Overview of Predictive Control Technology for Permanent Magnet Synchronous Motor Systems

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Abstract: Permanent magnet synchronous motors (PMSMs) are commonly used in the automation industry. With the speedy development of digital system processors, predictive control as a modern control scheme has been applied to improve the dynamic performance and work efficiency of PMSMs. This paper provides an overview of the research status of PMSM-based predictive control strategies. The deficiencies of the three most popular predictive schemes, deadbeat predictive control, finite-control-set model predictive control, and continuous-control-set model predictive control, and existing improvement strategies such as delay compensation schemes, robust control schemes, and multi-vector control schemes, are summarized. Finally, current technological trends are discussed, emphasizing future research directions for predictive control in PMSM drive systems.

Keywords: predictive control; continuous-control-set model predictive control (CCS-MPC); finite-control-set model predictive control (FCS-MPC); deadbeat predictive control (DPC); permanent magnet synchronous motor (PMSM)

1. Introduction

Permanent magnet synchronous motors (PMSMs) have established widespread attention and research because of their compact structure, high torque-to-current ratio, high power density, good fault tolerance, and high work efficiency [1–6]. At present, permanent magnet synchronous motors are widely used in many industrial fields, such as for ships, engineering machinery, aerospace engines, and intelligent robots [7–11].

At the same time, with the development of electric vehicles, PMSMs are widely used in the field of vehicles due to their flexible control methods and high reliability, and are gradually becoming mainstream vehicle drive motors [12–16].

The classic control methods of the PMSM drive system include vector control [17–19] and direct torque control [20–24]. Generally, the PI controller (proportional-integral) of vector control involves more intermediate variables in the design process of parameter tuning. However, DTC control has a large torque ripple and causes high-frequency noise. Therefore, with the development of modern control technology, position sensorless control [25–30], sliding mode control [31–35], fault-tolerant control [36–41], and predictive control [42–46] have been studied. Since the input signals of power electronic devices are discrete, discrete-based digital control technology has developed rapidly. At the same time, with the rapid development of the field of digital signal processing, the computing power of chips has been greatly enhanced, so predictive control has attracted much attention.

Predictive control was proposed and used as early as the 1980s. According to different predictive models and optimization algorithms, it is classified according to different characteristics of predictive methods in the field of electric drive. Predictive control can be divided into DPC [47–52], hysteresis predictive control [53–55], trajectory predictive control [56–58], and MPC. Table 1 details the characteristics of each model. Among them, MPC can be divided into finite-control-set model predictive control and continuous-control-set model predictive control.
Table 1. Prediction Algorithm Feature Comparison Summary Table.

<table>
<thead>
<tr>
<th>Methods</th>
<th>Whether PWM Modulation Is Required</th>
<th>Fixed Switching Rate</th>
<th>Algorithm Complexity</th>
<th>Whether to Include Constraint Processing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deadbeat Predictive Control</td>
<td>Yes</td>
<td>Yes</td>
<td>Normal</td>
<td>No</td>
</tr>
<tr>
<td>Hysteresis Predictive Control</td>
<td>No</td>
<td>No</td>
<td>Normal</td>
<td>No</td>
</tr>
<tr>
<td>Trajectory Predictive Control</td>
<td>No</td>
<td>No</td>
<td>Normal</td>
<td>Yes</td>
</tr>
<tr>
<td>Continuous-set model predictive control</td>
<td>Yes</td>
<td>Yes</td>
<td>Complicated</td>
<td>Yes</td>
</tr>
<tr>
<td>Finite-set model predictive control</td>
<td>No</td>
<td>No</td>
<td>Complicated</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Predictive control has received more attention and has been extensively studied, which can improve the dynamic performance and stability of permanent magnet synchronous motors to adapt to complex and harsh application environments. With the development of modern control technology, power electronics technology, and finite element simulation technology [59–61], predictive control has been extensively studied. New predictive control strategies have been proposed one after another, meeting higher prediction accuracy, higher reliability, and better dynamic response performance.

In predictive control, DPC and MPC are most suitable for PMSM, and they are also the two most widely studied at present. Deadbeat predictive control has the advantages of decent dynamic performance, high control precision, and low calculation amount. For deadbeat current predictive control, it calculates the voltage based on a discretized mathematical model and converts it into a switching signal through pulse width modulation technology.

Model predictive control, as a modern control theory, is based on discrete dynamic systems and optimizes the control variables in the future according to the predictive model of the system to achieve the optimal control effect. In MPC, the controller can compute the best control input according to the current state and the predicted value of the future state, and then revise the prediction model and update the control strategy through feedback. MPC can jointly control multiple control variables, and can deal with complex control problems including nonlinear, time-varying, and multivariable problems. Therefore, MPC is perfectly suitable for PMSM strongly coupled nonlinear systems.

