Cooperative control of deadbeat predictive and state error port-controlled Hamiltonian method for permanent magnet synchronous motor drives

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Abstract
In this article, a cooperative control combining deadbeat predictive control (DBPC) and state error port-controlled Hamiltonian (EPCH) method is presented for permanent magnet synchronous motor drives. This effective combination is achieved by a cooperation scheme based on the error function. First, the DBPC is introduced to provide a fast dynamic response, and the state EPCH method based on the loss model is constructed to get good steady-state performance and high efficiency. After that, to combine the advantages of both controllers, the improved sigmoid function based on real-time position error is designed as a cooperation scheme. Each control method can be utilized effectively within the corresponding range. Meanwhile, the switching process is continuous and smooth without unnecessary chattering. Thus, the proposed method not only solves the contradiction between dynamic and steady performance but also optimises energy consumption. Finally, the proposed method is verified experimentally. The results show that the motor control system based on the proposed method has fast dynamic transient response and good steady-state performance with high efficiency.

1 | INTRODUCTION

A permanent magnet synchronous motor (PMSM) has been widely used in industrial applications due to its excellent reliability, high power density and high efficiency [1, 2]. Various control approaches and modern control techniques are applied for the PMSM control system. These methods are generally divided into two parts: signal control and energy control. Nevertheless, some control requirements, such as fast and accurate tracking performance and energy efficiency, have led to the creation of new approaches called cooperative control methods. These approaches that take advantage of the two controllers are considered suitable choices.

In recent years, the model predictive control (MPC), as one of the classic signal control methods, has attracted much attention in improving the dynamic response of the control systems [3–6]. Among them, deadbeat predictive control (DBPC) is often applied to the PMSM system for current control since it has fixed switching frequency and can achieve good dynamic performance without much computational efforts [7–9]. The deadbeat current loop control structure, instead of traditional proportional integral (PI) control, is used in cascade control. The basic idea of this method is to make the actual current reach the reference in the minimum number of steps. The control signal then can be converted into a switching signal via space vector pulse width modulation. However, the performance of DBPC, which depends on the accurate mathematical model of a PMSM, will degrade with parameter uncertainties. Some methods have been investigated to solve this problem. For instance, in [10], a discrete-time predictive controller with integral action is proposed to enhance the robustness of the PMSM system with parameter uncertainties and unmodelled dynamics. In [11], a closed-loop term is added to the deadbeat control, which can directly compensate for the current tracking errors even with mismatches of the rotor flux linkage and stator resistance. In [12], a Luenberger observer is presented to handle the parameter mismatch of PMSM drives. In [13], a deadbeat control method based on an enhanced predictive model is studied to improve dynamic tracking performance, and an exponentially extended state observer is introduced to enhance robustness to disturbances. In [14], the improved deadbeat predictive controller using stator current...
and disturbance observer is designed to compensate for both parameter mismatch and one-step delay of the PMSM. In [15], a high-order sliding mode observer is introduced into the speed loop and current loop to provide accurate prediction and compensation when the system is influenced by external disturbances and parameter mismatches. In [16], a deadbeat speed controller composed of a deadbeat stabilising feedback control term and compensation control action is applied for a PMSM drive system.

The aforementioned control methods are based on the basic idea of signal transformation, and the control objective of these methods is to track the reference value quickly. However, satisfactory steady-state performance cannot be obtained by these methods. The port-controlled Hamiltonian (PCH) method based on energy transform not only has a simple model structure but also excellent steady-state performance [17–19]. This method uses interconnection and damping injection to design the desired Hamiltonian method, and zero-state error can be obtained. Another critical issue based on energy control is efficiency, especially in the continuous long-time operation of industrial applications. The operating efficiency depending on the control methods can be improved by the optimal control strategies. In different loss minimisation algorithms (LMA), loss model control (LMC) is a popular method. In this method, the optimal stator current or flux linkage is designed in real time according to the operating speed and load conditions [20, 21]. Abdelati et al. developed an energy-saving control method based on the Pontryagin minimum principle to obtain optimal energy consumption [22]. In [23], a LMA using deadbeat direct torque and flux control is presented, and the motor can work even at the voltage limit during flux weakening. In [24], an analytical solution of the optimal stator current design is presented for loss minimisation. In [25], an optimal current strategy, which is solved in a closed form and conveniently implemented, is designed to minimise the total stator loss. Moreover, to solve the parameter uncertainties of the loss model-based controller, some motor parameters are estimated online [26, 27].

