Improved Multi-step FCS-MPCC with Disturbance Compensation for PMSM Drives

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Abstract—In this paper, an improved multi-step finite control set model predictive current control (FCS-MPCC) strategy with speed loop disturbance compensation for permanent magnet synchronous machine (PMSM) drives system is proposed. In order to improve the steady-state performance of the system, multi-step prediction has been proposed in FCS-MPCC strategy. However, because the conventional multi-step prediction has the defect of heavy computational burden, an improved multi-step finite control set model predictive current control (IM-MPCC) strategy is proposed. Furthermore, in order to improve the dynamic response of the system, a disturbance compensation (DC) mechanism based on extended state observer (ESO) is added to estimate and compensate the total disturbance in the speed loop for PMSM system. The simulation results validate the effectiveness of the proposed control strategy.

Index Terms—Finite Control Set Model Predictive Current Control (FCS-MPCC), Multi-step Prediction, PMSM, Extended State Observer (ESO)

I. INTRODUCTION

Permanent magnet synchronous motor (PMSM) has the advantages of small size, high power density, high ratio of moment of inertia and high operating efficiency, which makes it widely used in electric vehicles, ships, railway transportation and industrial robot control and other fields[1]-[2]. However, PMSM drive system is a complex nonlinear multivariable coupling system, which is easily interfered by system parameter uncertainty and external disturbance, which make it difficult to meet the increasing control requirements in the field of high-precision servo control[3]. Traditional linear control strategies, have slow response time under parameter changes and external disturbances, which may lead to unsatisfactory dynamic performance of the system[4]-[6]. In order to solve these problems, many new nonlinear control technologies have been studied and applied to the PMSM drives system, such as sliding model control[7], model reference adaptive control[8], active disturbance rejection control[9], model predictive control (MPC)[10], etc.

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Because of simple implementation, straightforward handling of nonlinearities and constraints, and good dynamic response, the MPC has attracted more attention in recent years. Model predictive control can be divided into continuous control set model predictive control (CCS-MPC)[11]-[12] and finite control set model predictive control (FCS-MPC)[13]. Compared with CCS-MPC, FCS-MPC does not need complex pulse width modulation, which directly control the inverter with switching signals[14].

But, since FCS-MPC is based on a certain number of control sets, there must be a defect that large ripples lead to unsatisfactory steady-state performance[15]. In order to reduce the torque and magnetic flux ripple, in [16], two non-zero vectors are applied in one control cycle to obtain better steady-state performance. In [17], a passivity-based model predictive control (PB-MPC) strategy is proposed, which improves the steady-state performance of the system while reducing the computation. T.Geyer et al.[18] propose a modified sphere algorithm, which can solve the optimization problem underlying MPC for long horizons. But, in the case of multi-level, the spherical decoding algorithm also has its limitations. Therefore, an improved spherical decoding algorithm is proposed in [19], which makes direct MPC with long horizons an attractive and computationally viable control scheme. However, the complexity of the algorithm makes it difficult to implement. These methods are improved compared with the multi-step FCS-MPC, but the control system is still vulnerable to the system parameters uncertainty and external disturbances[20].

In order to suppress the system parameters uncertainty and external disturbances, so as to improve the dynamic response of the system, disturbance observer technology is gradually introduced into the field of high performance control of PMSM drives[21]-[23]. In [1], the predictive function control method (PFC) is combined with the extended state observer (ESO) to obtain the optimal control rate by minimizing the quadratic performance index, which has certain anti-interference effect. But in the case of strong disturbance, the result is not satisfactory.

Motivated by the above-mentioned challenges, an improved multi-step FCS-MPCC strategy with speed loop disturbance compensation is proposed to achieve improve the
steady-state performance and dynamic response for PMSM system. The design philosophy of the proposed strategy is explicitly demonstrated in the following two phases. First, based on single-step prediction, use the optimal voltage vector and the sub-optimal voltage vector calculated by the cost function as the vector waiting to be applied. According to the range of the optimal voltage vector which predicted in the second step, the vector applied to the inverter is determined in the first step. Second, in order to improve the dynamic response of the system, a disturbance compensation mechanism based on extended state observer (ESO) is added to estimate and compensate the total disturbance for the speed loop.

