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Design of PMSLM Position Controller Based on Model Predictive Control Algorithm

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ABSTRACT In order to simplify the permanent magnet synchronous linear motor (PMSLM) system structure, optimize the moving performance of the control system, and further improve the position tracking accuracy of the PMSLM, a PMSLM position controller based on the model prediction algorithm is proposed (PMPC). This paper designs two position model predictive controller schemes: the first scheme is to directly use the linear displacement and q-axis current of the PMSLM to establish a second-order mathematical model, and combine the model predictive algorithm to design the PMPC. The second scheme is to first combine the linear motor motion equation and thrust equation with the model prediction algorithm to design a velocity model predictive controller (VMPC), then on the basis of the VMPC, use the relationship between the PMSLM displacement and the running speed to comprehensively design the PMPC is used as the outer loop controller of the control system. The two PMSLM control methods designed in this paper only need position loop and current loop to achieve precise trajectory tracking. Then, the analysis of the two control schemes shows that the second scheme is superior to the first scheme in terms of control performance. Finally, the PMPC model of the second scheme is built by simulation software to simulate and test. By analyzing the experimental data, it shows that the control method not only simplifies the control system in terms of structure, but also improves the accuracy of PMSLM tracking the direction change of the motion trajectory, and optimizes the control ability of the control system.

INDEX TERMS Tracking, position control, permanent magnet synchronous linear motor, model predictive control (MPC).

I. INTRODUCTION

With the innovation of AC motors and the continuous development of power electronics, DC servo systems are gradually being replaced by AC servo systems [1], [2]. Because proportional-integral-derivative (PID) controllers are easy to build, not easy to be disorder, and easy to realize digitization, the current engineering AC servo system control mostly uses PID control. However, the PID control system has poor robustness, and its performance is easily affected by parameter changes and external interference [3]. Therefore, in order to achieve more perfect AC motor control, it is very urgent to design a better control strategy [4].

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After continuous research by experts, many excellent control algorithms have been applied to AC servo control systems, such as neural network control [5]–[8], sliding mode variable structure control [9]–[12], fuzzy control [13]–[15], model predictive control [16]–[18]. Among them, MPC is an excellent new control method that has emerged in recent year. It has attracted more and more researchers' attention due to its low dependence on model parameters and good robustness. The model predictive control algorithm predicts the increment of the control quantity in the next few cycles without excessive use of motor parameters, and calculates the appropriate control value through the optimization function.

Model predictive control algorithms have been widely used in AC servo control systems. Literature [19] takes the asynchronous motor vector control algorithm as an example, uses the stator voltage equation of the asynchronous motor to design a controller based on the model prediction algorithm instead of the traditional current loop proportional-integral (PI) controller, effectively improve the system's ability to resist external interference and enhance the system's adjustable performance. Reference [20] designed a control system based on model predictive control to solve the problem that PI parameters have a greater impact on the performance of the induction motor field weakening control system and the PI parameters are difficult to tune, and it effectively improves the response speed and response of the control system and the control robustness of the system. Aiming at the phenomenon that PI control can only achieve a compromise control effect between suppressing the overshoot and shortening the overshoot time, the literature [21] uses the model prediction algorithm to design anti-saturation permanent magnet synchronous motor (PMSM) speed conversion regulators, effectively suppresses overshoot and shortens the adjustment time of the system. The above documents apply the model prediction algorithm to various regulators controlled by asynchronous motors and permanent magnet synchronous motors, and have achieved good control effects. MPC can also be used in the control of PMSLM with high speed, high precision, large stroke and high dynamic characteristics.

For the non-linear, multi-variable, and strongly coupled permanent magnet synchronous motor control system, it is very important to design appropriate control methods to have good speed stability and robustness to load disturbances [12], [22]. Literature [23] takes advantage of the strong anti-disturbance and easy implementation of the terminal sliding mode control technology, and designs a terminal sliding mode controller for the position control of PMSLM, the motor control ring can quickly and accurately stabilize to the best point. Literature [24] uses the fast non-singular terminal sliding mode control (FNSTSMC) method to reach the stable area in a short time, and designs a FNSTSMC method to improve the tracking accuracy of PMSLM.

In order to enhance the motion performance of the PMSLM control system, optimize the position tracking performance of the PMSLM, and to simplify the structure of the PMSLM control system. This paper uses the advantages of the MPC algorithm and draws on the control ideas of literature [23] and literature [24] to design a PMSLM-PMPC based on the model prediction algorithm. This paper designs two motor position controller schemes: one is to use the linear displacement and q-axis current of the PMSLM to establish a second-order mathematical model, and to design the position controller according to the model prediction algorithm; the other first is to use the motion equation and thrust equation of the permanent magnet linear synchronous motor to design the VMPC controller, which effectively improves the speed control capability of the permanent magnet linear synchronous motor system. Then the relationship between the displacement and operation of the permanent magnet linear synchronous motor is applied to the VMPC controller to design

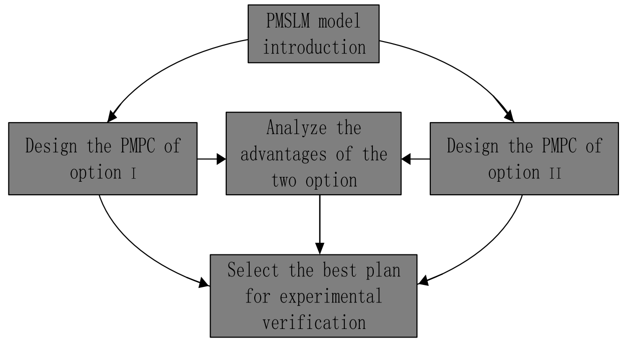


FIGURE 1. Research process flow chart.

a position controller. Finally, the advantages and disadvantages of the two controllers are analyzed, and the optimal position controller is selected for simulation experiments to verify the feasibility of the control method proposed in this paper. Experimental data shows that the control scheme can improve the control ability of the system and improve the position tracking accuracy of the permanent magnet linear synchronous motor.

The theoretical difficulty in this paper is how to design a position model predictive controller with superior control performance using model predictive algorithms. The research process of the proposed control strategy in this paper is shown in the figure below. In this paper, the mathematical model of permanent magnet synchronous linear motor is analyzed, and then the first position model predictive controller described in the third section is designed. Through analysis, it is found that the first position controller not only increases the complexity of PMSLM control system, but also affects the performance of the control system because the correction link of the controller can't fully compensate the correction errors in the system. Therefore, the design method of position model predictive controller is further studied in this paper. In the fourth section, the velocity model predictive controller is first designed, and then the second position model predictive controller is designed according to the relationship between the operating speed of the PMSLM and the linear displacement. The second position model prediction controller designed in this paper not only simplifies the complexity of PMSLM control system, but also avoids the situation that the correction link of the controller can't fully compensate the correction error in the system.

II. PMSLM MODEL

In this paper, the bilateral magnetic pole ironless PMSLM is used as a platform for experimental verification, and its basic architecture is shown in the architecture below.