The application of individual signal controllers or energy controllers is not generally sufficient to achieve satisfactory control performance. Recently, the concept of using cooperative control to combine controllers and improve their performance has become quite attractive [28, 29]. To this end, a large number of scientists are devoted to the related works of cooperative control methods. For instance, in [30], to obtain good transient and steady-state performances, a hybrid dual-mode method based on DBPC and field-oriented control is applied for PMSM drives. The two modes are alternately activated according to the saturation state. In [31], a current predictive controller based on the combination of dead-beat (DB) and direct predictive control is investigated to ensure fast torque monitoring and high-performance operation. In [32], to achieve a fixed switching frequency and fast transient response, a hybrid control strategy of DB and MPC based on switching control technology is presented. In [33], a dynamic optimisation strategy combining the maximum torque per ampere (MTPA) method and conventional LMC is studied in which a measurement error function of motor loss is established to produce a smooth transition between the MTPA and the LMC method. In [34], a hybrid control scheme of partial feedback linearisation (FBL) and dead-beat control is designed to accelerate the transient response while maintaining the stability of the internal dynamics. Hamdy et al. proposed an experimental verification of this approach for a non-linear gantry crane system [35]. In [36], a hybrid controller which combines adaptive neuro-fuzzy controller, proportional integral derivative (PID) controller and sliding mode controller with PID module is studied for speed control of the PMSM. The outputs of these three controllers are added to the saturation function in parallel to get the final control signals. In [37], a hybrid control technique based on finite-set control and direct torque control (DTC) is designed in which a measure resembling DTC is adopted to optimise the switching state of the inverter and minimise the cost function. In [38], an online efficiency optimisation based on the fuzzy logic controller is presented to obtain a fast transient response and minimise power loss. In [39], a hybrid controller, which combines the hierarchical sliding mode control algorithm and robust passivity-based control, is applied for the current control of a flexible joint robot. In [40], an optimal FBL controller based on the Hamiltonian optimal control theory and Pontryagin’s minimum principle is designed to achieve accurate torque control and energy optimisation. In [41], a smooth switching control strategy based on FBL and PCH method is introduced to ensure the stability and rapidity of the robot system. The literatures discussed above are summarized in Table 1.

In order to further optimise the control performance of PMSM drives, this article applies a novel cooperative scheme to realise the cooperative control of DBPC and EPCH. First, DBPC is introduced to provide a fast transient response, and the EPCH method is developed to make the motor operate stably at maximum efficiency. Then, to combine the advantages of the two controllers and achieves smooth switching in the transient process, the improved sigmoid function is designed as a cooperative scheme. In fact, this scheme is based on the weighting sum of the two controllers, and the weighting factors change dynamically with the position error in the operation process. Finally, the experiment is carried out for a non-salient PMSM system. The results show that the motor system based on cooperative control has good position tracking performance and high efficiency.

This article is organised as follows: In Section 2, the mathematical model of a non-salient PMSM is introduced. The cooperative control scheme, deadbeat controller and the Hamiltonian controller are designed. The experimental results with the LINKS-RT platform are illustrated and discussed in Section 3. Finally, some conclusions are drawn in Section 4.
2 | PROPOSED COOPERATIVE CONTROL

2.1 | Mathematical model of the PMSM

The dynamic model of the non-salient PMSM in the synchronous reference frame is expressed as follows [17]:

\[
\begin{align*}
L \frac{di_d}{dt} &= -R_i i_d + n_p \omega L_i q + u_d \\
L \frac{di_q}{dt} &= -R_i i_q - n_p \omega L_i d - n_p \omega \Phi + u_q \\
J \frac{d\omega}{dt} &= \tau - \tau_L - R_f \omega = n_p \Phi i_q - \tau_L - R_f \omega \\
d\theta &= \omega 
\end{align*}
\]  

(1)

where \(i_d\) and \(i_q\) are the stator currents in the d-q axis, \(u_d\) and \(u_q\) are the stator voltages in the d-q axis, and \(\tau\) and \(\tau_L\) are the electromagnetic torque and load torque, respectively. \(\omega\) is the mechanical angle of the motor, \(\Phi\) is the angle of the motor, \(R_i\) is the stator resistance, \(L\) is the stator inductance, and \(\Phi\) is the permanent magnet flux. \(J\) is the moment of inertia, \(n_p\) is the number of the pole pairs, \(R_f\) is the viscous friction coefficient.

The PMSM control system based on the proposed method is shown in Figure 1.

2.2 | Design of DBPC

If the sampling time \(T_s\) is short enough, the derivative of the current is expressed as follows:

\[
\frac{di(k)}{dt} \approx \frac{i(k + 1) - i(k)}{T_s}
\]

(2)

where \(i(k)\) is the stator current of DBPC in the \(k\)th sampling period.