The structure of this paper is as follows: Section II introduces the mathematical model of PMSM and the conventional multi-step model. Section III explains the proposed control strategy in this paper. The simulation results and conclusion of the proposed strategy are shown in Section IV and Section V respectively.

II. CONVENTIONAL FCS-MPCC

A. PMSM Model

The mathematical model of PMSM can be described as follows:

\[ u_d = R_s i_d + L_d \frac{d i_d}{dt} - \omega_r L_q i_q \]  
\[ u_q = \omega_r L_d i_d + R_s i_q + L_q \frac{d i_q}{dt} + \omega_r \psi_f \]  
\[ J \frac{d \omega}{dt} = - \frac{3}{2} p_n (\psi_f i_q + (L_d - L_q) i_d i_q) - B \omega - T_L \]

where \( u_d, i_d, L_d \) represent d axis voltage, current, inductance respectively. \( u_q, i_q, L_q \) represent q axis voltage, current, inductance respectively. \( R_s, p_n, \psi_f \) represent the stator resistance, the number of pole pairs, rotor flux respectively. \( \omega_r, \omega, J, B \) and \( T_L \) represent electrical angular velocity, mechanical angular velocity, moment of inertia, friction coefficient, load torque respectively.

B. Single-step FCS-MPCC

Compared with the system which adopts FOC strategy, the cost function which is based on the error is introduced to the current internal loop instead of PI controller. The numbers of the voltage vectors in the finite control set depend on the selected inverter, and the optimal voltage vector is obtained by minimize the cost function, which can be applied to the inverter directly.

According to the model (1),(2) the differential form of the current is obtained by discretizing the current state equation by the forward Euler method.

\[ i_d(k+1) = (1 - R_s G) i_d(k) + L_d G \omega_r e(k) i_q(k) + G u_d(k) \]  
\[ i_q(k+1) = -L_d H \omega_r e(k) i_d(k) + (1 - R_s H) i_q(k) + H u_q(k) - \psi_f H \omega_r e(k) \]

where \( T_s \) is the sample time, \( G = \frac{T_s}{T_p}, \) \( H = \frac{T_s}{T_p} \).

Because there exists the computation delay in the actual system, the optimal voltage vector at the present sampling period will be applied to the inverter at the next sampling period, which will influence the system performance. It is necessary to make one-step delay compensation for the system. Equation (4),(5) can be used to compensate one step before the model prediction, then the predicted current value and cost function value can be obtained by putting different voltage vector from the finite voltage vector control set \( \{u_{fv}\} \) into the following formula:

\[ i_{dv}^{pre}(k+1) = (1 - R_s G) i_d(k+1) + L_d G \omega_r e(k+1) \]
\[ i_{qv}^{pre}(k+1) = -L_d H \omega_r e(k+1) i_d(k+1) + H u_q^f(k+1) \]
\[ g = |i_d^s - i_d^{pre}(k+1)| + |i_q^s - i_q^{pre}(k+1)| \]

where, \( i_s^* \) is current reference. In formula (8), the first term and second term evaluate the predicted current error, the last term is the current constraint condition, which can be expressed as

\[ \text{lim}(i_{dv,q}^{pre}(k+1)) = \begin{cases} 0, & \text{if } i_{dv}^{pre}(k+1) \leq i_{max} \\ \infty, & \text{if } i_{dv}^{pre}(k+1) > i_{max} \\ \text{or } i_{qv}^{pre}(k+1) \leq i_{max} \\ \infty, & \text{if } i_{qv}^{pre}(k+1) > i_{max} \end{cases} \]

where \( i_{max} \) is the maximum instantaneous current.