The PMSLM stator voltage equation has the following form:

$$\begin{cases} u_d = Ri_d + L_d \dfrac{d}{dt} i_d - \omega_c L_q i_q \\ u_q = Ri_q + L_q \dfrac{d}{dt} i_q + \omega_c (L_d i_d + \psi_f) \\ \omega_c = \dfrac{\pi \cdot \upsilon}{\tau} \end{cases} \tag{1}$$

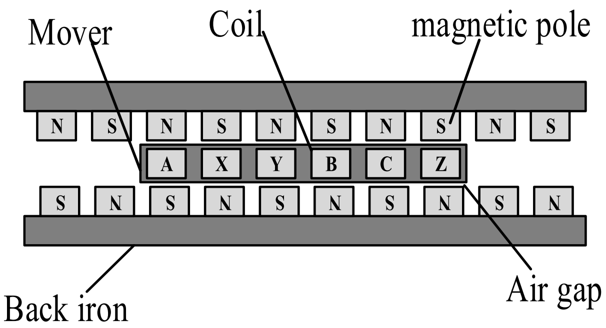


FIGURE 2. Basic architecture of bilateral linear motor.

where R indicates the resistance parameter, τ indicates the magnetic pole moment, υ indicates the running speed, u_d, u_q represents d, q axis voltage parameters, i_d, i_q represents d, q axis current parameters, L_d, L_q represents d, q axis inductance parameter, ψ_{mf} represents flux parameters.

Thrust equation of PMSLM:

$$F_{\mathrm{em}} = p_{\mathrm{n}} \frac{3\pi}{2\tau} \cdot [\psi_{\mathrm{mf}} \cdot i_{\mathrm{q}} + (L_{\mathrm{d}} - L_{\mathrm{q}}) \cdot i_{\mathrm{d}} \cdot i_{\mathrm{q}}] \tag{2}$$

where F_{em} represents motor thrust; p_n represents the number of pole pairs.

Since the bilateral magnetic pole ironless PMSLM is a surface-mounted PMSLM, so the thrust equation can be simplified to:

$$F_{\mathrm{em}} = p_{\mathrm{n}} \cdot \frac{3\pi}{2\tau} \cdot \psi_{\mathrm{mf}} \cdot i_{\mathrm{q}} \tag{3}$$

Motion equation of linear motor:

$$m \cdot \frac{\mathrm{d}\nu}{\mathrm{d}t} = F_{\mathrm{em}} - f - B \cdot \nu \tag{4}$$

where m represents mass of the mover; B represents viscous friction factor; and f represents system disturbance.

Combining Eq. (3) and Eq. (4) can get:

$$\begin{aligned} &\frac{\mathrm{d}\nu}{\mathrm{d}t} = a_{\mathrm{M}} \cdot i_{\mathrm{q}} + b_{\mathrm{M}} \cdot \nu + c_{\mathrm{M}} \cdot f \\ &a_{\mathrm{M}} = \frac{1}{m} p_{\mathrm{n}} \cdot \frac{3\pi}{2\tau} \cdot \psi_{\mathrm{mf}} \quad b_{\mathrm{M}} = -\frac{B}{m} \; c_{\mathrm{M}} = -\frac{1}{m} \end{aligned} \tag{5}$$

There are two design methods for the position controller of PMSLM: The first method is to combine Eq. (5) with the linear displacement l of the linear motor to establish the motion model of the second-order linear motor, and then design the position controller based on the MPC algorithm; The second method first uses Eq. (5) to design the VMPC, and then uses the relationship between the linear displacement l of the linear motor and the running speed v to design the PMPC of the control system.

III. POSITION MODEL PREDICTIVE CONTROLLER: OPTION I

According to the linear motor's mechanical motion equation, a second-order linear motor model is established.

$$\frac{\mathrm{d}^2 l}{\mathrm{d}t^2} = a_{\mathrm{M}} \cdot i_{\mathrm{q}} + b_{\mathrm{M}} \cdot \frac{\mathrm{d}l}{\mathrm{d}t} + c_{\mathrm{M}} \cdot f \tag{6}$$

Also in the process of designing the position controller, because the value of the disturbance term is uncertain and has nothing to do with the sampling time, it can be ignored. Discretize Eq. (6) to get:

$$\frac{l(\mathrm{n}+2) - 2 \cdot l(n+1) + l(n)}{\mathrm{T}_{\mathrm{s}}^2} = a_{\mathrm{M}} \cdot i_{\mathrm{q}}(n) + b_{\mathrm{M}} \cdot \frac{l(n+1) - l(n)}{\mathrm{T}_{\mathrm{s}}} \tag{7}$$

among them, T_s is the sampling time.

sort out formula (7) to get:

$$l(n+2) = a_{\mathrm{L}} \cdot i_{\mathrm{q}}(n) + b_{\mathrm{L}} \cdot l(n+1) - c_{\mathrm{L}} \cdot l(n) \tag{8}$$

among them

$$a_{\mathrm{M}} \cdot \mathrm{T}_{\mathrm{s}}^2 = a_{\mathrm{L}} \quad (2 + b_{\mathrm{M}} \cdot \mathrm{T}_{\mathrm{s}}) = b_{\mathrm{L}} \; (1 + b_{\mathrm{M}} \cdot \mathrm{T}_{\mathrm{s}}) = c_{\mathrm{L}}$$

The position controller is divided into three modules for design. First, make a model prediction. Observing Eq.(8), we can find that the state quantity predicted in each cycle is related to the state quantity of the previous two cycles. Assuming that the control quantity in the three cycles remains unchanged, we get three ideal conditions forecast value of period:

$$\begin{cases} l_0(n+1|n) = a_{\mathrm{L}} \cdot i_{\mathrm{q}}(n-1) + b_{\mathrm{L}} \cdot l_m(n) - c_{\mathrm{L}} \cdot l_m(n-1) \\ l_0(n+2|n) = a_{\mathrm{L}} \cdot i_{\mathrm{q}}(n-1) + b_{\mathrm{L}} \cdot l_0(n+1|n) - c_{\mathrm{L}} \cdot l_m(n) \\ l_0(n+3|n) = a_{\mathrm{L}} \cdot i_{\mathrm{q}}(n-1) \\ \qquad\qquad +b_{\mathrm{L}} \cdot l_0(n+2|n) - c_{\mathrm{L}} \cdot l_0(n+1|n) \end{cases} \tag{9}$$

In the formula, $l_0(n+i|n)$ is the predicted value of the linear displacement in the ideal state estimated at the beginning of the n cycle, $i = 1, 2, 3$.

In order to make the predicted state quantity more accurate, considering the variation of the control quantity in the control system, the actual predicted value of the control system is:

$$\begin{cases} l_m(n+1|n) = a_{\mathrm{L}} \cdot i_{\mathrm{q}}(n) + b_{\mathrm{L}} \cdot l_m(n) - c_{\mathrm{L}} \cdot l_m(n-1) \\ l_m(n+2|n) = a_{\mathrm{L}} \cdot i_{\mathrm{q}}(n+1) \\ \qquad\qquad +b_{\mathrm{L}} \cdot l_m(n+1|n) - c_{\mathrm{L}} \cdot l_m(n) \\ l_m(n+3|n) = a_{\mathrm{L}} \cdot i_{\mathrm{q}}(n+2) \\ \qquad\qquad +b_{\mathrm{L}} \cdot l_m(n+2|n) - c_{\mathrm{L}} \cdot l_m(n+1|n) \end{cases} \tag{10}$$

In the formula, $l_m(\nu + i|\nu)$ is the linear displacement prediction value obtained when considering the change of the system control quantity, $i = 1, 2, 3$.