By substituting Equation (2) into Equation (1), the discrete current predictive model of the PMSM is obtained as follows:

\[
i(k + 1) = i(k) + T_s[A(k)i(k) + Bu_e(k) + C(k)]
\]

(3)

with

\[
A(k) = \begin{bmatrix} -\frac{R_i}{L} & n_p \omega(0) \\ -n_p \omega(k) & -\frac{R_i}{L} \end{bmatrix}, \quad B = \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \quad C(k) = \begin{bmatrix} 0 \\ -\frac{\Phi}{L} n_p \omega(k) \end{bmatrix}.
\]

where \(i(k) = [i_d(k) \ i_q(k)]^T\), \(u_e(k) = [u_{ed}(k) \ u_{eq}(k)]^T\).

\(u_{ed}(k)\) and \(u_{eq}(k)\) are the d- and q-axis stator voltages of DBPC.

The discrete current error \(e(k)\) is defined as follows:

\[
e(k) = i_d'(k) - i(k) = \begin{bmatrix} i_{ed}'(k) \\ i_{eq}'(k) \end{bmatrix} - \begin{bmatrix} i_d(k) \\ i_q(k) \end{bmatrix}
\]

(4)

\[\text{FIGURE 1} \quad \text{Block diagram of the PMSM control system. EPCH, error port-controlled Hamiltonian; DBPC, deadbeat predictive control; PI, proportional integral; PMSM, permanent magnet synchronous motor; SVPWM, space vector pulse width modulation}\]
where \( i_{r}^{q}(k) = \begin{bmatrix} i_{r}^{p}(k) & i_{r}^{q}(k) \end{bmatrix} \). The reference d-axis current \( i_{r}^{d}(k) \) is always equal to 0 because \( i_d = 0 \) control is adopted in DBPC. The reference q-axis current \( i_{r}^{q}(k) \) is regulated by the PI speed controller. In addition, PI control is also used in the position controller.

By combining Equations (3) and (4), the difference equation of the current error can be obtained as follows:

\[
e(k + 1) = e(k) - T_s[A(k)i_e(k) + Bu_e(k) + C(k)]
\]  
(5)

Here, the control objective is to drive the current error to zero in finite time.

Although deadbeat control can provide a good transient response, this method relies on the accurate mathematical model, which means that parameter uncertainties would significantly reduce the system’s control performance. In order to enhance the robustness against parameter disturbance, the current prediction vector with a discrete-time integral term is designed as follows:

\[
\hat{i}_e(k + 1) = i_e(k) + T_s[A(k)i_e(k) + Bu_e(k) + C(k)] - \frac{1}{T_s}K\hat{\xi}
\]  
(6)

with

\[
K = \begin{bmatrix} k & 0 \\ 0 & k \end{bmatrix}, \quad \hat{\xi} = \sum_{n=0}^{k} \hat{e}(n).
\]

where \( \hat{i}(k + 1) \) is the current prediction. \( K \) is the systematic gain matrix. \( \hat{e}_n \) is the error prediction and it can be defined as follows:

\[
\hat{e}(k) = e(k) - \hat{i}(k)
\]  
(7)

According to the DBPC control theory [10], the actual currents reach the reference currents after one sampling period, that is,

\[
\begin{cases}
\hat{i}_d(k + 1) = i_{r}^{d}(k) \\
\hat{i}_q(k + 1) = i_{r}^{q}(k)
\end{cases}
\]  
(8)

The control effort is given in the following form:

\[
u_e(k) = -B^{-1}\left[A(k)\hat{i}_e(k) + C(k)
\right.

\[
- \frac{1}{T_s} \left[i^e - \hat{i}(k) + K(\hat{\xi}(0) + \cdots + \hat{\xi}(k - 1))\right]
\]

\]  
(9)

Since

\[
i^e - \hat{i}(k) = e(k) + \hat{\xi}(k)
\]  
(10)

the control effort of DBPC can be expressed as follows:

\[
u_e(k) = -B^{-1}\left[A(k)\hat{i}_e(k) + C(k)
\right.

\[
- \frac{1}{T_s} \left[e(k) - (K - I)\hat{\xi}(k) + K\hat{\xi}\right]
\]

\]  
(11)

The difference equations of the complete deadbeat control system can be calculated as follows:

\[
e(k + 1) = [K - I - T_sA(k)]\hat{e}(k) - K\hat{\xi}
\]  
(12)

\[
\hat{\xi}(k + 1) = K \hat{\xi}
\]  
(13)

\[
\xi(k + 1) = \xi(k) + \hat{\xi}(k + 1)
\]  
(14)

After the discrete voltage vector passes through the zero-order holder, the continuous-time DBPC controller is obtained as follows:

\[
u_e(t) = H(s)\nu_e(k)
\]  
(15)

with

\[
H(s) = \frac{1 - e^{-Ts}}{s}
\]  
(16)

The stability of the signal subsystem is demonstrated in reference [10].