C. Conventional Multi-step FCS-MPCC

The prediction time domain can be extended to N step on the basis of single-step FCS-MPCC, the following equations (10),(11),(12) can be obtained:

\[ i_{dv}^{pre}(k+N) = (1 - R_s G) i_d(k+N) + L_d G \omega_r e(k+N) \]
\[ i_{qv}^{pre}(k+N) = -L_d H \omega_r e(k+N) i_d(k+N) + H u_q^f(k+N) \]
\[ g = \sum_{n=1}^{N} \left[ |i_d^{*} - i_d^{pre}(k+n)| + |i_q^{*} - i_q^{pre}(k+n)| + \text{lim}(i_{dv,q}^{pre}(k+n)) \right] \]

\[ \text{lim}(i_{dv,q}^{pre}(k+n)) = \begin{cases} 0, & \text{if } i_{dv}^{pre}(k+n) \leq i_{max} \\ \infty, & \text{if } i_{dv}^{pre}(k+n) > i_{max} \end{cases} \]

\[ \text{or } i_{qv}^{pre}(k+n) \leq i_{max} \]

where \( n = 1, 2, \ldots, N \), \( N \) is the predicted step size, the current limit condition is expressed as (13).

![Fig. 1: The finite voltage vector control set.](Image)
has to calculate at least 72 times; with the increase of step size, the amount of calculation will increase exponentially, and when \( N = 3 \), the controller needs at least 584 operations. Although the long prediction step size may bring better steady-state performance to the system, the algorithm is difficult to implement because of the limited processing capacity of the processor in the actual system.

III. IMPROVED MULTI-STEP FCS-MPCC WITH SPEED DISTURBANCE COMPENSATION

The voltage vector selected by the traditional FCS-MPC method is only optimal for one control cycle, and it is not optimal for multiple control cycles, which makes the steady-state performance of the system unsatisfactory. As shown in Fig. 2, the current value after one step delay compensation at time \((k+1)T_{pre}\), the current prediction value of the finite control set is obtained through the prediction model at time \((k+1)T_{pre}\), and the second step prediction is performed at time \((k+2)T_{pre}\). It is easy to find that the control quantity closest to the reference value obtained at time \((k+1)T_{pre}\) is not optimal at time \((k+2)T_{pre}\). This problem illustrates that single-step prediction may make the system have unsatisfactory steady-state performance. The proposed strategy of IM MPCC in the paper can improve these shortcomings and has less computational burden.

![Fig. 2: Multi-step FCS-MPCC.](image)

Furthermore, a disturbance compensation (DC) mechanism based on extended state observer (ESO) has been added to estimate and compensate the total disturbance of the speed loop to improve the dynamic response of the system. The proposed strategy is shown in Fig.3.

A. Improved Two-step FCS-MPCC

On the basis of single-step prediction, the eight voltage vectors are calculated by the prediction model equation (6, 7) and the cost function equation (8) to obtain the voltage vectors that minimize and subminimize the cost function. We call it the optimal output voltage vector \( u_{out_{min1}} \) and the sub-optimal output voltage vector \( u_{out_{min2}} \) at time \((k+1)T_{pre}\).

\[
\begin{align*}
u_{out_{min1}} &= \begin{bmatrix} S_{a_{min1}} \\ S_{b_{min1}} \\ S_{c_{min1}} \end{bmatrix}, \{ \min 1(g_i), i = 0,1,...7 \} \\
u_{out_{min2}} &= \begin{bmatrix} S_{a_{min2}} \\ S_{b_{min2}} \\ S_{c_{min2}} \end{bmatrix}, \{ \min 2(g_i), i = 0,1,...7 \} 
\end{align*}
\]

Calculate the optimal and sub-optimal current prediction values at time \((k+2)T_{pre}\) through the prediction model, and express the prediction model as follow:

\[
\begin{align*}
\mathbf{i}^{pre}_{d_{min1}}(k+2) &= (1 - R_s G) \mathbf{i}^{pre}_{d_{min1}}(k+1) + G u^d_{i k} + L_d G \omega_r c(k+2) \mathbf{i}^{pre}_{d_{min1}}(k+1) \\
\mathbf{i}^{pre}_{q_{min1}}(k+2) &= -L_s H \omega_r c(k+2) \mathbf{i}^{pre}_{q_{min1}}(k+1) + H u^d_{i k} + (1 - R_s H) \mathbf{i}^{pre}_{q_{min1}}(k+1) - \psi_f H \omega_r c(k+2)
\end{align*}
\]

