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Enhanced Robust Model Predictive Control for Permanent Magnet Synchronous Motor Drives

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ABSTRACT

Traditional Model Predictive Control (MPC) methods are typically designed for high switching frequency environments to achieve precise control. However, high switching frequencies significantly increase inverter switching losses, leading to substantial heat generation and power loss, which reduces overall control performance. At low switching frequencies, traditional MPC methods struggle to maintain system robustness and high performance. To address these issues, this paper presents an improved model predictive voltage control (MPVC) method designed to maintain excellent dynamic and steady-state performance and robustness in permanent magnet synchronous motors (PMSMs) operating at low switching frequencies. The proposed method first accurately models the PMSM mathematically, then uses current differences to obtain real-time equivalent inductance and flux-linkage data. Next, an improved cost function is constructed to determine the optimal voltage vector to be applied to the motor while reducing the system's switching frequency. Simulation results validate the effectiveness and feasibility of this method.

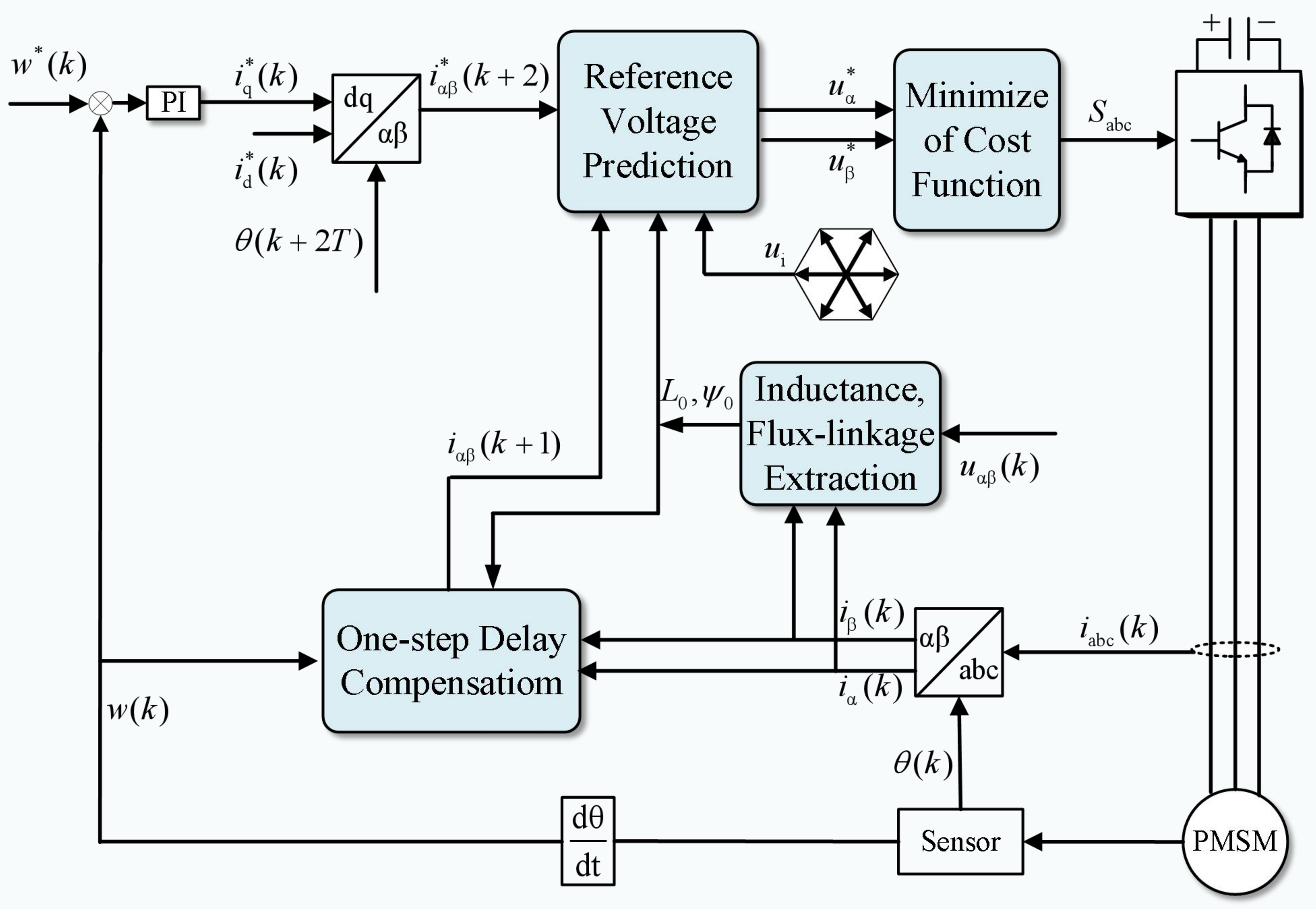


Fig. 1. Control schematic diagram of the proposed method.

The Theory of Proposed Method

A. Accurate predictive model

When the control frequency is low, the truncation error of the Eulerian discretization is large, and in order to improve the accuracy of the predicted current, the current at time (k+1) can be expressed

$$\begin{cases} i_\alpha^p(k+1) = (1-\frac{R\cdot T}{L})\cdot i_\alpha(k) + \frac{T}{L}\cdot u_\alpha(k) - \frac{\psi}{L}\cdot A \\ i_\beta^p(k+1) = (1-\frac{R\cdot T}{L})\cdot i_\beta(k) + \frac{T}{L}\cdot u_\beta(k) - \frac{\psi}{L}\cdot B \end{cases} \quad (1)$$