For the safety and reliability of the motor, it is necessary to consider the action value limitation. Here, a constraint laid on the problem is that the current amplitude never exceeds the maximum transient permissible current defined by the technical specifications.

\[
i(k) < i_{\text{max}}
\]  
(17)

By substituting Equation (6) into Equation (17), we get that the control voltage should handle the following constraints:

\[
u_e \leq \frac{1}{BT_s}[i_{\text{max}} - (1 + A(k)T_s)i_e(k) - T_sc(k) + K\hat{\xi}]
\]  
(18)

The deadbeat controller would track a desired trajectory while satisfying all these constraints.
2.3 | Design of the EPCH

By taking into account the loss of copper and iron, the equivalent circuits of the d-q axis for the PMSM are shown in Figure 2. The mathematical model of the equivalent circuits for the non-salient PMSM is described as follows [23]:

\[
\begin{align*}
L_i \frac{di_d}{dt} &= -(R_s + R_c)i_d + R_c i_{ad} + u_{ad} \\
L_i \frac{di_q}{dt} &= -(R_s + R_c)i_q + R_c i_{aq} + u_{eq} \\
L_m \frac{di_{ad}}{dt} &= R_c(i_d - i_{ad}) + n_p \omega L i_{ad} \\
L_m \frac{di_{aq}}{dt} &= R_c(i_q - i_{aq}) - n_p \omega (L_d i_{ad} + \Phi) \\
\frac{d\theta}{dt} &= \omega \\
\end{align*}
\]

with

\[
\begin{align*}
i_{ad} &= i_d - i_{id}, \quad i_{aq} = i_q - i_{iq}, \\
i_{id} &= -\frac{n_p \omega L i_{ad}}{R_c}, \quad i_{iq} = \frac{n_p \omega (\Phi + L i_{ad})}{R_c}.
\end{align*}
\]

where \(i_{ad}\) and \(i_{aq}\) are d- and q-axis iron loss current components. \(u_{ad}\) and \(u_{eq}\) are d- and q-axis stator voltages of the EPCH. \(L_d\) is leakage inductance. \(L_m\) is magnetising inductance. \(R_c\) is the core loss resistance.

The motor losses consist of copper loss, iron loss and mechanical loss. The mechanical loss cannot be controlled, but electrical losses such as copper loss and iron loss belong to controllable losses. The copper loss \(P_{Cu}\) and the iron loss \(P_{Fe}\) of the PMSM are calculated as follows:

\[
P_{Cu} = \frac{3}{2} R_c \left( \frac{i_d^2 + i_q^2}{R_c} \right)
\]

\[
= \frac{3}{2} R_c \left[ \left( i_{ad} - \frac{n_p \omega L i_{ad}}{R_c} \right)^2 + \left( i_{aq} + \frac{n_p \omega (\Phi + L i_{ad})}{R_c} \right)^2 \right]
\]

\[
(22)
\]

\[
P_{Fe} = \frac{3}{2} R_c \left( \frac{i_d^2 + i_q^2}{R_c} \right) = \frac{3}{2} \frac{n_p^2 \omega^2}{R_c} \left[ (L i_{ad})^2 + (\Phi + L i_{ad})^2 \right]
\]

\[
(23)
\]

The total controllable losses \(P_L\) can be calculated by combining Equations (22) and (23):

\[
P_L = P_{Cu} + P_{Fe}
\]

\[
= \frac{3}{2} R_c \left[ \left( i_{ad} - \frac{n_p \omega L i_{ad}}{R_c} \right)^2 + \left( \frac{L i_{ad} + R_f \omega}{n_p \omega} + \frac{n_p \omega (\Phi + L i_{ad})}{R_c} \right)^2 \right]
\]

\[
+ \frac{3}{2} \frac{n_p^2 \omega^2}{R_c} \left[ \left( \frac{L i_{ad} + R_f \omega}{n_p \omega} \right)^2 + (\Phi + L i_{ad})^2 \right]
\]

\[
(24)
\]

The output power and efficiency are given by the following equations:

\[
P_o = \tau_L \omega
\]

\[
\eta = \frac{P_o}{P_o + P_L} \times 100\%
\]

\[
(25)
\]

\[
(26)
\]

During steady-state operation with constant torque, it satisfies the following equation:

\[
i_{aq} = \frac{\tau_L^* + R_f \omega^*}{n_p \omega}
\]

\[
(27)
\]

where \(\tau_L^*\) is the reference value of load torque. Then, the total electrical losses \(P_L\) can be expressed as a function of the d-axis current component \(i_{ad}\).