Substitute Eq. (17) in Section 4 into Eq. (10), and use Eq.(9) to simplify. The simplification method is the same as the following Eq. (19), (20) and (21). After simplification, the relationship between the state quantity and the control quantity change can be obtained, which is shown in the form of the state equation.

$$\begin{bmatrix} l_m(n+1|n) \\ l_m(n+2|n) \\ l_m(n+3|n) \end{bmatrix} = g_l \cdot \begin{bmatrix} \Delta i_{\mathrm{q}}(n) \\ \Delta i_{\mathrm{q}}(n+1) \\ \Delta i_{\mathrm{q}}(n+2) \end{bmatrix} + \begin{bmatrix} l_0(n+1|n) \\ l_0(n+2|n) \\ l_0(n+3|n) \end{bmatrix} \tag{11}$$

among them

$$g_l = \begin{bmatrix} a_L & & \\ a_L \cdot (1 + b_L) & a_L & \\ a_L^* \cdot b_L^* & a_L \cdot (1 + b_L) & a_L \end{bmatrix}$$

define $a_L^* \cdot b_L^* = a_L \cdot b_L \cdot (1 + b_L) - c_L$ in matrix g_l.

The predicted linear displacement of the motor is corrected and predicted to obtain the corrected linear displacement $l_p(n+1) = l_m(n+1) + h \cdot e_l(n+1)$, among them $e_l(n+1) = l(n+1) - l_m(n+1)$.

Then use the optimization function to get the optimal control increment, and finally calculate the optimal control amount.

$$i_q(n+1) = i_q(n) + \Delta i_q(n+1) \tag{12}$$

Due to various uncertain error factors, the estimated value may differ from the true value. It can be seen from Eq. (9) that the predicted value of each cycle needs the predicted value of the first two cycles to determine, so the second-order model predictive controller has one more prediction period than the first-order predictive model predictive controller, which increases the control system calculation amount. The correction coefficient of the correction module cannot fully compensate the error due to the limitation of the range, and it will cause the error to accumulate further, thereby affecting the control performance of the control system.

IV. POSITION MODEL PREDICTIVE CONTROLLER: OPTION II

In order to simplify the complexity of the PMSLM control system, and at the same time to avoid the defects of the controller designed in the third section. This part first designs a speed model predictive controller, and then uses the relationship between the linear displacement of the motor and the running speed to design a position with simple mechanism and high control performance controller.

A. VELOCITY MODEL PREDICTIVE CONTROLLER

The Eq.(5) of the PMSLM is expressed in discrete form.

$$\frac{v(n+1) - v(n)}{T_s} = a_M \cdot i_q(n) + b_M \cdot v(n) + c_M \cdot f \tag{13}$$

Since the parameter of the disturbance term is uncertain and has nothing to do with the sampling time, it can be omitted in the process of redesigning the controller. The simplified Eq.(13) is:

$$\begin{aligned} v(n+1) &= T_s \cdot a_M \cdot i_q(n) + (1 + T_s \cdot b_M) \cdot v(n) \\ &= a_T \cdot i_q(n) + b_T \cdot v(n) \end{aligned} \tag{14}$$

where T_s is the sampling time.

Eq.(14) is used as the algorithm model of the design model predictive controller. And use $v(n+1)$ as the predicted value of $n+1$ periods. Then the predicted value of the $n+2$ period is:

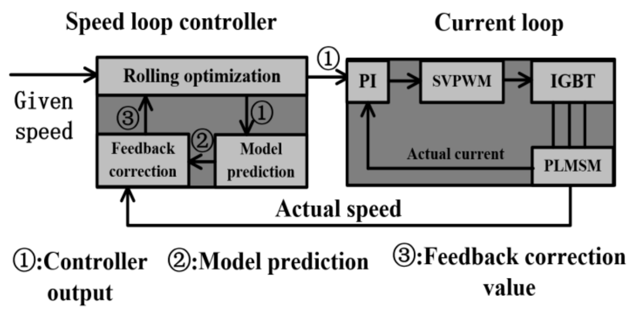


FIGURE 3. PMSLM speed loop control system.

$$\begin{aligned} &v(n+2) \\ &= a_T \cdot i_q(n+1) + b_T \cdot v(n+1) \\ &= a_T \cdot (i_q(n) + \Delta i_q(n)) + b_T \cdot v(a_T \cdot i_q(n) + b_T \cdot v(n)) \\ &= a_T \cdot \Delta i_q(n) + (a_T + a_T \cdot b_T) \cdot i_q(n) + b_T^2 \cdot v(n+1) \end{aligned} \tag{15}$$

When using the model predictive control algorithm to design the speed loop controller, in order to realize the design process more easily, the controller is modularized. The linear motor speed loop control system is shown in Fig. 3.

(1) Model prediction: This module predicts the speed of the controlled object.

(2) Feedback correction: This module corrects the predicted motor running speed.

(3) Rolling optimization: Optimize the obtained control increment to obtain the optimal control amount.

In actual control, the state quantity is predicted for three cycles. Since the control quantity is unpredictable, the control quantity of the next three cycles can maintain the control quantity $i_q(n-1)$ of the $(n-1)$ cycle, and the predicted value is:

$$\begin{cases} v_0(n+1|n) = a_T \cdot i_q(n-1) + b_T \cdot v_m(n) \\ v_0(n+2|n) = a_T \cdot i_q(n-1) + b_T \cdot v_0(n+1|n) \\ v_0(n+3|n) = a_T \cdot i_q(n-1) + b_T \cdot v_0(n+2|n) \end{cases} \tag{16}$$

In the formula, $v_0(n+i|n)$ is the predicted value of the speed in the ideal state estimated at the beginning of the n cycle, $i = 1, 2, 3$.

Assuming that the difference between the control variables in every two cycles is $\Delta i_q(n+i)(i = 0, 1, 2)$, the control variables in the next three cycles are:

$$\begin{cases} i_q(n) = i_q(n-1) + \Delta i_q(n) \\ i_q(n+1) = i_q(n) + \Delta i_q(n+1) \\ i_q(n+2) = i_q(n+1) + \Delta i_q(n+2) \end{cases} \tag{17}$$

When considering the increment of the control quantity in each cycle, the predicted value of the state quantity of the controlled object obtained by the model prediction algorithm is:

$$\begin{cases} v_m(n+1|n) = a_T \cdot i_q(n) + b_T \cdot v_m(n) \\ v_m(n+2|n) = a_T \cdot i_q(n+1) + b_T \cdot v_m(n+1|n) \\ v_m(n+3|n) = a_T \cdot i_q(n+2) + b_T \cdot v_m(n+2|n) \end{cases} \tag{18}$$

In the formula, $v_m(v+i|v)$ is the speed prediction value obtained when considering the change of the system control quantity, $i = 1, 2, 3$.