where $A = \cos(\theta(k) + w\cdot T) - \cos(\theta(k))$

$B = \sin(\theta(k) + w\cdot T) - \sin(\theta(k))$

B. Inductance and Flux-linkage Extraction

The actual sampling and predicted currents at moment (k+1) can be obtained in Eq. (2) and (3) below, respectively:

$$\begin{cases} i_\alpha(k+1) = (1-\frac{R\cdot T}{L_0})\cdot i_\alpha(k) + \frac{T}{L_0}\cdot u_\alpha(k) - \frac{\psi_0}{L_0}\cdot A \\ i_\beta(k+1) = (1-\frac{R\cdot T}{L_0})\cdot i_\beta(k) + \frac{T}{L_0}\cdot u_\beta(k) - \frac{\psi_0}{L_0}\cdot B \end{cases} \quad (2)$$

$$\begin{cases} i_\alpha^p(k+1) = (1-\frac{R\cdot T}{L})\cdot i_\alpha(k) + \frac{T}{L}\cdot u_\alpha(k) - \frac{\psi}{L}\cdot A \\ i_\beta^p(k+1) = (1-\frac{R\cdot T}{L})\cdot i_\beta(k) + \frac{T}{L}\cdot u_\beta(k) - \frac{\psi}{L}\cdot B \end{cases} \quad (3)$$

where L, ψ stand for the model parameters of the SPMSM; L_0, ψ_0 stand for the actual parameters of the SPMSM.

Similarly, the predicted and sampling values of the current at moment k can be obtained, and subtracting one from the other yields their current difference.

$$\begin{cases} E_\alpha = i_\alpha^p(k) - i_\alpha(k) \\ \quad = RT(\frac{1}{L_0} - \frac{1}{L})\cdot i_\alpha(k-1) - T(\frac{1}{L_0} - \frac{1}{L})\cdot u_\alpha(k-1) \\ \quad -(\frac{\psi}{L_0} - \frac{\psi_0}{L})\cdot A \\ E_\beta = i_\beta^p(k) - i_\beta(k) \\ \quad = RT(\frac{1}{L_0} - \frac{1}{L})\cdot i_\beta(k-1) - T(\frac{1}{L_0} - \frac{1}{L})\cdot u_\beta(k-1) \\ \quad -(\frac{\psi}{L_0} - \frac{\psi_0}{L})\cdot B \end{cases} \quad (4)$$

At this point, based on the known current, voltage data, accurate inductance and flux-linkage values can be extracted that are only relevant to the real-time detected values.

