Improved Deadbeat Predictive Current Control to Enhance the Performance of the Drive System of Permanent Magnet Synchronous Motors

Xin Ba, Peng Wang, Chengning Zhang, Jian Guo Zhu, *Senior Member, IEEE,* and Youguang Guo, *Senior Member, IEEE*

***Abstract*—Thanks to the features of fast dynamic response, excellent static tracking performance, and less computation efforts, the deadbeat predictive current control (DPCC) has been widely applied for permanent magnet synchronous motors (PMSMs) in various applications like electric vehicles, where high speed operation is often adopted for achieving high power density of the drive system. However, the DPCC is a model-parameter-sensitive control method, so inaccuracy of the PMSM model or model parameter mismatch will cause significant deviation in predicting the further behavior of the control variables. To address this issue, an improved DPCC with a novel predictive model of PMSM is proposed in this paper. The novel predictive model considers the core loss of PMSM, which may be a significant part of electromagnetic loss but neglected in the traditional DPCC. As a case study, the proposed DPCC is used to analyze the characteristics of a claw pole PMSM drive system. To validate the merits of the improved DPCC, the analysis results are compared with those of the traditional DPCC.**

***Index Terms*—Core loss, deadbeat predictive current control, permanent magnet synchronous motor, predictive model.**

I. Introduction

THE development of high-performance permanent magnet synchronous motors (PMSMs) has become a hotspot of academic research and industrial application [1-4]. Recently, the surge in demand for highly efficient PMSMs is mainly caused by high-speed applications like electric vehicles, which require high power density. With the high-speed operation, the core loss may exceed the copper loss and become the main kind of loss. The core loss is usually divided into the eddy current loss, hysteresis loss, and anomalous loss. The eddy current shows the most sensitive characteristics of the motor speed, and thus decreasing the eddy current loss is an effective way to reduce the core loss. Soft magnetic composite (SMC) materials featuring very low eddy current loss, magnetic and thermal isotropy, and low-cost manufacturing prospect appear to be proper core material in higher-speed machines [5-7]. Moreover, the claw pole motors have complex stator structures, which is very hard for fabrication by the electrical steel sheet, but it is easy by molding SMC material.

In the last decades, model predictive controls (MPCs) have become a hotspot of academic research and industrial application since they can provide superior dynamic and steady-state characteristics. Among various MPC methods, the deadbeat predictive current control (DPCC) has superior dynamic response capabilities, making it suitable for high-speed drive [8-10]. However, the DPCC is a parameter-sensitive control method of the PMSM model, and hence parameter mismatch will cause the predicted control variables to deviate significantly from the expected values. Some parameter compensation methods have been developed to address this problem, but often they cannot provide satisfactory results.

In the DPCC, the equivalent circuit model (ECM) of PMSMs, also known as the predictive model, is the essence for the further behavior prediction of the control variables, such as the q-axis current. The predictive values of the control variables are derived though the ECM of the PMSM, and at the end of each control period, the difference between the predictive and actual values of control variables is forced towards zero. Thus, the DPCC is a model-dependent algorithm, and the inaccurate ECM will directly affect the values of the control variables and furtherly increase the errors. Therefore, improving the accuracy of the ECM of the PMSM can be very effective for the performance enhancement of the DPCC drive system.

In this paper, an improved DPCC with novel current predictive model of PMSM is proposed. First, the new predictive model is built, which takes the motor core loss into account and can productively reduce the errors between the predictive and the actual values of the control variables. Therefore, an improved DPCC containing a higher-precision predictive model is developed. Finally, in order to validate the superior control performance and disturbance robustness of the improved DPCC, comparisons have been made between the traditional and improved approaches.

Manuscript received April 14, 2021; accepted ###, 2021. *(Corresponding author: Chengning Zhang.)*

X. Ba is with the National Engineering Laboratory for Electric Vehicles, Beijing Institute of Technology, Beijing 100081, China and also with the School of Electrical and Data Engineering, University of Technology Sydney, NSW 2007, Australia (E-mail: Xin.BA@student.uts.edu.au).