Using Eq.(17) to replace the control variable in Eq.(18) and simplifying with Eq.(16), the relationship between the predicted value and the change of the control variable can be obtained.

$$\begin{aligned} v_m(n+1|n) &= a_T \cdot i_q(n) + b_T \cdot v_m(n) \\ &= a_T \cdot (i_q(n-1) + \Delta i_q(n)) \\ &\quad + b_T \cdot v_m(n) \\ &= a_T \cdot \Delta i_q(n) + v_0(n+1|n) \end{aligned} \tag{19}$$

$$\begin{aligned} v_m(n+2|n) &= a_T \cdot i_q(n+1) + b_T \cdot v_m(n+1) \\ &= a_T \cdot (i_q(n-1) + \Delta i_q(n) + \Delta i_q(n+1)) \\ &\quad + b_T \cdot (a_T \cdot \Delta i_q(n) + v_0(n+1|n)) \\ &= a_T \cdot \Delta i_q(n+1) + a_T \cdot b_T \cdot \Delta i_q(n) \\ &\quad + v_0(n+2|n) \end{aligned} \tag{20}$$

$$\begin{aligned} v_m(n+3|n) &= a_T \cdot i_q(n+2) + b_T \cdot v_m(n+2) \\ &= a_T \cdot (i_q(n-1) + \Delta i_q(n) \\ &\quad + \Delta i_q(n+1) + \Delta i_q(n+2)) \\ &\quad + b_T \cdot (a_T \cdot \Delta i_q(n+1) + v_0(n+2|n)) \\ &= a_T \cdot \Delta i_q(n+2) + a_T \cdot b_T \cdot \Delta i_q(n+1) \\ &\quad + a_T \cdot b_T^2 \cdot \Delta i_q(n) \\ &\quad + v_0(n+3|n) \end{aligned} \tag{21}$$

Eq.(19), (20) and (21) are expressed in the form of Eq.(22) to facilitate the calculation of the design process in the future.

$$\begin{bmatrix} v_m(n+1|n) \\ v_m(n+2|n) \\ v_m(n+3|n) \end{bmatrix} = g \cdot \begin{bmatrix} \Delta i_q(n) \\ \Delta i_q(n+1) \\ \Delta i_q(n+2) \end{bmatrix} + \begin{bmatrix} v_0(n+1|n) \\ v_0(n+2|n) \\ v_0(n+3|n) \end{bmatrix}$$

$$g = \begin{bmatrix} a_T & & \\ a_T \cdot b_T & a_T & \\ a_T \cdot b_T^2 & a_T \cdot b_T & a_T \end{bmatrix} \tag{22}$$

There may be errors between the predicted value obtained in the model prediction process and the real value in the system. In order to enable the controller to control the system stably, an error compensation method is used to correct the predicted value.

$$e(n+1) = v(n+1) - v_m(n+1) \tag{23}$$

$$v_p(n+1) = v_m(n+1) + h \cdot e(n+1) \tag{24}$$

$v_m(n+1)$ is the predicted value obtained during the model prediction process, v is the actual output value of the controlled object, and $e(n+1)$ is the error between the output value and the predicted value. Based on the error, the future predicted value is corrected through the feedback coefficient h $(0 < h <= 1)$.

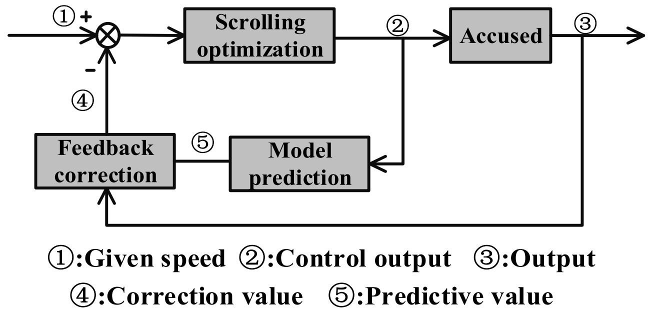


FIGURE 4. Velocity model predictive control system.

In the linear motor speed loop control system, in order to ease the change range of the control increment between each cycle, the evaluation function is used to obtain the optimal control variable change.

$$J(k) = \sum_{i=1}^{3} q_i \cdot [v_r(n+i) - v_m(n+i)]^2 + \sum_{j=1}^{3} r_j \cdot \Delta i_q\,(n+j-1)^2 \tag{25}$$

By calculating the extreme points of Eq. (23), the optimal control increment of the control system can be obtained.

$$\Delta i_q(t+1) = (g^T \cdot Q \cdot g + R)^{-1} \cdot g^T \cdot R \cdot [v_r(n) - v_p(n)] \tag{26}$$

Substituting the control increment into Eq.(17) can calculate the optimal control amount for this cycle. In order to prevent the current signal output by the controller from showing a relatively large overshoot when the input signal undergoes a large step change, the output of the controller is limited, and the upper limit of the limiter is set to 16 according to the experimental results And -16.

In Eq.(24), q_i and r_j indicate difference weighting coefficient and control weighting coefficient, Q and R indicate difference weighting coefficient matrix and pre-control coefficient matrix:

$$\mathrm{Q} = \mathrm{diag}(q_1, \ldots, q_p), \quad \mathrm{R} = \mathrm{diag}(r_1, \ldots, r_m).$$

The coefficient matrices Q and R are first roughly set according to the research method of literature [25], and then adjusted according to the experimental results to achieve the optimal control effect.

The velocity model predictive control system is shown in the Fig.4 below.

B. POSITION MODEL PREDICTIVE CONTROLLER

The equation of the second-order mechanical motion mathematical model of discrete linear motor is:

$$\frac{l(n+2) - 2 \cdot l(n+1) + l(n)}{T_s^2} = a_M \cdot i_q(n) + b_M \cdot \frac{l(n+1) - l(n)}{T_s} \tag{27}$$

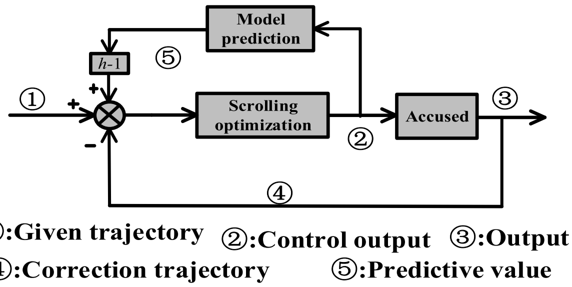


FIGURE 5. Position model predictive control system.

Define the displacement tracking error of the PMSLM as $e_1 = l_r - l$, then the motor speed error is:

$$e_2 = \frac{dl_r}{dt} - \frac{dl}{dt} = \frac{de_1}{dt} \tag{28}$$

Incorporating Eq.(16) and Eq.(17) into Eq.(26), the relationship between the linear motor's running speed and the given positioning value can be obtained.

$$\Delta i_q(n) = c_l \cdot [v_r(n) - h \cdot v(n) + (h-1) \cdot v_m(n)] \tag{29}$$

among them $c_l = (g^T \cdot Q \cdot g + R)^{-1} \cdot g^T \cdot R$ 。

In order to achieve precise linear motor position control, the coefficient h of $v(t)$ in Eq.(29) is changed to h_l.

$$\Delta i_q(n) = c_l \cdot [v_r(n) - h_l \cdot v(n) + (h-1) \cdot v_m(n)] \tag{30}$$

Let $h_l = 1$ in the formula, because $v_r(n) - v(n) = e_2$, put Eq.(28) into Eq.(30) to get Eq.(31) linear motor linear displacement and current increment relationship, and then calculate the optimal control quantity according to Eq.(10).

$$\begin{aligned}\Delta i_q(n) &= c_l \cdot [\frac{de_1}{dt} + (h-1) \cdot v_m(n)] \\ &= c_l \cdot [\frac{dl_r}{dt} - \frac{dl}{dt} + (h-1) \cdot v_m(n)]\end{aligned} \tag{31}$$

The position model predictive control system is shown in the Fig.5 below.