$$\begin{cases} \psi_0 = \dfrac{X\cdot D - Y\cdot C}{Y\cdot A - X\cdot B} \\ L_0 = \dfrac{(C+\psi_0\cdot A)\cdot L}{X} \end{cases} \tag{5}$$

C. Construction of the Cost Function

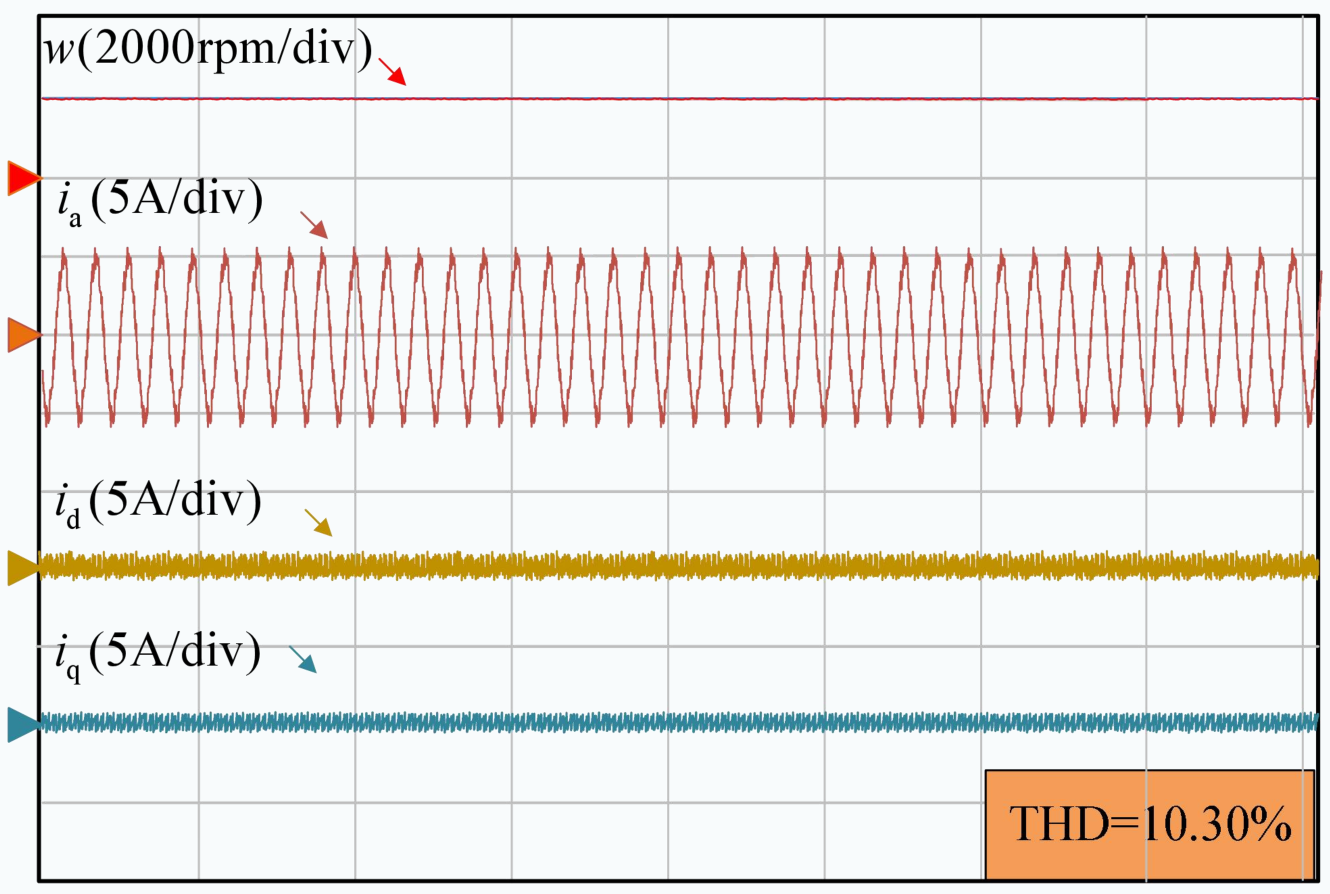
To maintain good control performance at low switching frequencies, this paper proposes an improved cost function (6). This function includes the traditional current error term and adds a switching frequency penalty term (7).