By differentiating the given function \(P_L\) with respect to \(i_{ad}\) and making the derivative equate to zero, the
condition of minimising controllable losses can be derived as follows:

\[
\frac{\partial P_L}{\partial i_{ad}} = 0
\]  

(28)

The optimal current \(i_{ad}\) minimising the controllable losses is obtained as follows:

\[
i_{ad} = -\frac{n_p^2 \omega^2 L \Phi(R_s + R_c)}{R_s R_c^2 + n_p^2 \omega^2 L^2(R_s + R_c)}
\]  

(29)

Define the mechanical momentum, state vector and input vector as follows:

\[
\rho = J \omega
\]

(30)

\[
x = [x_1 \ x_2 \ x_3 \ x_4 \ x_5 \ x_6]^T = [L_i i_d \ L_i i_q \ L_m i_{ad} \ L_m i_{eq} \ \rho \ \theta]^T
\]

(31)

\[
u_c = [u_{ad} \ u_{eq}]^T
\]

(32)

The Hamiltonian function of the PMSM system is the sum of electric energy, mechanical potential energy and kinetic energy, which should be defined as follows:

\[
H(x) = \frac{1}{2} \left[ \frac{1}{L_l} x_1^2 + \frac{1}{L_l} x_2^2 + \frac{1}{L_m} x_3^2 + \frac{1}{L_m} x_4^2 + \frac{1}{J} x_5^2 \right] + \tau_l x_6
\]

(33)

The Hamiltonian model of the PMSM with dissipation is obtained as:

\[
\begin{align*}
\dot{x} &= [J(x) - R(x)] \frac{\partial H(x)}{\partial x} + g(x) u_c y = g^T(x) \frac{\partial H(x)}{\partial x}
\end{align*}
\]

(34)

where \(x \in \mathbb{R}^n\), \(u, y \in \mathbb{R}^m\), \(R(x) = R^T(x) \geq 0\), \(J(x) = -f^T(x)\), \(g(x)\) is the interconnection structure.

By substituting Equation (19) into Equation (34), the PCH system of the PMSM is derived as follows:

\[
J(x) = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & n_p L \omega & 0 & 0 & 0 \\
0 & 0 & -n_p L \omega & 0 & -n_p \Phi & 0 \\
0 & 0 & 0 & n_p \Phi & 0 & -1 \\
0 & 0 & 0 & 0 & 1 & 0 \\
\end{bmatrix}
\]

\[
R(x) = \begin{bmatrix}
R_s + R_c & 0 & -R_c & 0 & 0 & 0 \\
0 & R_s + R_c & 0 & -R_c & 0 & 0 \\
-R_c & 0 & R_c & 0 & 0 & 0 \\
0 & -R_c & 0 & R_c & 0 & 0 \\
0 & 0 & 0 & 0 & B & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
\end{bmatrix}
\]

\[
g(x) = \begin{bmatrix}
1 & 0 \\
0 & 1 \\
0 & 0 \\
0 & 0 \\
0 & 0 \\
\end{bmatrix}
\]

(35)

According to Equation (20) and Equation (29), the equilibrium state of the control system is as follows:

\[
x^* = \begin{bmatrix}
L_i i_d \ i_i \ L_m i_{ad} \ L_m i_{eq} \ \rho^* \ \theta^*
\end{bmatrix}^T
\]

(36)

where

\[
\begin{align*}
\tau_d &= -\frac{n_p^2 \omega^2 L \Phi (R_s + R_c)}{R_s R_c^2 + n_p^2 \omega^2 L^2 (R_s + R_c)} - \frac{\omega^2 L (\tau_l^* + R_l \omega^2)}{R_c \Phi} \\
\tau_q &= \frac{\tau_l^* + R_l \omega^2}{n_p \Phi} + \frac{n_p \omega^2 \Phi}{R_c} - \frac{n_p^3 (R_s + R_c)^2 L \Phi (R_s + R_c)}{R_s R_c^2 + n_p^2 (R_s + R_c)^2 L^2 (R_s + R_c)} \\
\tau_{ad} &= -\frac{n_p^2 \omega^2 L \Phi (R_s + R_c)}{R_s R_c^2 + n_p^2 \omega^2 L^2 (R_s + R_c)} \\
\tau_{eq} &= \frac{\tau_l^* + R_l \omega^2}{n_p \Phi}
\end{align*}
\]

(37)

Let \(\bar{x} = x - x^*\) be the state error, \(H_d(\bar{x})\) is the expected state error Hamiltonian function as shown below:

\[
H_d(\bar{x}) = \frac{1}{2} \left[ \frac{1}{L_l} (x_1 - x_1^*)^2 + \frac{1}{L_l} (x_2 - x_2^*)^2 + \frac{1}{L_m} (x_3 - x_3^*)^2 + \frac{1}{L_m} (x_4 - x_4^*)^2 + \frac{1}{J} (x_5 - x_5^*)^2 + \rho (x_6 - x_6^*)^2 \right]
\]

(38)

where \(H_d(\bar{x}) > 0\), \(H_d(0) = 0\).