V. PROOF OF CONTROLLER STABILITY

Aiming at the stability analysis of the model predictive controller of the motor control system, literature [26] uses the Lyapunov method to prove the asymptotic stability of the single closed-loop model predictive controller designed by combining the speed loop and the current loop.

For this article, the position model predictive controller combining the position loop and the velocity loop is designed using the model predictive control algorithm, and the Lyapunov stability criterion of the discrete system will be used for analysis. The stability proof is: For discrete systems, the state equation is: $x(k+1) = Gx(k)$.

The necessary and sufficient conditions for judging its gradual stability are: For any given positive definite matrix Q_1, There will always be a positive definite matrix P which is the solution of Lyapunov equation $G^T \cdot P \cdot G - P = -Q_1$, and $V[x(k)] = x^T(k) \cdot P \cdot x(k)$ is a Lyapunov function of the system.

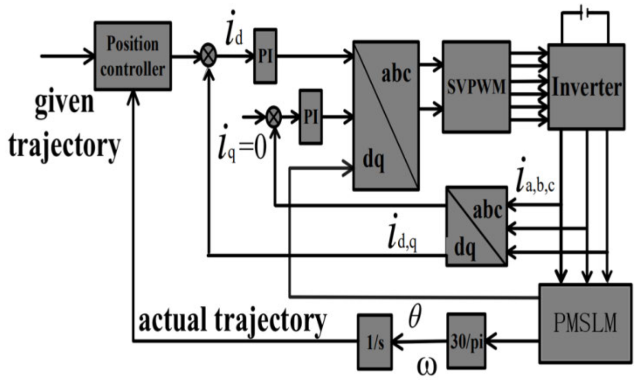


FIGURE 6. Linear motor control system.

For the position model predictive controller designed in this paper, its space state equation is:

$$\begin{cases} x(n+1) = A \cdot x(n) + Bu(n) \\ y(n+1) = C \cdot x(n+1) \end{cases} \tag{32}$$

among them, the state variable matrix is $x(n) = [\, v(n) \;\; l(n) \,]$, the input variable is $u(n) = i_q(n)$, The coefficient matrix is

$$A = \begin{bmatrix} b_T & 0 \\ T_s & 1 \end{bmatrix} \quad B = \begin{bmatrix} a_T \\ 0 \end{bmatrix} \quad C = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

Let the coefficient matrix of the space state Eq. (32) of the model predictive controller be denoted by G.

$$A = \begin{bmatrix} b_T & 0 \\ T_s & 1 \end{bmatrix} = G \tag{33}$$

Choose P as a second-order positive definite matrix, $G^T \cdot P \cdot G = G^T \cdot G > 0$, And the sampling time T_s is 0.55 ms, Therefore, there is a positive definite matrix Q_1, which makes the equation $G^T \cdot P \cdot G - P = -Q_1$ hold, that is, the model predictive controller is asymptotically stable.

VI. SIMULATION AND EXPERIMENT

A. SYSTEM SIMULATION

Fig. 6 shows the designed PMSLM-PMPC control system. Compared with the traditional three-loop motor control system, the control system designed in this paper simplifies the complexity of the motor control system, only two control loops are needed to realize PMSLM position control. As shown in Fig. 6, the position controller in the control system is designed on the basis of the velocity model predictive controller. The given trajectory signal and the actual tracking trajectory signal are introduced into the position controller, and the two signals are calculated by the model prediction algorithm in the controller to obtain the optimal current loop control quantity.

1) VMPC DATA ANALYSIS

In order to test the superiority of the speed model predictive controller developed, and to verify whether the speed model

TABLE 1. PMSLM main parameters.

Parameter	Value
Stator resistance Rs	4.0Ω
Q-axis inductance L	8.2 mH
Moment mass m	1.425kg
Viscous friction coefficient B	44N·m·s
Pole distance τ	0.016m

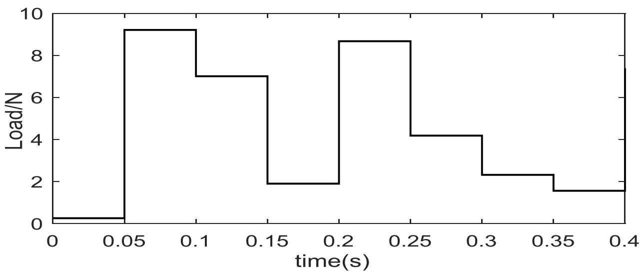


FIGURE 7. Random load on the motor.

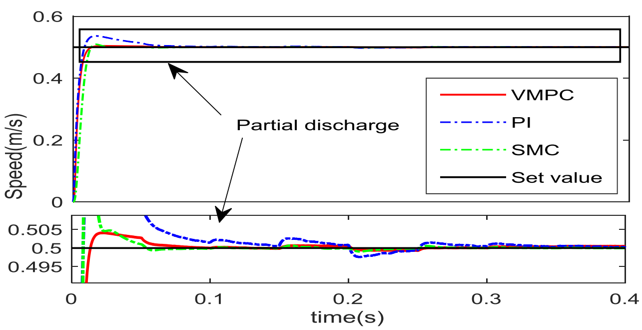


FIGURE 8. Speed contrast waveform of PMSLM.

predictive controller can enhance the ability of the PMSLM control system to resist interference. Two classical PMSLM control systems with a PI controller and a sliding mode controller (SMC) are established respectively as comparative models. In the process of simulation comparison, the parameters of the PI control system speed loop are: $K_p = 0.14$, $K_i = 7$; The sliding surface defined by the speed loop controller of the SMC control system is $s = c \cdot x_1 + x_2(\boldsymbol{x}_1, \boldsymbol{x}_2$ is the state variable), The adopted approach rate is $\dot{s} = -\varsigma \cdot \mathrm{sgn}(s) - q \cdot s$, The parameter of the controller is: $c = 60$, $\varsigma = 200$, $q = 300$; Keep the parameters of the current loop controller the same. The data waveform is shown in Fig. 7 to Fig. 8. Fig. 9 shows the random load added to the motor during motor operation.

Observing Fig. 8, it can be seen that the motor is set to run at 0.5m/s. The 0N to 10N random load shown in Fig. 7 can be regarded as the disturbance of the motor itself during the operation of the motor. Fig. 8 and Fig. 9 are the speed comparison waveforms of the three control methods and the error waveforms between the running speed and the set speed. Studying Fig. 7 and 8, we can find that in the time period from 0 to 0.05s, the load is close to 0N, and the motor running speed of the control system based on the VMPC and the SMC is close to the set speed, but based on The motor motion waveform of the VMPC device is relatively small; It will take some time for the motor running speed based on the PI controller to approach the set speed. In the time from 0.05 seconds to 0.1 seconds, the load is about 9N, and the motor running speed of the speed model predictive controller and the control system based on the sliding mode controller reach the set speed stably at the same time, but the motor of the VMPC running speed fluctuates less and the waveform is relatively smooth; At this time, the motor running speed based on the PI controller has not reached the set speed.

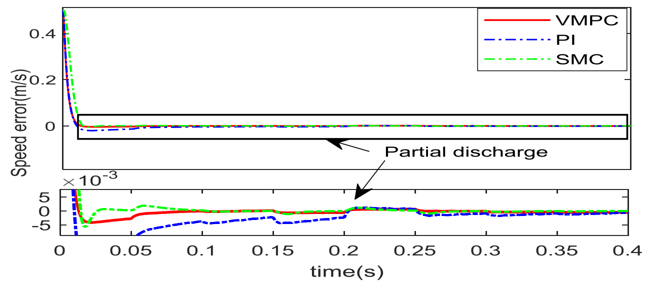


FIGURE 9. Velocity tracking error waveform of PMSLM.