$$cf = |u_\alpha^* - u_\alpha^{\mathrm{i}}| + |u_\beta^* - u_\beta^{\mathrm{i}}| + H\cdot J_1 \tag{6}$$

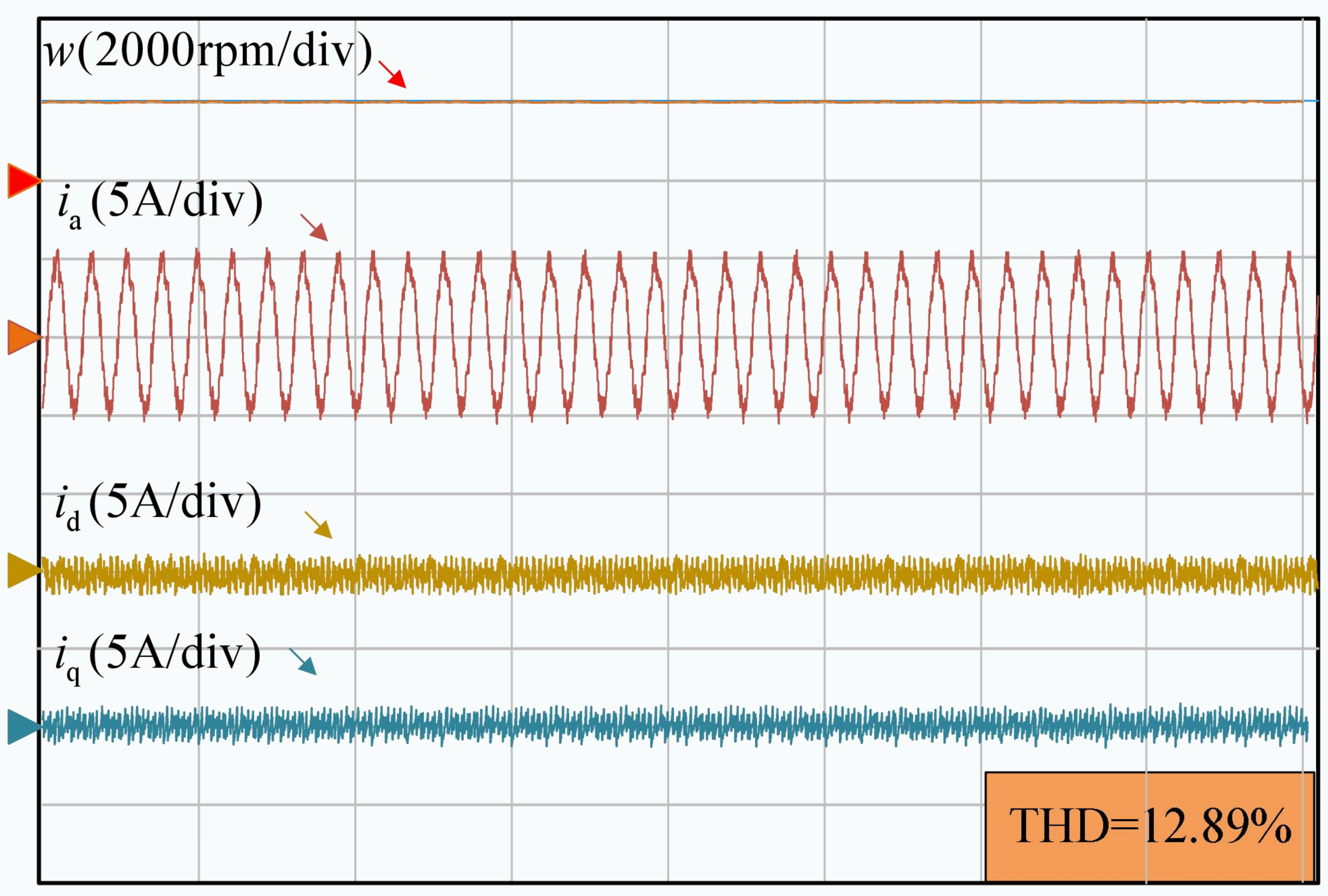
$$J_1 = \left|S_{\mathrm{abc}}^2(k-1) - S_{\mathrm{abc}}^1(k)\right| \tag{7}$$

Simulation Results and Verification

Simulation results and validation Simulation and validation are carried out in MATLAB software to compare the performance of the proposed method and traditional method.