If Equations (39) and (40) hold,

\[
J_d(\bar{x}) = J(\bar{x}) + J_a = -J_d^T(\bar{x})
\]

(39)
\[
R_d(\ddot{x}) = R(\ddot{x}) + R_a = R_d^T(\ddot{x}) \geq 0 \quad (40)
\]

The following equations would be obtained:
\[
g(x)u_c = [J_a - R_a - J(x')] \frac{\partial H_d(x)}{\partial x} \\
+ [J(\ddot{x}) - R(x) - R(x')] \left[ \frac{\partial H_d(x)}{\partial x} - \frac{\partial H(x)}{\partial x} \right] \\
+ g(x*)u^* \quad (41)
\]

Then, the closed-loop EPCH system can be rewritten in the following form:
\[
\ddot{x} = [J_d(\ddot{x}) - R_d(\ddot{x})] \frac{\partial H_d(\ddot{x})}{\partial x} \quad (42)
\]

Let
\[
J = \begin{bmatrix}
0 & a & 0 & 0 & 0 & 0 \\
-a & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & n_p L_s & 0 & n_p L_{eq} \\
0 & 0 & -n_p L_s & 0 & -n_p L_{eq} + \Phi & 0 \\
0 & 0 & n_p L_{eq} & 0 & -1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\]

\[
R = \begin{bmatrix}
R_s + R_c + r & 0 & -R_c & 0 & 0 & 0 \\
0 & R_s + R_c + r & 0 & -R_c & 0 & 0 \\
-R_c & 0 & 0 & R_c + r_m & 0 & 0 \\
0 & -R_c & 0 & 0 & 0 & B \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix} \quad (43)
\]

The control signals of the EPCH controller can be obtained as follows:
\[
\begin{align*}
    u_{ed}(t) &= (R_s + R_c)i_d^* - r(i_d - i_d^*) - R_c i_{ed}^* \\
    &+ a(i_q - i_q^*) \\
    u_{eq}(t) &= (R_s + R_c)i_q^* - r(i_q - i_q^*) - R_c i_{eq}^* \\
    &- a(i_d - i_d^*)
\end{align*} \quad (44)
\]

where \( r \) and \( a \) are adjustable parameters. From reference [17], it is verified that the energy subsystem is asymptotically stable at \( \ddot{x} = 0 \).

### 2.4 Design of the cooperative control scheme

In this section, the proposed controller is based on a cooperative control scheme of DBPC and the EPCH. The main idea of this scheme is to use different controllers in different operation conditions via an appropriate cooperative function. The cooperative function designed in this article is as follows:

\[
F(\chi) = 1 - \left( \frac{2}{e^{-\delta} + 1} - 1 \right) \quad (45)
\]

where \( \delta \) is the adjustable parameter, \( 0 < F(\chi) \leq 1 \). \( \chi \) is the position tracking error as follows:

\[
\chi = \theta - \theta^* \quad (46)
\]

The smooth switching coefficient is selected as the function of the position error, which means that switching control can be carried out as long as the position error exists. The function curves with different \( \delta \) are shown in Figure 3. Based on the designed cooperative function, the proposed controller can realise continuous and smooth switching between DBPC and the EPCH, thus improving the dynamic and steady performance and the energy consumption.

Subsequently, the control rule developed in the combination procedure is summarised. The motor operates in a stable state under normal conditions, and dynamic conditions may occur at any time. When the position error increases, \( F(\chi) \) decreases and the control effort of the deadbeat controller applied to the motor is enhanced, thereby shortening the transition time to the steady state. When the difference decreases, \( F(\chi) \) increases and the Hamiltonian method based on the loss model is regarded as the primary control method, thus improving steady-state precision and energy efficiency. More precisely, the deadbeat controller is applied in the dynamic state, and the Hamiltonian controller is utilised in the steady state. Finally, a complete control system using a cooperative function to combine with the designed controllers is built.

The cooperative controller can be designed as shown below:

\[
\begin{align*}
    u_d &= F(\chi)u_{ed}(t) + [1 - F(\chi)]u_{ed}(t) \\
    u_q &= F(\chi)u_{eq}(t) + [1 - F(\chi)]u_{eq}(t)
\end{align*} \quad (47)
\]
2.5 Stability analysis of the cooperative control system

The Lyapunov functions of the signal controller and the energy controller are $V_s$ and $V_e$, respectively. In order to prove the stability of the whole closed-loop system, the Lyapunov function is selected as follows:

$$V = V_s + V_e$$  \hspace{1cm} (48)

On the condition that $\chi \to \infty$, $F(\chi) \to 0$. This means that the signal controller based on DBPC is regarded as the main control force of the PMSM system. We have $V = V_s > 0$, $\dot{V} = V_s \leq 0$, and the control system is stable.