In addition, MPC can be flexibly adjusted according to different control objectives, so as to improve the control performance and efficiency of the motor and meet different control requirements. For example, model predictive current control (MPCC) [62,63] takes the current as the control target and uses the current and the given current as constraints at the next moment to optimize the optimal voltage vector output at this moment. The model predictive torque control (MPTC) takes torque and flux linkage as the control targets [64,65]. In addition, it also includes model predictive flux control [66] and model predictive speed control [67].

However, there are many problems in the application of FCS-MPC, CCS-MPC, and DPC in PMSM. For example, they share a mismatch of parameters, which leads to a decrease in prediction accuracy, which leads to a decrease in system reliability. For their existing problems, the existing compensation measures and research directions are mainly shown in Figure 1.

The main work of this paper is to introduce the existing problems and improvement schemes of PMSM predictive control from the perspective of technology development. The main contribution is a summary of the current state of research on different types of predictive control methods. In essence, the paper explores and studies predictive control. The feasibility, versatility and effectiveness of these methods are analyzed and summarized.
Additionally, the future development and research direction of predictive control are further discussed.

![Diagram of predictive control methods](image)

**Figure 1.** The main research direction and classification of predictive control.

2. Composition of a PMSM Drive System Based on Predictive Control

2.1. Structure of a PMSM System

Traditional predictive control is based on a discrete mathematical model of the drive motor. Additionally, it is predicted according to the characteristics of the switching state of the voltage source inverter.

Take the most common three-phase PMSM as an example. Figure 2 is a topology diagram of the most common two-level three-phase voltage inverter in PMSM. The three-phase full bridge used consists of six IGBT power devices. According to the principle that the upper and lower switching devices of the inverter (VSI) cannot be turned on at the same time, eight switch combinations are formed. The conduction of the upper bridge arm of the inverter is 1 and the conduction of the lower bridge arm is 0. For different switch states, 8 basic voltage vectors can be obtained, and each vector can be expressed by Equation (1).

\[
U_{out} = \frac{2}{3} U_{dc} (s_A + s_B e^{j\frac{2}{3}\pi} + s_C e^{-j\frac{2}{3}\pi})
\]

where \(U_{dc}\) is the DC bus voltage, \(j\) is an imaginary number. Map the basic spatial voltage vectors of 8 combinations onto the complex plane, as shown in Figure 2b. The red arrow from Figure 2a indicates the space voltage vector corresponding to the inverter switching signal (100).
Figure 2. Topology of voltage source inverter and spatial distribution diagram of voltage vectors. (a) Topology of voltage source inverter (b) Spatial distribution diagram of voltage vector.

The realization of the PC algorithm relies on the discrete mathematical model. Based on the above-mentioned three-phase PMSM inverter topology as an example, the mathematical model of the three-phase PMSM is introduced.

For the convenience of control, the motor equation of PMSM has been transformed by Clark and Park, which can be written as:

\[
\begin{bmatrix}
    u_d \\
    u_q
\end{bmatrix}
= R_s \begin{bmatrix}
    i_d \\
    i_q
\end{bmatrix} + \frac{d}{dt} \begin{bmatrix}
    \psi_d \\
    \psi_q
\end{bmatrix} + \omega_e \begin{bmatrix}
    -\psi_q \\
    \psi_d
\end{bmatrix}
\]  

where \(u_d, i_d, \text{ and } \psi_d\) represent voltage, current, and magnetic flux on the \(d\)-axis, respectively; \(i_q, u_q, \text{ and } \psi_q\) are represent current, voltage, and magnetic flux on the \(q\)-axis, respectively; and \(\omega_e\) is the electrical angular velocity. \(\psi_q\) and \(\psi_d\) can be expressed as:

\[
\begin{bmatrix}
    \psi_d \\
    \psi_q
\end{bmatrix}
= \begin{bmatrix}
    L_d \\
    L_q
\end{bmatrix} \begin{bmatrix}
    i_d \\
    i_q
\end{bmatrix} + \begin{bmatrix}
    0 \\
    \psi_f
\end{bmatrix}
\]  

where \(L_d\) and \(L_d\) are the stator inductance of \(d\) and \(q\) axis. \(\psi_f\) is the permanent magnet flux linkage.

The electromagnetic torque equation of the motor is expressed as Equation (4), and the mechanical equation can be expressed as Equation (5).

\[
T_e = \frac{3}{2} p_n i_q \left( (L_d - L_q) i_d + \psi_f \right)
\]  

\[
f \frac{d\omega_m}{dt} = T_e - T_L - B\omega_m
\]  

where \(p_n\) is the number of pole pairs, \(J\) is the rotational inertia, \(B\) is the damping coefficient, \(\omega_m\) is the mechanical angular velocity, and \(T_e\) and \(T_L\) are the electromagnetic torque and the load torque, respectively. The mathematical model of the time invariant model of PMSM in a synchronous rotating reference frame can be expressed as:

\[
\begin{align*}
pi_q(t) &= -\frac{R_s}{L_q} i_q(t) - \frac{L_d}{L_q} \omega_m(t) i_d + \frac{1}{L_q} u_q(t) - \frac{\psi_f \omega_m(t)}{L_q} \\
pi_d(t) &= -\frac{R_s}{L_d} i_d(t) + \frac{L_q}{L_d} \omega_m(t) i_q + \frac{1}{L_d} u_d(t)
\end{align*}
\]  

where \(pi_d(t)\) and \(pi_q(t)\) represent the reciprocal of the \(d\)-axis and \(q\)-axis currents, respectively. Based on the predictive current control, the motor equation is generally discretized through...
the forward Euler formula [68], combined with Equations (2) and (3). The equation in the continuous time domain can be rewritten as:

\[
\begin{bmatrix}
    u_d(k) \\
    u_q(k)
\end{bmatrix} = \begin{bmatrix}
    \frac{L_d}{T_s} & \frac{i_d(k+1) - i_d(k)}{T_s} \\
    \frac{L_q}{T_s} & \frac{i_q(k+1) - i_q(k)}{T_s}
\end{bmatrix} + \begin{bmatrix}
    0 \\
    \omega_f q_f
\end{bmatrix} + \begin{bmatrix}
    R_s & -\omega_L L_q \\
    \omega_L L_d & R_s
\end{bmatrix} \begin{bmatrix}
    i_d(k) \\
    i_q(k)
\end{bmatrix}
\]

(7)

where \( T_s \) is the sampling time, “\( k \)” represents the current moment, and “\( k + 1 \)” represents the next instant.

It is worth noting that the relationship between these motor equations and parameters is the basis of PMSM predictive control, not only for predictive current control, but also for predictive torque and predictive flux linkage control, etc.

2.2. Analysis of the Predictive Control Principle

First of all, the following analysis is based on a one-step forecast unless otherwise stated. Deadbeat control makes use of the discrete mathematical model of the system to predict the output required by the system at the next time according to the state of system at the current time. This algorithm can theoretically make the error of the controlled quantity zero. For example, for the deadbeat current prediction, its derivation formula is shown in Equation (8).

\[ u_s^{ref} = R_s i_s(k) + \frac{L_s}{T_s} \left( i_s^{ref} - i_s(k) \right) + E_s \]

(8)

where \( u_s^{ref} = [u_d^{ref} u_q^{ref}]^T; i_s^{ref} = [i_d^{ref} i_q^{ref}]^T; L_s = [L_d L_q]^T; \) and \( E_s \), respectively, represent the counter electromotive force on the \( d-q \) axis.

For the deadbeat predictive control current control, it calculates the reference voltage at the next time through the discrete mathematical model of the motor and the predicted current value and outputs the switching signal to drive the motor through the pulse width modulation technology. The control flow chart is shown in Figure 3. In Figures 3 and 4, * represents the reference value. However, because its prediction depends on the precise mathematical model, disturbance or parameter mismatch will affect its control performance, which is also the main direction of current research.

**Figure 3.** Deadbeat predictive control diagram.

**Figure 4.** (a) Control block diagram of FCS-MPC; (b) control block diagram of CCS-MPC.
The MPC constrains the control target through the cost function. The basic design is the cost function design to ensure the system tracking characteristics and realize the reference tracking control. This part is the core of the system control. Usually, the cost function is designed as Equation (9).

\[
J(x) = \sum_{m=1}^{n} Q_m \left| x_m^* - x_m^p \right| = Q_1 \left| x_1^* - x_1^p \right| + Q_2 \left| x_2^* - x_2^p \right| + \ldots + Q_n \left| x_n^* - x_n^p \right| \tag{9}
\]

where \( n \) represents the number of tracked items, \( x^* \) represents the reference value, and \( x^p \) represents the predicted value based on the model.

For the FCS-MPC current control, it calculates the finite number of voltage vectors through the cost function according to the characteristics of the voltage source inverter. By selecting the vector output with the minimum value of the cost function, the switch of the inverter is driven to make the motor system run, and its control block diagram is shown in Figure 4a.

In contrast with FCS-MPC, the CCS-MPC uses an iterative approach to continuously approach the optimal solution. Its objective function is complex, and can be expressed as:

\[
\begin{align*}
J(x), & \quad x \in D \subset R \\
g_u(x) & \geq 0, \quad u = 1, 2, \ldots, s \\
h_v(x) & = 0, \quad v = 1, 2, \ldots, q
\end{align*} \tag{10}
\]

where \( J(x) \) represents the optimization objective function, that is, the value function; \( D \) is the value range of \( x \); and \( g_u \) and \( h_v \) represent s numbers of inequalities and q numbers of equality constraints, respectively. According to the nonlinear optimization theory, the general solution method of Equation (10) is the interior point method, which is a method to approach the optimal solution through iteration.

For CCS-MPC, it uses pulse width modulation technology to provide precise and fast current and speed control by using a voltage vector with arbitrary amplitude and phase angle on the voltage complex plane. Figure 4b is the control block diagram of CCS-MPC. However, since the constrained quadratic optimization problem has no explicit solution, it is tough to determine the optimal resolution in a short time by iterative solution, which limits the application of continuous model predictive control in motor drive systems.

