s and 3s from 3 to -3 radian and vice versa the MPC has a good tracking ability incompare with the other cascade and reference model with lowest time delay. The motor speed in MPC has higher overshoot in compare with the other techniques which is illustrated in figure 5 due to the producing the higher current (higher torque) than others for obtaining the faster transient response.

Consequently MPC has a good transeint behavior and tracking ability related to the cascade and reference model. For verification of MPC results due to simulation the implementation of MPC is done The experimental set up of motor-load and controllers is shown in Figure 6. For three-phase voltage source generation we used the three-phase inverter which is controlled by DSP hardware eZdsp F2812. The switching frequency of the system is adjusted to 20 kHz and the band-width of current controller is 2 kHz. Speed measurement is done by a 2048 pulse encoder with three Hall-effect sensors.

For protection of three phase inverter the q axis current is limited to the range of $-10A \leq i_{qmax} \leq 10A$. For better and optimize control of PMSM the d axis current is set to zero and q axis current is set to 1 A.

For protection of three phase inverter the q axis current is limited to the range of $-10A \leq i_{qmax} \leq 10A$. For better and optimize control of PMSM the d axis current is set to zero and q axis current is set to 1 A. The position, speed and q-axis current which are carried out by simulation and experimental results are illustrated in Figures 7, 8 and 9 respectively. Figure 7 shows the simulation and measured position of PMSM using MPC. The proposed position estimation algorithm is also suitable over a wide position range -3 to 3 radian. The position error between simulation and experimental results based on Figure 7 is 1.7% which is obtained

using absolute difference between simulation and experimental values divided by experimental values in one period. This error value demonstrates that simulation and measured position is very close together during a transient command variation due to the suitable selection of feed-forward signals and well tuning of controller coefficients. Figure 8 illustrates the speed of PMSM during position control process that it shows a good agreement between simulation and experimental results with 2.2% error.

The error of position and speed show that the proposed MPC combined with cascade structure is verified by experimental results. Finally Figure 9 shows the variation of q-axis stator current using simulation and measured values during the position control of PMSM.

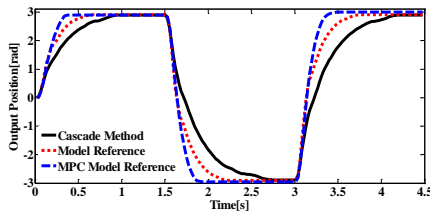


Figure 4. PMSM position control using cascade structure, model reference and MPC

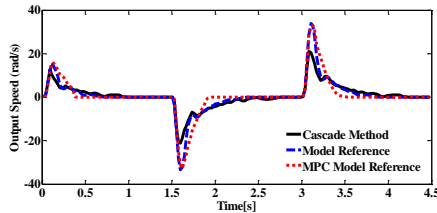


Figure 5. PMSM speed variation using cascade structure, model reference and MPC

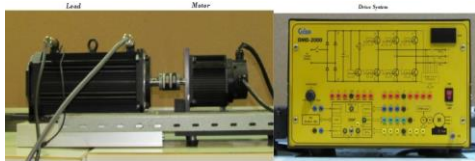


Figure 6. experimental set up of PMSM position control

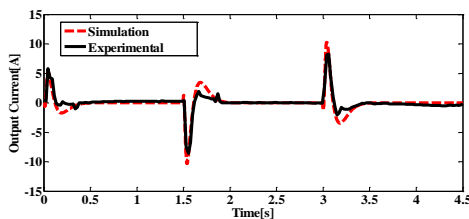


Figure 7. PMSM position using MPC (simulation and measured)

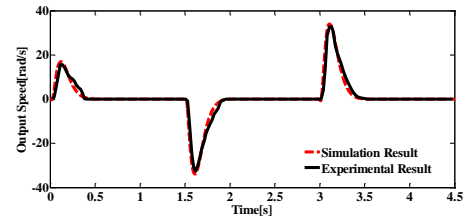


Figure 8. PMSM speed using MPC (simulation and measured)

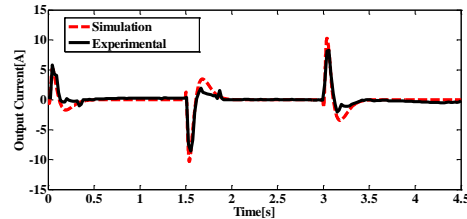


Figure 9. q-axis current using MPC (simulation and measured)

It demonstrate the q-axis current using simulation result has a good agreement with experimental results. Therefore combination of MPC and cascade structure in position control of PMSM was successful.

5. CONCLUSION

In this paper model reference control method with combination of model predictive control is proposed in order to achieve a faster transient response with suitable error. This idea lead obtaining the fast transient response with appropriate steady state error related to the cascade structure and reference model methods. The simulation results of model predictive control compared with the cascade structure and reference model. Simulation results show the model predictive control has much better results contain faster transient response and good steady state error in compare with the others. Verification of simulation results carried out by experimental results very well.

6. ACKNOWLEDGEMENT

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ABSTRACT

سرعت و دقت پاسخ گذرا مهمترین نیاز یک سیستم کنترل موقعیت ماشین الکتریکی است. ساختار مرسوم کنترل آبنشاری به علت دارا بودن پهنای باند نامناسب حلقه های داخلی دارای سرعت پاسخ ضعیفی است. در این مقاله، برای کاهش سرعت پاسخ موتور مغناطیس دائم از مدل مرجع با استفاده از سیگنالهای پیش خور استفاده شده است. در این ساختار سیگنالهای پیش خور بوسیله مدل مرجع ساده شده موتور مغناطیس دائم تولید می شوند. در این مقاله این سیگنالهای پیش خور که مورد استفاده روش ترکیبی کنترل پیش بین هستند با ساختار کنترل آبنشاری ترکیب شده است. با استفاده از این ایده سرعت پاسخ سریع با دقت بالا و نیز قابلیت دنبال کردن سیگنال مرجع تضمین شده است. نتایج شبیه سازی و آزمایشگاهی بر ایده مطرح شده صحه گذاشتند.

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