On the condition that $0 < \chi < \infty$, the cooperative function $F(\chi)$ is all the constants between 0 and 1. As the error decreases, the control effect of the DBPC controller gradually reduces and the EPCH controller gradually becomes dominant. Since the types of the two controllers have not changed during the operation, the Lyapunov function of the whole system is $V = V_s + V_e$. Then $\dot{V} = V_s + V_e$. Through the stability analysis of the DBPC control system and the EPCH control system, that is, $V_s > 0$, $V_e \leq 0$ and $V_e > 0$, and $V_s \leq 0$, it can be concluded that the whole control loop is stable, that is, $V > 0$ and $V \leq 0$.

On the condition that $\chi = 0$, $F(\chi) = 1$. This means that the energy controller based on the EPCH plays a role in the PMSM system. Since $V = V_s > 0$ and $\dot{V} = V_e \leq 0$, the control system is stable.

Therefore, we can draw the conclusion that the cooperative control system is stable.

3 EXPERIMENTAL RESULTS

In this section, various experiments on the PMSM drive system are performed to evaluate the proposed cooperative control method. The experimental system is established in the LINKS-RT rapid prototyping experiment platform, which is produced by Beijing Links Corporation. In the experimental platform, the algorithms are compiled in the MATLAB/Simulink environment of the PC side, and the variables such as the position and current are monitored by using the software RT-SIM. The real-time transmission of the control signals and the data between the PC and the simulator can be achieved. Figures 4 and 5 show the experimental configuration and the experimental platform, respectively. The parameters of the PMSM are listed in Table 2. The sampling period is set to 0.0002 s, and the PWM switching frequency is set as 10 kHz. The value of $R_e$ is measured by applying an offline method introduced in [42]. The adjustable parameters of the proposed
method are selected as follows: \( k = 1.2, r = 5, a = 2 \) and \( \delta = 1 \).

In order to illustrate the performance of the proposed method, comparative experiments with the DBPC and EPCH methods are carried out in which two typical position references are considered. Then, the influence of the scale parameter \( \delta \) on the position tracking performance is evaluated. To make a fair comparison, the proposed controller is finally compared with the classical PI controller under the same operating conditions. The proportional and integral gains are chosen by trial and error.

**Case 1** The reference position is chosen as \( \theta^* = 50\sin(t) \) rad. The experimental results are shown in Figures 6–9. In order to evaluate the performance of the proposed controller, four statistical criteria are introduced, namely position tracking response, position error, \( d-q \) axis current response and three-phase current response. The experimental results of DBPC and the EPCH method are shown in Figures 6 and 7, respectively. It can be seen that the two controllers can track the reference accurately and quickly. The maximum absolute magnitude of the steady-state error is limited to 1 rad when the DBPC method is chosen, and the maximum absolute magnitude of the steady-state error is 0.3 rad when the EPCH method is applied. The experimental result of the proposed method is given in Figure 8. Compared with the other

| Control scheme | Control method | Basic principle |
|----------------|----------------|-----------------|
| Switching control structure | FOC + DBPC [39] | Saturation state |
| | DBPC + MPC [32] | Defined switching condition |
| | MTPA + LM [33] | Losses error |
| | ANFC + PID + SMC-PID [36] | Saturation function |
| | FSC + DTC [37] | Cost function |
| | HSMC + PBC [39] | Current error |
| | FBL + PCH [41] | Position error |
| Cascade control structure | DB + DPC [31] | |
| | FBL + DB [34, 35] | |
| | LMA + FLC [38] | |
| | FBL + MPC [40] | |

Abbreviations: ANFC, adaptive neuro-fuzzy controller; DB, dead beat; DBPC, deadbeat predictive control; DPC, direct predictive control; DTC, direct torque control; FBL, feedback linearisation; FLC, fuzzy logic controller; FOC, field-oriented control; FSC, finite-set control; HSMC, hierarchical sliding mode control; LMA, loss minimisation algorithms; LMC, loss model control; MPC, model predictive control; MTPA, maximum torque per ampere; PBC, passivity-based control; PCH, port-controlled Hamiltonian; PID, proportional integral derivative; SMC-PID, sliding mode controller with PID module.

FIGURE 4 Experimental configuration of the PMSM system
two controllers, it can be found that although their position tracking responses stay in similar bands, the steady-state error of the proposed controller is almost zero. Moreover, the d-q axis current and the phase current remain stable in the entire operation. Figure 9 is the magnification of position response. It is obvious that the proposed method has better tracking performance compared with the DBPC and EPCH method.