According to the brief introduction and analysis of the above theories, many problems with them can be found. With the widespread application of predictive control, more and more scholars make contributions and carry out research to improve the performance of motor drive systems. The next chapter will detail the existing research methods.

3. An Overview of the Recent Development for Predictive Control Methods of PMSM

Here, we introduce and analyze related methods in order to clearly understand the development of different methods, and to discover more advantages and future development directions of DPC and MPC. We present these methods here, selected from papers validated with experimental results that allow quantification of the performance of the methods.

3.1. Deadbeat Predictive Control of PMSM

Based on the PMSM discretized drive system, sampling delay, inverter delay, and control system delay will all lead to a decrease in the prediction accuracy of the DPC strategy. In addition, the robustness of algorithms has been extensively studied due to over-reliance on mathematical models.

3.1.1. Delay Compensation

In [49,69], a deadbeat multi-step prediction compensation scheme is proposed. Multi-step prediction was carried out according to the current and voltage, and the voltage at time \( k + 2 \) was obtained as the reference voltage, and the voltage calculation formula is shown in Equation (11). Calculate the required current value according to time \( k \). After the
first step of prediction is completed, the predicted current value at time \( k + 1 \) needs to be saved in the register, and the second step prediction parameters are performed according to the current given value, motor inductance, resistance, flux linkage, and other related parameters to obtain the voltage value of \( u_{dq}(k+2) \). Therefore, the delay existing in the current loop is compensated, and the bandwidth of the current loop is improved [70].

\[
\begin{bmatrix}
  u^*_d \\
  u^*_q \\
\end{bmatrix} = \begin{bmatrix}
  u_{d(k+2)} \\
  u_{q(k+2)} \\
\end{bmatrix} = \begin{bmatrix}
  L_d & 0 & i^*_d \\
  0 & L_q & i^*_q \\
\end{bmatrix} + \begin{bmatrix}
  R_s - \frac{L_q}{L_d} & -L_d \omega_e & i_{d(k+1)} \\
  L_d \omega_e & R_s - \frac{L_d}{L_q} & i_{q(k+1)} \\
\end{bmatrix} + \begin{bmatrix}
  0 \\
  \psi_f \omega_e \\
\end{bmatrix}
\]

(11)

where \( u^*_d, u^*_q \) are reference voltages; \( i^*_d, i^*_q \) are reference currents.

Based on deadbeat predictive speed control, a control strategy considering the inherent delay of the speed loop with a disturbance observer is proposed in [71]. Velocity observers were proposed for cascading PSCs to alleviate this inherent latency problem. The problem of increasing robustness is also the most researched in deadbeat predictive control.

3.1.2. Robust Control Strategy

DPC relies on accurate discrete models, and system disturbances caused by parameter mismatches and load mutations will seriously affect the performance of motor control [72,73]. In order to solve this problem, the main research directions can be summarized into two groups. One is online parameter identification, to identify changes in parameters in real-time, and bring real parameter values into the control system to improve the accuracy [74,75]. Reference [76] proposed an online parameter identification method based on the Kalman filter algorithm to identify the parameters after decoupling the inductance and permanent magnet flux linkage. The identification accuracy was high, while the complexity was simplified and the multi-load load was significantly reduced.

Reference [77] proposes a multi-parameter identification method for high-frequency sinusoidal voltage injection when the motor is running at low speed, which not only takes into account both online and offline identification, but also avoids the coupling effect between multiple parameters. It effectively guarantees the identification accuracy of steady-state and transient resistance and flux linkage, and has a good identification effect. In [78], an improved DPCC with parameter identification is proposed. The parameter identification method was based on the reconstructed eigenvector of the current injection disturbance observer. Both the low-frequency band and the high-frequency band could ensure zero error in the steady-state current.

In [79], a method combining the deadbeat control and adaptive control methods is proposed. Reference [80] proposes a motor parameter identification strategy using the autoregressive least square method to adjust the deadbeat flow controller parameter. In [81], a method of citing the Lyapunov function to eliminate the current tracking error, which needs to control the rate of change of the Lyapunov function to be less than zero, is proposed. Reference [82] proposes a method to deal with sampling error through the sensitivity function.