Compared with the conventional two-step prediction, the proposed improved two-step prediction will obtain 16 cost function values, reducing at least 48 model and cost function calculations. The new cost function select act voltage vector applied to inverter at time \((k+1)T_{pre}\) based on the range of optimal voltage vector predicted at time \((k+2)T_{pre}\).

\[
g_{sum} = \begin{bmatrix} A \\ B \end{bmatrix} = \begin{bmatrix} g_{min1}^0 & g_{min1}^1 & \ldots & g_{min1}^7 \\ g_{min2}^0 & g_{min2}^1 & \ldots & g_{min2}^7 \end{bmatrix}
\]

\[
V_{out} = \begin{cases} u_{out_{min1}}, & if \ min(g_{sum}) \in A \\ u_{out_{min2}}, & if \ min(g_{sum}) \in B \end{cases}
\]

where, \( A \) and \( B \) respectively represent the set of cost function values at time \((k+2)T_{pre}\) calculated based on the optimal voltage vector and the sub-optimal voltage vector, \( g_{sum} \) is the set of all predicted cost function values at time \((k+2)T_{pre}\), and \( V_{out} \) is the voltage applied to the inverter in the end. If the minimum cost function value in \( g_{sum} \) belongs to \( A \) set, the optimal voltage vector at time \((k+1)T_{pre}\) is applied; if the minimum cost function value in \( g_{sum} \) belongs to \( B \) set, the suboptimal voltage vector at time \((k+1)T_{pre}\) is applied. This strategy can be topologically applied to the long prediction step size model. Compared with the conventional FCS-MPCC cost optimization method, this strategy has obvious advantages in less computation but similar steady-state performance. When the prediction steps \( N = 3 \), the number of calculations of the model and cost function is only 56 times. The final selection function in multi-step prediction can be described as

\[
g_{sum} = \begin{bmatrix} A \\ B \\ C \\ \ldots \end{bmatrix}^T
\]
If the minimum cost function value in $g_{sum}$ belongs to set before the $\frac{2^{n-1}}{2^n}$-th, the optimal voltage vector at time $(k+1)T_{pre}$ is applied; if the minimum cost function value in $g_{sum}$ belongs to other set in $\frac{2^{n-1}}{2^n}$-th to $2^{n-1}$-th, the suboptimal voltage vector at time $(k+1)T_{pre}$ is applied. Since the final voltage vector acting on the inverter is always the voltage vector at time $(k+1)T_{pre}$, the effect is not as obvious when the prediction step is too long, so, the final step size is two.

**B. Speed Loop Disturbance Compensation**

Considering the uncertainty of system parameter uncertainty and external disturbance, the state variable $d_{\omega} = \frac{J_0}{J_n} - \frac{g_{pu}}{J_n} + \frac{p}{2}\psi_f (\frac{d}{d_{\omega}})$ is introduced, $J_0$ is the moment of inertia of the rotor. If the sampling time is small enough, $d_{\omega}$ can be regarded as approximately unchanged, so let $d_{\omega} = 0$.

From this, the new equation of state can be deduced as

$$\dot{\omega} = \frac{u^*}{J} + d_{\omega}, \quad d_{\omega} = 0 \quad (22)$$

According to the formula (22), the extended state observer (ESO) is designed as

$$\begin{align*}
\dot{z}_1 & = \frac{1}{k} z_2 - \beta_1(z_1 - \omega) \\
\dot{z}_2 & = -\beta_2(z_1 - \omega) \quad (23)
\end{align*}$$

As long as the parameters $\beta_1$ and $\beta_2$ of the observer are adjusted appropriately, the system speed estimation value $z_1$ and the total disturbance estimation value $z_2$ can be obtained through the state observer. It can be seen from equation (23) that if the system $d_{\omega}$ is observed and compensated, the PMSM speed control system can be approximated as a first-order integral system.

The linear state error feedback control law is adopted for the input $u_0$, so the control law based on disturbance compensation controller can be obtained as

$$\begin{align*}
u_0 & = k_p(\omega^* - z_1) \\
i_{q}^* & = u_0 - k_z z_2 \quad (24)
\end{align*}$$

where $k = \frac{2\omega}{2\psi_f}$, $k_p$ is the magnification factor, $\omega^*$ is the reference speed.