**Case 2** The reference position is selected as $\theta^* = 100$ rad. In this case, the efficiency characteristic is added to the criteria. These statistical metrics facilitate a fair comparison between different control methods, which can be readily employed for practical applications. The experimental results of the three control methods (DBPC, EPCH, cooperative control) are shown in Figures 10–14.
When the DBPC method is used in the entire operation, the control system has fast transient response and can reach the reference at 2.3 s, as shown in Figure 10. However, it suffers from overshoot and position tracking error. In the control process, the larger the overshoot, the shorter the steady-state time and vice versa. Steady time restricts the suppression of overshoot, which needs to be balanced according to the control objective. Fast transient response is required in DBPC, so reasonable overshoots caused by sudden changes in position are acceptable. The maximum absolute magnitude of the steady-state error is around 0.1 rad.

When the EPCH method is applied in the entire operation, it can be found from Figure 11 that the steady-state error and overshoot are reduced, and the maximum absolute magnitude of the steady-state error is about 0.05 rad. Moreover, the current ripple is also reduced. However, this method reaches the reference at 4 s, which is significantly slower than that of DBPC.

When the proposed method is employed in the entire operation, the experimental results are as shown in Figure 12. With this method, the system reaches the reference at 2.3 s, and the steady-state error is close to zero. Compared with Figure 10, the transient response of the proposed method is almost the same as that of DBPC, but the steady-state error is smaller than that of DBPC. Compared with Figure 11, the proposed method reaches the reference value about 2 s earlier.
than the EPCH, but the steady-state error of both the methods is the same. It can be found that the proposed method retains the advantages of DBPC and the EPCH.

To further validate the effectiveness of the proposed method, more results at different instances of the position are provided in Figure 13.

The comparison result of the efficiency characteristic is given in Figure 14. It is clearly shown that the efficiency of the proposed method is 89.5%, the efficiency of DBPC is 87%, and the efficiency of the EPCH is 91%. The energy efficiency of the proposed method is improved by 2.5% compared with DBPC and is basically consistent with that of the EPCH.

Case 3 The position tracking error curves with different scale parameters $\delta$ are shown in Figure 15. It can be clearly seen that the response speed of the cooperative controller is accelerated with the decrease of $\delta$. However, if $\delta$ is too small, the switching condition cannot be satisfied. The motor has been working under the regulation of the DBPC controller.

Case 4 The proposed method is compared with the classical PI control, and the experimental results are presented in Figures 16–20. The results of position tracking behaviours and corresponding tracking errors are shown in Figures 16 and 17, respectively. The classical PI control reaches the given position at 3.9 s and exhibits a large overshoot. In comparison, the proposed method offers better performance in terms of position tracking. The speed comparison results of the PI controller and the proposed controller are shown in Figure 18. It can be seen that the speed of the PI controller is close to that of the proposed controller. In addition, the PI controller can provide a smaller
current shock due to its long settling time, see Figure 19. Figure 20 shows the efficiency comparison between PI and the proposed method. The efficiency of the PI controller is approximately 87.5%. It can be seen that compared with the classical PI control, the efficiency of the proposed method is improved by 2%.

4 | CONCLUSION

This article presents a novel cooperative control method to optimise the performance and efficiency of the PMSM system. A cooperative control scheme based on error function is adopted to combine DBPC and EPCH controllers. First, the DBPC and EPCH methods are applied to ensure the rapidity...
and stability of the system, respectively, and loss minimisation is considered in the design of the EPCH controller. Then, considering that individual signal or energy controllers cannot achieve satisfactory performance, a cooperative function based on the position error is designed to combine the advantages of the two controllers. Each control method can be effectively used under the corresponding operating conditions. Meanwhile, the switching process is continuous and smooth without unnecessary chattering. Finally, the proposed controller is compared with the DBPC controller and the EPCH controller in terms of position tracking performance and efficiency optimisation capability. For completeness, the PI control is also investigated. Experimental results show that the proposed controller has fast transient response and good steady-state performance with high efficiency.

The main contributions of the proposed method are as follows:

(1) DBPC and EPCH controllers, respectively, are designed for the PMSM system.
(2) LMC is introduced into the EPCH control to minimise energy consumption.
(3) Based on the two designed controllers, a novel cooperative control scheme is proposed. Compared with single-type controllers, it not only improves the dynamic and steady performance of the control system but also ensures its high efficiency.

However, the designed DBPC controller only provides a fast response in the current loop. Therefore, future work will focus on improving the rapidity of the entire control system.

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CONFLICT OF INTEREST
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