The other type of research direction avoids the loss of robustness due to parameter mismatch and current tracking error through disturbance compensation by introducing a disturbance observer into the traditional DPCC [83]. Table 2 compares the advantages of existing disturbance observers. In [84], a current and disturbance observer was designed which could not only reduce the current harmonics caused by parameter mismatch, but also suppress the influence caused by current measurement errors through compensation. Based on the ideal model, Ref. [85] combined a sliding mode velocity controller and discrete DPC. Furthermore, a high-order sliding mode observer was designed for estimating disturbances and uncertainties in the double closed-loop, and for feedback. In [86], an exact model-based motion estimator was studied to estimate back-EMF and disturbances due to parameter changes.
3.2. FCS Model Predictive Control of PMSM

3.2.1. Optimization of the Cost Function

FCS-MPC can control multi-objective constraints. However, it is often necessary to consider the weight coefficient [90,91] when considering the parameter dimension. In order to simplify the design of the weight coefficient, many scholars have split or designed the cost function separately. For example, in [92], the flux torque cost function is split separately, as shown in (12). On this basis, Ref. [93] evaluated \( J_1 \) and \( J_2 \) twice in sequence, and reduced the number of alternative switch states for the second evaluation. In addition,
the optimization of multi-cost functions were examined in [94], the optimization of serial cost functions in [95], the standardization of control variables in [96], and the control of corresponding vectors in [97].

\[
J = K_T \left[ T_e^{ref} - T_e(k+1) \right]^2 + K_\psi \left[ \psi_s^{ref} - \psi_s(k+1) \right]^2
\]

(12)

where \( K_T \) and \( K_\psi \) are weight coefficients; \( T_e^{ref} \) is reference torque; and \( \psi_s^{ref} \) is reference magnetic flux.

For the design of weight coefficients, genetic algorithms, the neural network, and fuzzy control are widely used [98–100]. In [101], the neural network was used to conduct training data and realize the best full-time fast automatic selection; the control block diagram is shown in Figure 6. In [102], An optimization scheme based on an intelligent neural network is proposed to calculate the weight coefficient, but this strategy still needs to establish a cost function to evaluate the constrained target and involve the weight coefficient.

![Figure 6](image)

**Figure 6.** Flow chart of weight coefficient calculation based on neural network.

In addition to calculating accurate weight coefficients, Refs. [103–105] only considered the relationship between voltage vectors to optimize the design of the cost function and eliminate the weight coefficients. In [106,107], the weight coefficient was canceled by replacing torque and flux vector, so that the cost function only included flux. For polyphase PMSM, an auxiliary voltage vector combination was referenced. In [108], the harmonic current was eliminated by vector combination and the weight coefficient of the x-y subspace in the cost function was eliminated.

### 3.2.2. Multi-Vector Application Control

Due to the limited switch state adopted by FCS-MPC, the output voltage vector amplitude of the inverter was fixed, resulting in high-frequency current harmonics. Many scholars have tried to control the motor by outputting multiple switch state combinations in a discrete control cycle. Therefore, they are collectively referred to as “multi-vector strategies” [109–113].

In [114], the active voltage vectors and zero vector were applied in a single cycle. Adjust the amplitude of the active voltage vector through the zero vector. On this basis, reference [109] proposes a dual vector control strategy. After determining an optimal vector, the strategy continued to use the prediction algorithm to determine the second voltage vector, thus synthesizing a vector with an adaptable phase angle or amplitude to control the motor. “Three vector strategy” has been proposed successively [115]. Figure 7 is from [115], and as shown in Figure 8 is the schematic diagram of three vector functions. In [111]’s “three-vector strategy”, this strategy used a prediction algorithm to determine three vectors and used the space vector synthesis principle to obtain the three-phase duty cycle corresponding to the inverter. Among many finite set model predictive control
algorithms, the output vector amplitude and phase of this strategy can be adjusted freely, and the control accuracy of torque and flux linkage were greatly improved.

Figure 7. Voltage vector range of three methods based on MPTC. (a) One-vector-based. (b) Two-vector-based. (c) Three-vector-based.

Figure 8. Prediction sequence diagram. (a) Ideal situation; (b) actual situation.

In addition, the virtual voltage vector is proposed [116]. In [117], a hybrid control based on voltage vector combination is proposed. It uses more virtual vectors and unifies the switching frequency, which also makes the calculation more complex, but improves the quality of the stator current. For polyphase motors, a virtual voltage vector combination has been proposed based on the characteristics of the space voltage vectors [118–120]. In [119], a multi-vector control strategy for the dual three-phase PMSM drive system is proposed. By predicting the rotor position, the rotor position information is introduced into the predictive model, and the optimal voltage vector is calculated through the optimization algorithm to achieve the optimal torque and minimum current waveform distortion. A summary of the applications of different voltage vectors mentioned above is shown in Table 3 [18].

Table 3. Numerical Comparison under Different Model Predictive Control Strategies.

<table>
<thead>
<tr>
<th>Methods</th>
<th>Conventional MPC</th>
<th>Auxiliary Voltage Vector MPC</th>
<th>Double Vector MPC</th>
<th>Three-Vector MPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Executive time (μs)</td>
<td>18</td>
<td>24</td>
<td>31</td>
<td>33</td>
</tr>
<tr>
<td>Torque ripple (Nm)</td>
<td>1.21</td>
<td>1.06</td>
<td>0.78</td>
<td>0.86</td>
</tr>
<tr>
<td>Current THD analysis (%)</td>
<td>13.24</td>
<td>8.75</td>
<td>7.05</td>
<td>5.83</td>
</tr>
</tbody>
</table>

3.2.3. Multi-Step Predictive Control

As shown in Figure 2, when the traditional FCS-MPC acts on the three-phase PMSM it optimizes eight voltage vectors, while the number of vectors of the polyphase motor is more. Therefore, the single-step prediction will cause a delay, as shown in Figure 8.