Observing Fig. 9 we can find that with the change of load in the time period of 0.1 s to 0.4 s, the motor speed error waveform based on the VMPC controller is very small, and it can run at the set speed stably. The fluctuation of the motor speed error waveform based on the SMC controller is very obvious, indicating that the running speed of the motor is affected by the load. In order to show the superiority of VMPC more intuitively, the root mean square of the speed tracking error in the three control strategies are calculated: the root mean square of the speed tracking error of VMPC is 0.0297; the root mean square of speed tracking error of SMC is 0.0406; the root mean square PI is 0.0573. Studying the data in Fig. 10 finds that when the load changes randomly, the fluctuation of the q-axis current waveform based on VMPC is relatively small. The above analysis shows that the VMPC has better control performance.

2) PMPC DATA ANALYSIS

In order to verify the performance of the position model predictive controller studied, a three-loop full PI controller control system and a control system with a position loop as the terminal sliding mode controller (TSMC) were designed as comparison objects. In industrial production workers, linear motors usually perform motion trajectories that change the direction of motion. Some motion trajectories are smooth as shown in Fig. 11, and some motion trajectories are abrupt as shown in Fig. 13.

Fig. 11 shows the sine motion trajectory, the linear motor direction changed the direction of motion at about 2.6 s, 7.6 s and 12.6 respectively. By observing the local enlarged view of Fig. 11, it can be found that the motion trajectory of the PI

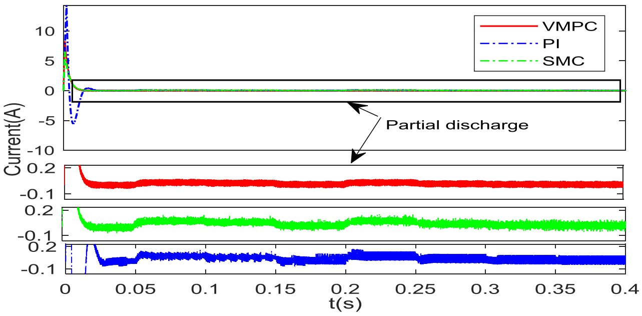


FIGURE 10. Control system q axis current contrast waveform.

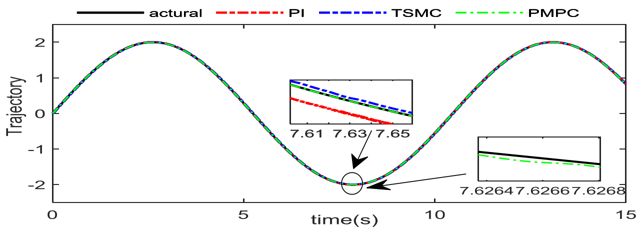


FIGURE 11. Tracking performance of PMSLM.

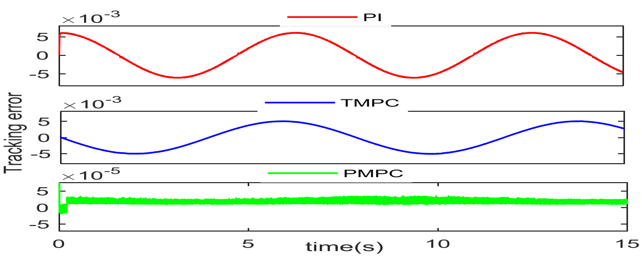


FIGURE 12. Tracking trajectory error of PMSLM.

control system has deviated from the set motion trajectory; The tracking performance of TSMC controller is better than that of PI controller, but compared with the PMPC controller designed in this paper, the tracking performance of TSMC is a little worse.

The trajectory tracking error when the trajectory of PMSLM is sinusoidal is shown in Fig. 12. The analysis data show that the system tracking error level of VMPC is 10^{-5}, and the tracking error level of PI and TSMC is 10^{-3}, which indicates that the control strategy designed in this paper has excellent tracking performance. In order to prove the superiority of the controller designed in this paper, the rolling square roots of the trajectory tracking errors of the three control schemes are calculated. The root mean square of PMPC tracking error is 2.003e-5; the root mean square of tracking error of TSMC is 0.0036; the root mean square of tracking error of PI is 0.0042. Fig. 13 shows the running speed when the linear motor tracks the sinusoidal motion trajectory.

The motion track in Fig. 14 is a sawtooth wave. It is the most desirable way to test the performance of the motor control system to change the direction of the motor suddenly during the operation of the motor. Observing the enlarged view in Fig. 14, it can be found that the PI controller cannot change

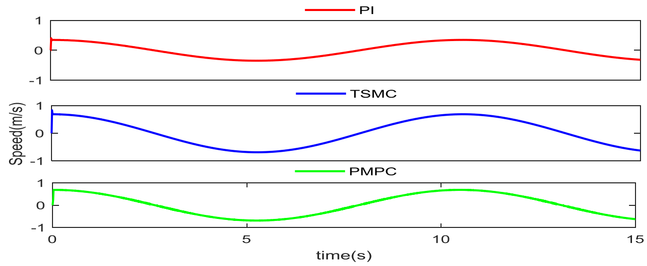


FIGURE 13. Speed contrast waveform of PMSLM.

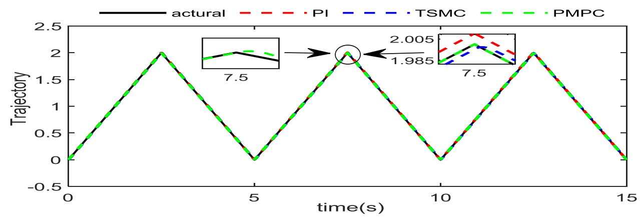


FIGURE 14. Tracking performance of PMSLM.

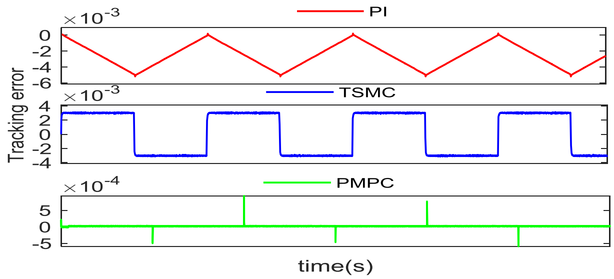


FIGURE 15. Tracking trajectory error of PMSLM.

the direction of the motor in time when the direction of the set running track changes suddenly. Although the TSMC controller can change the running direction of the motor in time, the running trajectory of the motor cannot track the running trajectory set on it. The PMPC controller designed in this paper can not only change the running direction of the motor in time, but also accurately track the set motion trajectory.

The trajectory tracking error of PMSLM when doing sawtooth wave motion is shown in Fig. 15. Observation shows that the error level of the PI controller is 10^{-3}, and it shows a periodic slope change with the motion trajectory; the error level of the TSMC is also 10^{-3}, and the tracking error shows a periodic square wave change. The error level of the PMPC is 10^{-4}, which is much smaller than PI and TSMC. In order to prove the superiority of the controller designed in this paper, the rolling square roots of the trajectory tracking errors of the three control schemes are calculated. The root mean square of PMPC tracking error is 2.4071e-5; the root mean square of tracking error of TSMC is 0.003; the root mean square of tracking error of PI is 0.003. Fig. 16 shows the running speed of the linear motor when tracking the isosceles triangle trajectory.