**IV. SIMULATION AND ANALYSIS**

In order to test the effectiveness of the control strategy proposed in Fig.3, some simulation results are given on the Matlab/simulink. The following three groups of simulation results are carried out. The first is to show the steady-state performance of IM MPCC for PMSM by comparing with conventional MPCC. The second is to verify that the proposed strategy can improve the dynamic response of the system by comparing with proposed IM MPCC. The last is to reflect the high-order harmonic reduction effect of the current control strategy by total harmonic distortion (THD). The specific simulation parameters of the surface-mounted permanent magnet synchronous motor are shown in Table I.

**TABLE I: Parameter Values of PMSM**

| Descriptions      | Parameters | Nominal Values |
|-------------------|------------|----------------|
| DC link Voltage   | $V_{dc}$   | 311 (V)        |
| Stator Resistance | $R_s$      | 1.3 Ω          |
| Stator Inductance | $L_s$      | 0.0085 (H)     |
| Flux              | $\psi_f$   | 0.175 (Wb)     |
| Pole Pairs        | $P$        | 4.0            |
| Inertia           | $J$        | 0.008 Kg.m²     |

**A. Steady-state Performance**

In order to test the control strategy has improved the steady-state performance of the system, the single-step model predictive current control (MPCC) strategy is compared with the proposed improved multi-step model predictive current control (IM MPCC) strategy in this part. The simulation results are shown in Fig 4. Except for the controller differences mentioned above, these two simulations have exactly the same structure and parameters. It can be seen that ripple of three-phase current (take A phase current $i_a$ as an example), torque ( $T_e$) and speed ( $\omega$) are all reduced.

**B. Dynamic Response**

In order to fairly test the dynamic response of the proposed control strategy, the improved multi-step model predictive control strategy with speed loop disturbance compensation (IM MPCC+DC) is compared with the control strategy without disturbance compensation. Except for this differences mentioned above, these two simulations have exactly the same structure and parameters. The dynamic response of the system results from the sudden change of load disturbance. The load disturbance is suddenly increased, and then suddenly reduced to 0 (load torque from 0 to 5Nm, and then jumps back to 0), the effect is shown in Fig 5. It can be seen that dynamic response of IM MPCC with speed loop DC is better than the strategy without DC.

**C. THD**

By comparing the high-frequency component with the basic component of the three-phase current, we can see that the three-phase current THD data of the three strategies are shown in Table II. It can be seen that compared with the initial single-step prediction measurement, the THD of the three-phase current of the proposed improved multi-step FCS-MPCC with speed disturbance compensation strategy for PMSM is reduced by 27.18% on average.

**V. CONCLUSION**

In this paper, an improved multi-step FCS-MPCC strategy with speed loop disturbance compensation for PMSM drives...
has been investigated. In order to improve the steady-state performance and reduce computation burden, an IM MPCC strategy is proposed. To further improve the dynamic response of the closed-loop system, a disturbance compensation (DC) mechanism based on extended state observer (ESO) has been added to estimate and compensate the total disturbance of the speed loop for PMSM system before the IM MPCC controller. The simulation results show that the steady-state performance and dynamic response are all improved in the proposed strategy. Therefore, the proposed control strategy in this paper has a good application prospect for high-precision PMSM drives and easier to implement.

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TABLE II: Three-phase Current THD Comparison Data

| Control Strategy       | Three-phase Current THD |
|------------------------|-------------------------|
|                         | $i_a$ | $i_b$ | $i_c$ |
| MPCC                   | 1.034% | 1.046% | 1.040% |
| IM MPCC                | 0.773% | 0.796% | 0.792% |
| IM MPCC+DC             | 0.737% | 0.776% | 0.759% |

Fig. 4: Steady-state performance comparison between conventional MPCC and IM MPCC. (a) Speed. (b) Torque. (c) and (d) Phase-current. (represent the phase current under zero load and 5Nm load, respectively.)

Fig. 5: Response of the IM MPCC strategy with and without disturbance compensation are compared. (a) Speed. (b) Torque.
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