In order to prevent prediction delay and low precision of single-step prediction, the “multi-step prediction” method was proposed [121–123]. For example, the model predictive torque control based on two-step prediction is proposed in [124]. First, the state of the
motor is predicted in one step to obtain the state of the motor in the next sampling period, and then the optimal voltage vector is calculated through a secondary optimization process, which is applied to the inverter drive motor.

In [125,126], two-step prediction is used to compensate for the delay. In [127], the Heun method is used to predict the current at the time of \( k + 1 \), and two-step prediction is carried out on the basis of this method. In [128], a correct PMSM based on numerical analysis is proposed. This method replaces the error caused by traditional forward Euler discretization. In [129,130], a multi-step predictive control strategy is proposed. First, the optimal and suboptimal current predictive values are calculated by the enumeration method, and then the current. However, multi-step prediction also leads to long calculation times and a more complex prediction process.

3.2.4. Reduce the Computational Burden

The traditional model predictive control method has higher computational complexity and control difficulty in the control of the polyphase motor. A simplified MPTC strategy for a dual three-phase permanent magnet synchronous motor is proposed in [131], which used 36 voltage vectors as prediction vectors \( \alpha-\beta \). The flux position and torque deviation in the \( x-y \) subspace were screened again to reduce the calculation time and effectively suppress the harmonic current. Meanwhile, considering the existence of a delay in the prediction process, a two-step prediction was approved to resolve delay issues.

For the problem of multiple predictive vectors, the initial response strategy was to use only 12 voltage vectors with the largest amplitude as the prediction sequence [132,133]. Although the number of predictive vectors was reduced to a certain extent, this led to problems such as large torque ripple and stator current distortion. The auxiliary space voltage vector was proposed [134–136]. Reference [126] proposed a model predictive control based on the combination of voltage vectors. The required reference voltage vector was obtained by using deadbeat direct torque and flux control methods, and the appropriate predictive vector was determined according to the position of the reference voltage vector in the sector. Additionally, the prediction model and cost function were simplified without redundancy constraints through voltage vector combination. The comparison results of the execution time of the above methods are shown in Table 4. In [137], the method of combining DPC and MPCC was proposed. According to the position of the reference voltage vector in the vector sector, the optimal voltage vector output was selected through the preset cost function Equation (13). The vector sector diagram is shown in Figure 9.

\[
J = ||v^* - |k(\alpha v_i) + l(\alpha v_j)||
\]

\[
k = \cos(15^\circ + 30^\circ n - \theta^*_{\alpha-\beta})
\]

\[
l = \sin(15^\circ + 30^\circ n - \theta^*_{\alpha-\beta})
\]

where \( \alpha v_i \) and \( \alpha v_j \) are the selected two auxiliary vector combinations; \( v^* \) is the reference voltage vector.

**Table 4. Execution Time Comparison.**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement (( \mu s ))</td>
<td>7.32</td>
<td>7.25</td>
<td>7.65</td>
<td>8.12</td>
</tr>
<tr>
<td>Reference vector Calculation (( \mu s ))</td>
<td>0</td>
<td>5.62</td>
<td>6.2</td>
<td>0</td>
</tr>
<tr>
<td>Prediction and evaluation (( \mu s ))</td>
<td>48.51</td>
<td>27.36</td>
<td>31.28</td>
<td>50.18</td>
</tr>
</tbody>
</table>
3.2.5. Robust Control Strategy

Some improved methods are proposed for the robustness of predictive control. Reference [141] is based on a disturbance observer, an improved stator flux observer, and an electromagnetic torque observer to obtain accurate parameter information to increase the robustness of the system. An enhanced predictive current control scheme with disturbance estimation and current compensation was proposed in [142]. A sliding mode observer was established to estimate the disturbance and compensate it to the prediction model in real-time. Meanwhile, a new hyperbolic tangent sliding mode approach was proposed to effectively suppress chattering. In [143], based on a discrete power system, the switch of the inverter will cause a deviation in the prediction, so the error compensation should be considered in the prediction process. In [144], based on the incremental moving horizon estimator, a direct MPCC with disturbance observer is proposed to improve the robustness of the motor system, and the feasibility of the method was verified by experiments based on a permanent magnet synchronous motor. Reference [145] proposes a model predictive control method based on an autoregressive disturbance estimator, which estimates the disturbance of the motor based on the disturbance observer and returns to the control system in real-time for compensation, effectively suppressing the influence of the disturbance on the torque and speed of the motor.