In the actual motor running process, the uncertainty disturbance will affect the real-time tracking performance of the

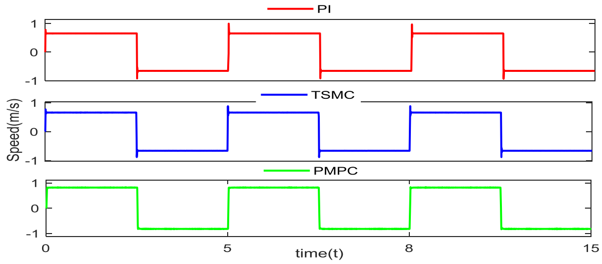


FIGURE 16. Speed contrast waveform of PMSLM.

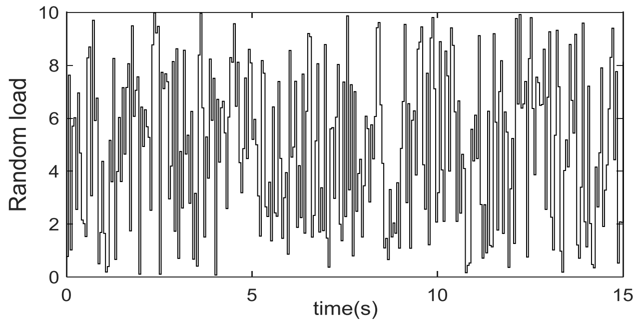
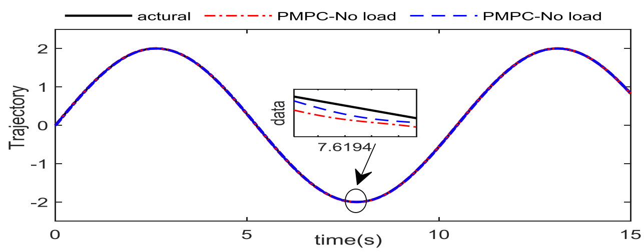
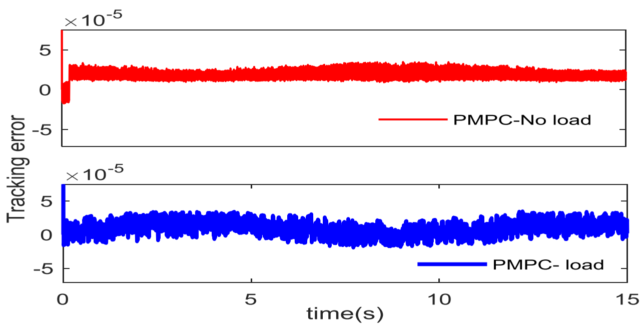


FIGURE 17. Random load on PMSLM.



(a) Trajectory tracking contrast waveform

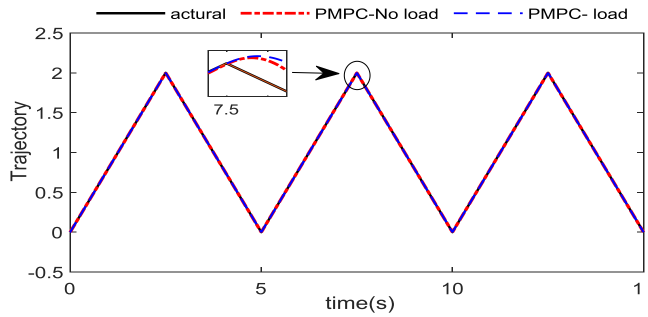


(b) Trajectory tracking error comparison waveform

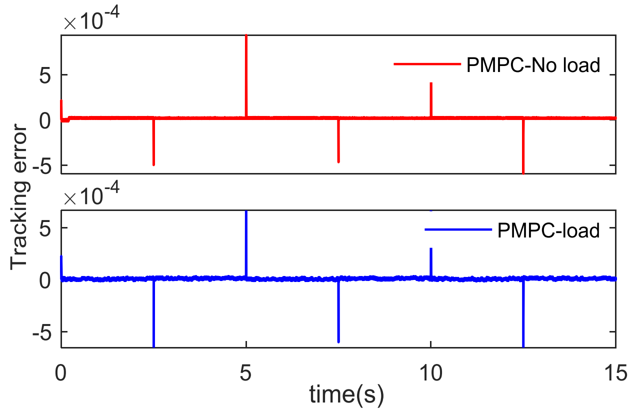
FIGURE 18. PMSLM sine wave position tracking.

trajectory. In order to prove that the controller designed in this paper has the ability to resist uncertainty interference, this paper will simulate the influence of uncertain factors in the actual motor operation by randomly changing the load of the linear motor. The random load situation is shown in Fig. 17.

Fig. 18 and Fig. 19 are the trajectory tracking comparison waveform diagrams of PMSLM when running with random load and when running without load. In Fig. 18, the root



(a) Trajectory tracking contrast waveform



(b) Trajectory tracking error comparison waveform

FIGURE 19. Position tracking of PMSLM triangle wave.

mean square tracking error of the trajectory without load is 2.003e-5, and the root mean square tracking error of the trajectory with load is 1.3549e-5. In Fig. 19, the root mean square tracking error of the unloaded trajectory is 2.4071e-5, and the root mean square tracking error of the loaded trajectory is 1.8599e-5. Observing the tracking error waveforms in Fig. 18 and Figure 19, it can be found that the error level with load is the same as the error level without load. Therefore, it is shown that the controller designed in this paper can resist the influence of random errors shown in Fig. 17, so it is proved that the controller designed in this paper can resist the interference of external uncertain factors.

B. EXPERIMENTAL PART

The research goal of this paper is to simplify the PMSLM control system and optimize the accuracy of trajectory tracking. The velocity model predictive controller is an intermediate process of designing the position model predictive controller.

In order to test the effectiveness of the researched PMPC, this article is based on the STM32 development board and Matlab automatic code generation tool for experimental verification. The use of STM32CubeMX software to generate the underlying configuration code allows R&D personnel to focus on the algorithm implementation part and improve work efficiency. The experimental platform of permanent

FIGURE 20. Permanent magnet synchronous linear motor.

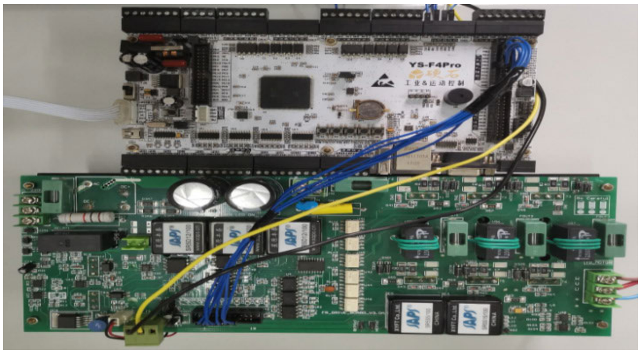


FIGURE 21. Control and drive circuit.