(a)



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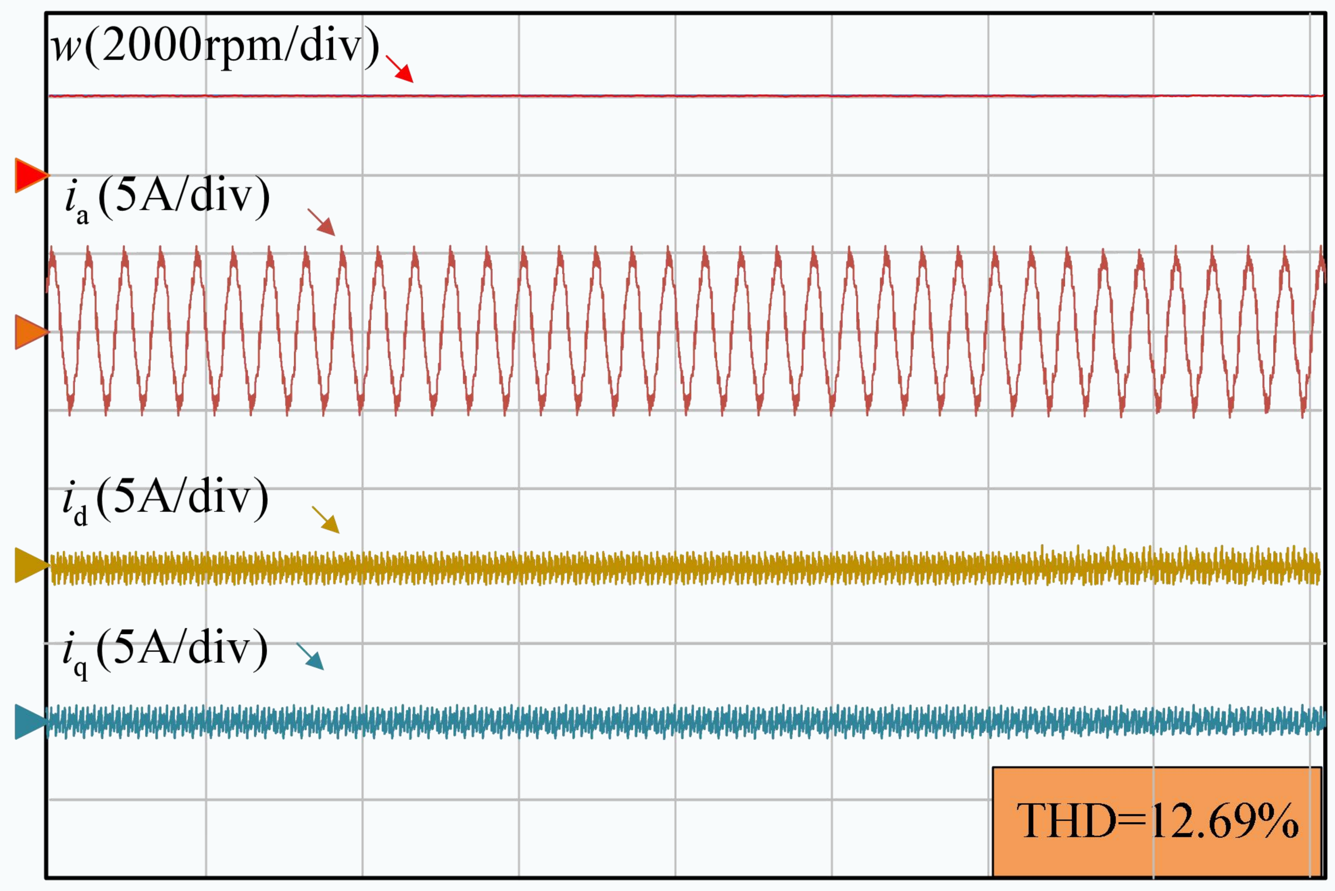
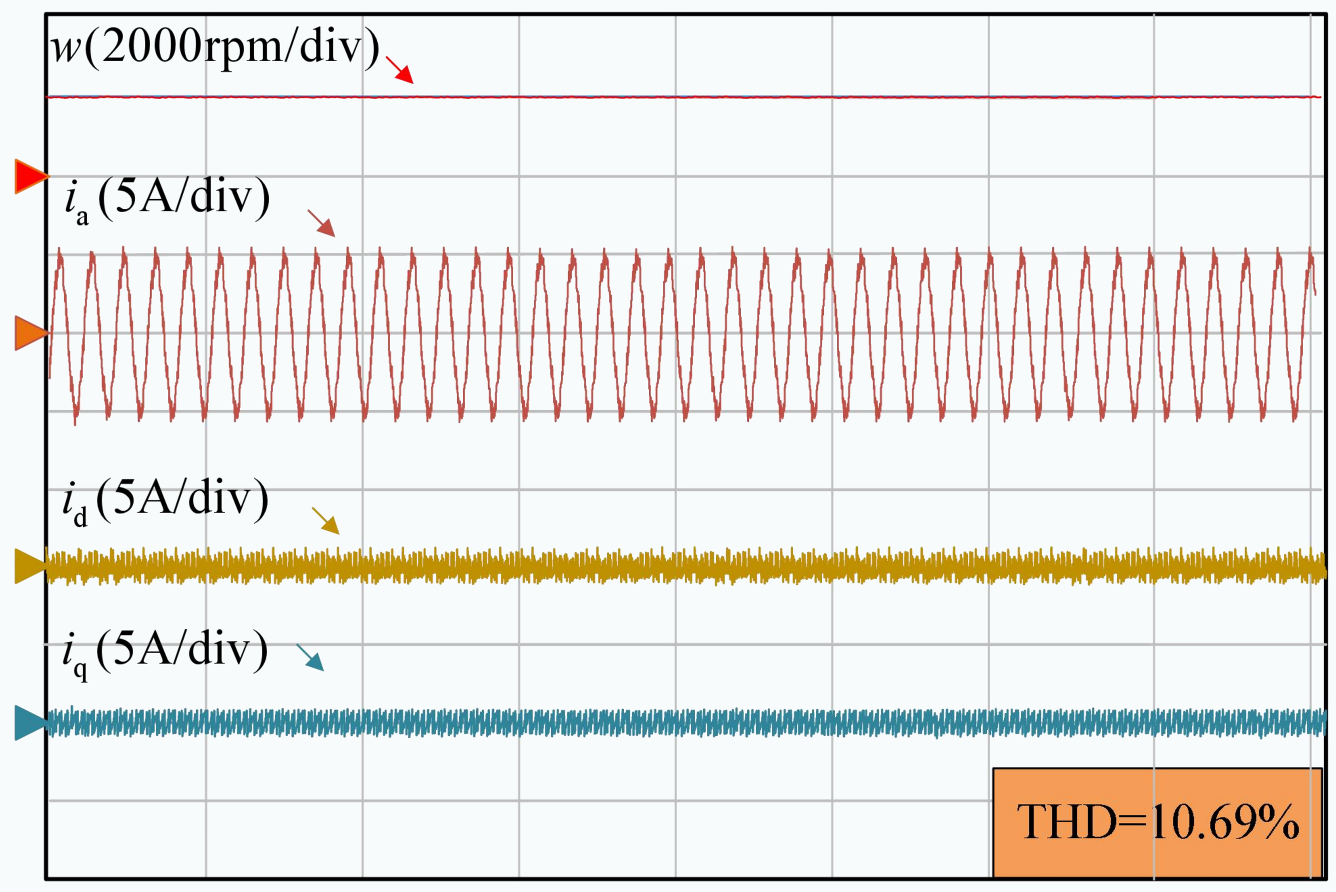


(c)



(d)

Fig. 2. Steady-state simulation results at 2000rpm, rated torque (a) The proposed method with accurate parameters (H=0) (b) The proposed method with accurate parameters (H≠0) (c) The proposed method with mismatched parameters (H≠0) (d) The traditional method with accurate parameters.