On the other hand, for parameter mismatch, reference [146] proposes a solution to the sensitivity of parameter mismatch of a surface-mounted permanent magnet synchronous motor. Figure 10 shows the structure diagram and experimental results of the disturbance controller. By taking into account the different conditions of resistance, inductance, and flux mismatch, the inductance perturbation estimation observer and perturbation controller were built to obtain precise inductance information and apply it to the compensation control system in real-time. A novel current update mechanism for finite set model predictive control was proposed. Reference [147] designed a discrete integral controller by predicting the current error to obtain the inductance information and replace the inaccurate flux linkage parameters, which improved the robustness of MPC while removing the current error under the parameter mismatch. For the robust control of predictive torque flux control, references [148,149] successively proposed a flux torque predictive controller.
with parameter robustness to obtain accurate predictive values and improve the control performance of the algorithm. Based on the problems of parameter mismatch, digital delay, and external interference, a predictive current control strategy based on an enhanced extended state observer was proposed in [150].

![Figure 10](image_url)

**Figure 10.** From [146]. (a) The block diagram of the controller with inductance disturbance; (b) The experimental diagram with the sudden increase of 100% inductance.

In [151], the algorithm for detecting discrete time parameters developed Popov’s hyperstability criterion, and determined discrete time model parameters based on adaptive system reference technology were used to achieve strong FCS-MPC control. Reference [152] added an LMS algorithm for web-based management, a new algorithm for system adaptive dynamic model calculation based on measured values. Reference [153] proposes the Adaline neural network algorithm applied to detect inductance in the $d$-$q$ axis. The constant magnetic flow of the motor rotor is combined with the control device to attain decent stable conditions and strong performance. Reference [154]’s data-based recursive calculation method offers real-time power management and a permanent magnet synchronous engine. The data-based strategy does not use physical parameters and has more advantages than all of these WB models. The method is used to evaluate the engine model online and continuously, and the non-linear compensation is weighed using an inverter.

### 3.3. CCS-Model Predictive Control of PMSM

#### 3.3.1. Generalized Predictive Control

Generalized predictive control is the most representative algorithm in model predictive control [155,156]. The cascaded generalized predictive control strategy for motor systems is proposed in reference [157]. The generalized predictive controllers of the speed loop and current loop are set, respectively. In [158], the stator voltage and current are always kept within the limits by designing external correction links, and the equivalence between the unconstrained optimal solution and constrained optimal solution can be guaranteed, so that the multivariable design scheme can be directly adapted to realize the generalized predictive control strategy of the motor drive system.

The constraints of the system under consideration are complex, so the use of LQR and amplitude-limiting links have been studied a lot. Reference [159] proposes a PMSM-constrained state feedback speed control method based on CCS-MPC, bringing a new posterior constraint introduction method. Based on the voltage equation, this method updates the model at each sampling time, calculates the boundary value of the control signal, and provides the allowable value of the future state variables. In ref. [160], a double-closed-loop MPC approach based on vector control is proposed.

#### 3.3.2. Explicit Model Predictive Control

Compared with generalized predictive control, explicit model predictive control can obtain the offline optimal resolution of constrained optimization problems directly, the high bandwidth model predictive control block diagram is shown in Figure 11, so it has significant advantages in the field of multivariable control [161,162]. High-bandwidth
predictive control converts the optimization problem in predictive control into a multi-parameter quadratic programming problem. The state space is decomposed into multiple convex partitions. The quadratic programming problem in each convex partition can determine the optimal control law offline [163]. At present, the explicit model predictive control based on a cascaded double closed-loop has been successfully applied to the motor drive system [158].

In addition, many scholars are also trying to use explicit model prediction to directly obtain an AC motor multi-input–multi-output speed controller, in order to eliminate the traditional cascade control mode and achieve direct control of motor speed [164]. Other scholars have considered replacing the precise explicit model predictive control method with the approximate explicit model predictive control method [165]. The accuracy of the control quantity is sacrificed in exchange for lower complexity, thus simplifying the offline and online calculation process [166,167].

3.3.3. Robust Control Strategy

In recent years, to improve the ability of generalized model predictive control and explicit model predictive control strategies to suppress unmodeled disturbances, scholars have proposed the following improved model predictive controls based on them: repetitive model predictive control (RMPC) [168] and iterative learning model predictive control (ILMPC) [169]. In reference [170], according to the discrete Fourier theory, the periodic disturbance is expressed as an internal model composed of multiple frequency signals in series, and the internal model is embedded in the prediction model so that the model prediction controller can suppress the disturbance corresponding to the elimination of the internal model of the signal generator. Reference [171] makes full use of the characteristics of periodic disturbance to directly embed the mathematical model of the repetitive controller into model predictive control. This kind of strategy does not need the frequency information of periodic disturbance, but only needs to determine the extreme range of the disturbance,

![High-bandwidth model prediction control block diagram.](image-url)
and then determine the predictive control law that can still meet the preset value function under the worst disturbance by solving the min–max optimization problem.