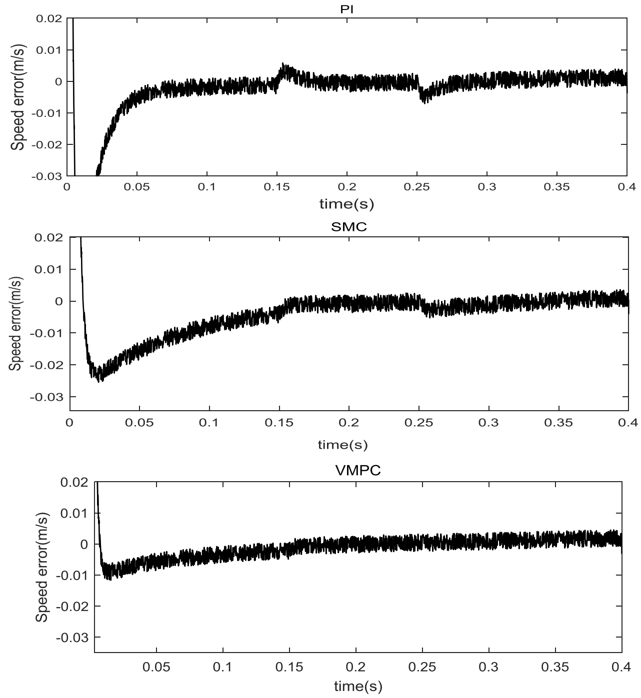


FIGURE 22. PMSLM running speed tracking error.

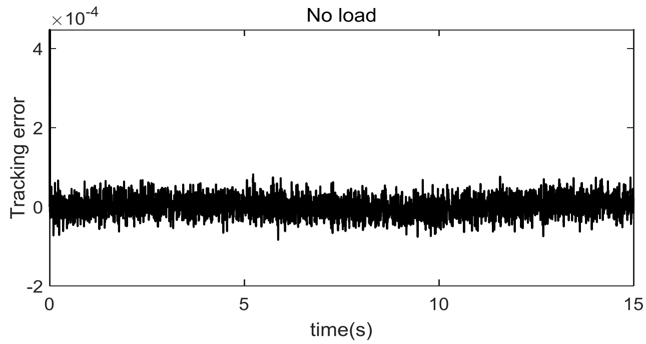


FIGURE 23. No load during motor operation.

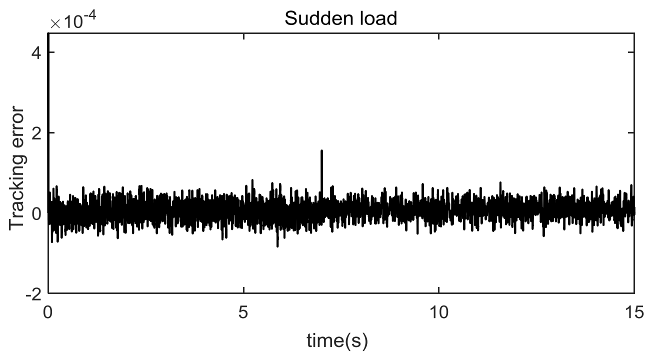


FIGURE 24. Sudden load during motor operation.

magnet synchronous linear motor is shown in Fig. 20. The code generation tool generates control algorithm c generation and the STM32 kernel code configured by STM32CUBE is connected, and then the successfully compiled code is downloaded to the STM32 development board. STM32 controls the PMSLM movement indirectly through the control driver; STM32 ADC module and timer module obtain the electrical signal and position signal of PMSLM through Hall sensor and MicorE grating encoder respectively; The sampling frequency of the experimental platform is 18KHz.

Fig. 22 shows the comparison waveforms of PMSLM motor running speed tracking error under the control of PI, SMC and VMPC controllers. In the experiment, set the running speed of PMSLM to 0.5m/s and start with load. At 0.15s, the motor starts to run with no load, and at 0.25s, the motor runs with load again. By comparing the three tracking error waveform diagrams, it can be found that the tracking error of the VMPC designed in this paper fluctuates less during the motor load and load reduction operation, which effectively illustrates the superiority of the VMPC control performance.

Fig. 23 shows the tracking error when the linear motor tracks the sinusoidal trajectory, and the motor is running without load; Fig. 24 shows the tracking error when the sinusoidal trajectory is followed by a sudden 50N load in 7.5s. Comparing Fig. 23 and Fig. 24, it is found that the tracking error only changes when the load is suddenly applied, and the error at other moments remains unchanged. Therefore, it shows that the PMPCK controller designed in this paper has superior ability to resist external disturbances.

Fig. 25 shows the trajectory tracking error waveform diagram of PMSLM when tracking the sawtooth trajectory under no-load conditions. Figure 26 shows the trajectory tracking error waveform diagram when the load is suddenly applied at 7.5s during the process of PMSLM tracking the sawtooth trajectory. Comparing Fig. 25 and Fig. 26, it can be found that the tracking trajectories in the two cases are almost the same, which further proves that the control strategy designed in this paper has superior anti-disturbance ability.

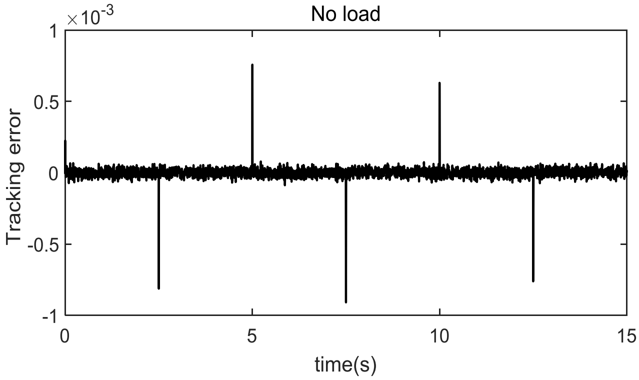


FIGURE 25. No load during motor operation.

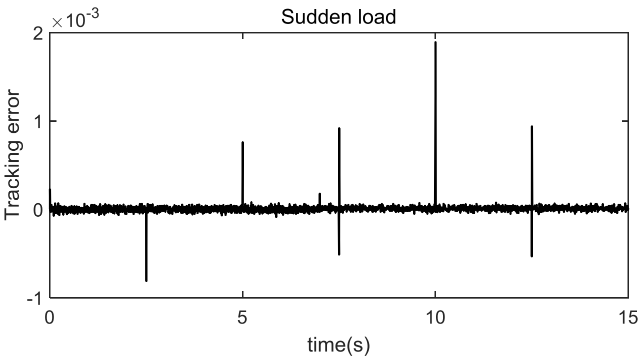


FIGURE 26. Sudden load during motor operation.

VII. CONCLUSION

In this paper, two schemes of position model predictive controller are designed, and the second scheme is verified by experiments. First, when the linear motor carries a random load, the VMPC controller designed is compared with the traditional PI and SMC controllers, which proves the superiority of the speed controller designed in this paper. Then the PMPC controller is compared with PI and TSMC control schemes. The results show that the scheme designed in this paper can effectively improve the control function of the control system and improve the position tracking accuracy of the control system.

This paper proves the effectiveness and superiority of the position model predictive controller designed in this paper through simulation and experiment. In future research, we will continue to study the application of model predictive control algorithms in permanent magnet synchronous linear motor control systems. Try to use the model prediction algorithm to design the PMSLM control system into a non-cascaded motor control system with position loop, speed loop and current loop controllers. And the non-cascade control strategy is applied to the multi-axis permanent magnet synchronous linear motor control system.

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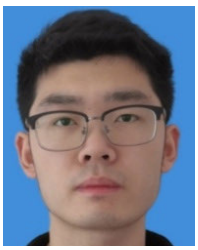

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