As illustrated in Fig. 3, under rated load conditions, the proposed method effectively limits the rise in average switching frequency across various speed conditions.

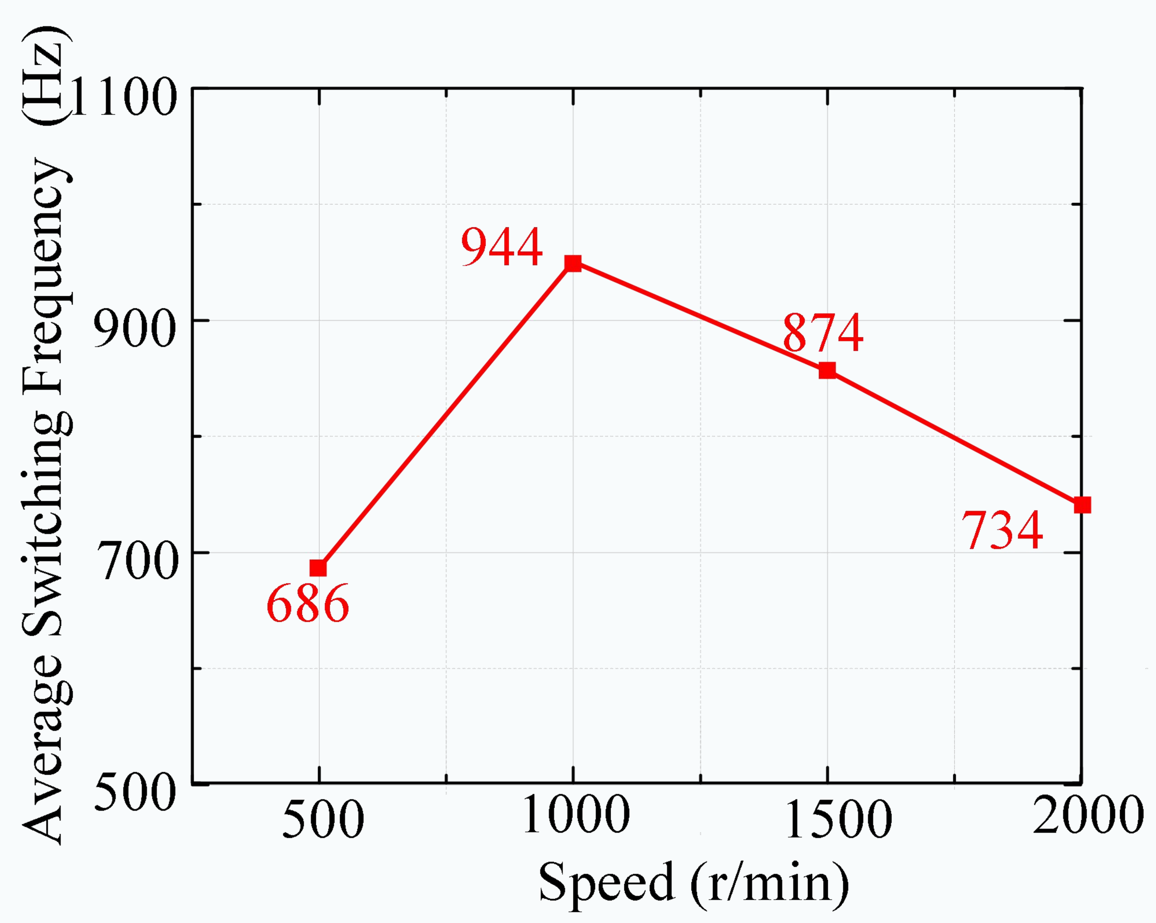


Fig. 3. The performance of average switching frequency at different speeds and rated load.

CONCLUSION

The main contributions of this paper include:

1) improving the robustness of the PMSM at low switching frequencies;

2) establishing an accurate mathematical model and a real-time detection model for the parameters, and improving the value function to enhance the control performance of the system;

3) verifying the feasibility and superiority of the method through simulation.