The unbiased model predictive controller (OFMPC) [172] is a type of controller that first expands the disturbance into the state variables of the prediction model, then designs a Romberg observer or a Kalman observer to observe the expanded system state variables (including the original state variables and disturbance variables), using the observation results to achieve the purpose of eliminating disturbance [173]. However, due to the influence of the dynamic performance of the observer, this type of model predictive controller can only eliminate the constant or slowly varying type of disturbance.

4. Future Directions

Through the introduction and summary of the existing literature, predictive control methods in the application of PMSM have received much attention and in-depth research. However, with higher requirements for control performance in industrial fields and other application scenarios, predictive control also needs to adapt to more situations. Some development directions focus on the following aspects.

4.1. Improvement of Steady-State Performance

DPC and MPC control strategies have been applied to permanent magnet synchronous motor systems. However, limited by the degree of freedom of control, the steady-state control performance of finite set model predictive control is still not good enough, and the sensitivity to motor parameters is high [73,141]. Existing steady-state error suppression strategies mostly use disturbance observation [83] and parameter identification [75,151], and the complexity of the system is high. The disturbance observation is based on the system model, and the observer type needs to be selected according to the controlled system and the observation bandwidth needs to be designed. Hence, there is still a lot of research space for the improvement of robustness and stability.

4.2. Reduce the Complexity of Multi-Step Prediction

For the problems of sampling delay and system delay, a multi-step prediction strategy has been proposed [70,123]. However, multi-step prediction will increase the computational burden of prediction and make the prediction process more complex. The method of reducing the prediction range is proposed in [131,138]. However, it depends on accurate position information sampling and an accurate mathematical model. Especially in practical applications, the reliability of the sensor and motor body needs to be considered. Therefore, multi-step prediction needs to be considered to adapt to more carriers.

4.3. Switching Frequency for FCS-MPC

Compared with DPC and CCS-MPC with pulse width modulation, FCS-MPC has no fixed switching frequency, and the pulse signal generated in a cycle is irregular. This will make the pulse sequence in the cycle difficult to realize, and the current and voltage harmonics will increase. At present, in the related literature fixed switching frequency of FCS-MPC has been proposed [104,118], but this will also increase the switching frequency and increase the loss of the inverter. Therefore, there is also research value in this aspect.

4.4. Combination of Predictive Control and Other Methods

At present, the combination of predictive control and other control methods of PMSM has also received attention. For example, in [27,174,175], a sensorless control method based on a finite position set is proposed. In [44], predictive control and fault-tolerant control are combined. This method does not need to reconstruct the mathematical model, and is simpler than the traditional fault-tolerant control. In addition, neural networks, genetic algorithms, and other methods have also been combined with predictive control [101,176,177]. Some existing joint schemes of predictive control and other methods are shown in Table 5.
### Table 5. Prediction of the development of existing methods.

<table>
<thead>
<tr>
<th>Methods</th>
<th>Features of Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimation observer + MPC or DPC</td>
<td>Parameter mismatch and disturbance</td>
</tr>
<tr>
<td>Fault-tolerant control + MPC</td>
<td>Open circuit fault of the motor</td>
</tr>
<tr>
<td>Adaptive control + MPC + DPC or MPC</td>
<td>Parameter identification</td>
</tr>
<tr>
<td>Event-triggered control + MPC</td>
<td>Complex prediction process</td>
</tr>
<tr>
<td>Active disturbance rejection control + MPC or DPC</td>
<td>Heavy computational burden</td>
</tr>
<tr>
<td>Neural network + MPC</td>
<td>Velocity tracking problem</td>
</tr>
<tr>
<td></td>
<td>Weight coefficient selection</td>
</tr>
</tbody>
</table>

### 5. Conclusions

This paper summarizes and comments on the research and development of DPC and MPC for permanent magnet synchronous motors. By introducing and classifying the basic principles of DPC and MPC, the problems of these two methods were analyzed and existing optimization schemes were reviewed. The solutions and related research achievements of FCS-MPC were summarized, such as reducing the computational burden, optimizing the switch frequency, and other optimization schemes such as multi-vectors strategy, delay compensation, and weighting factor adjustment. In addition, based on discrete models, the robustness of predictive control is the most worthy of consideration and optimization. However, there is still room for research and development on the relevant issues discussed above. With the rapid development of chip processors, predictive control is being applied more and more, and multi-step predictive control and robust control will also be the focus of research. The combination of predictive control and other existing control methods is also worth researching and exploring in the future.

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Conceptualization, J.P. and M.Y.; methodology, J.P. and M.Y.; software, J.P. and M.Y.; validation, J.P. and M.Y.; formal analysis, J.P. and M.Y.; investigation, J.P. and M.Y.; resources, M.Y.; data curation, J.P.; writing—original draft preparation, J.P.; writing—review and editing, M.Y.; visualization, M.Y.; supervision, M.Y.; project administration, M.Y.; funding acquisition, M.Y. All authors have read and agreed to the published version of the manuscript.

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