P. Wang is with the National Engineering Laboratory for Electric Vehicles, Beijing Institute of Technology, Beijing 100081, China (E-mail: wp_smile@163.com).

C. Zhang is with the National Engineering Laboratory for Electric Vehicles, Beijing Institute of Technology, Beijing 100081, China (E-mail:chengning_zhang@163.com).

J. G. Zhu is with the School of Electrical and Information Engineering, The University of Sydney, NSW 2006, Australia (E-mail: Jianguo.Zhu@syd.edu.au)

Y. Guo is with the School of Electrical and Data Engineering, University of Technology Sydney, NSW 2007, Australia (E-mail: Youguang.Guo-1@uts.edu.au).

In the following parts, the ECM of PMSMs with predictable core loss is established in Section II, whereas the drive system with improved DPCC of PMSM is described in Section III. The quantitative and qualitative comparison and analysis of the drive system with the improved and traditional DPCCs are presented in Section IV. Conclusion and some important discussion are drawn in Section V.

II. Equivalent Circuit Model of PMSMs with Predictable Core Loss

In [11], the authors of this paper proposed an equivalent circuit model (ECM) including core loss for analyzing a claw pole SMC PMSM, and experimentally validated the superior performance and accuracy in the motor analysis over a wide operation range, as shown in Fig. 1. In the figure, L_s is the synchronous inductance, E_0 is the back electromotive force (EMF), the power loss in R_c is the core loss of the PMSM, and the power loss in R_s is the copper loss. Therefore, the electromagnetic losses consisting of the core and copper losses have been properly considered in this model, resulting in a higher accuracy either in motor characteristic calculation or as the predictive model of PMSM in the model predictive control system.

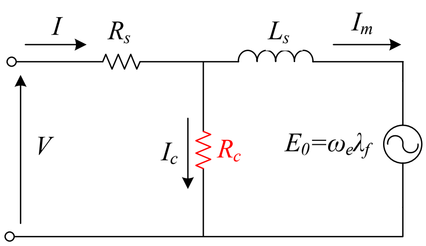

Fig. 1. Per-phase ECM of PMSMs with predictable core loss [11].

Although the per-phase ECM benefits in clear physical meaning and easy to understanding, the *d-q* axis ECM of PMSMs attracts more attention in the motor vector control area. Thus, a change of variables that formulates a transformation of the three-phase stationary circuit elements to the rotary reference frame can be written as:

$$\boldsymbol{u}_{qd0} = \boldsymbol{K}_s \boldsymbol{u}_{abc} \tag{1}$$

where $\boldsymbol{u}_{qdo}$ is the voltage vector with the rotary reference frame, $\boldsymbol{u}_{abc}$ the voltage vector with the three-phase stationary reference frame, and the matrix $\boldsymbol{K}_s$ and its inverse matrix $(\boldsymbol{K}_s)^{-1}$ are defined as:

$$\boldsymbol{K}_s = \frac{2}{3}\begin{pmatrix} \cos\theta & \cos(\theta-2\pi/3) & \cos(\theta+2\pi/3) \\ \sin\theta & \sin(\theta-2\pi/3) & \sin(\theta+2\pi/3) \\ 1/2 & 1/2 & 1/2 \end{pmatrix} \tag{2}$$

$$(\boldsymbol{K}_s)^{-1} = \begin{pmatrix} \cos\theta & \sin\theta & 1 \\ \cos(\theta-2\pi/3) & \sin(\theta-2\pi/3) & 1 \\ \cos(\theta+2\pi/3) & \sin(\theta+2\pi/3) & 1 \end{pmatrix} \tag{3}$$

Thus, (1) can be rewritten as:

$$\begin{aligned} \boldsymbol{u}_{qd0} &= \boldsymbol{K}_s \boldsymbol{R}_s (\boldsymbol{K}_s)^{-1} \boldsymbol{i}_{qd0} + \boldsymbol{K}_s p\left[(\boldsymbol{K}_s)^{-1} \boldsymbol{\lambda}_{qd0}\right] \\ &= \boldsymbol{K}_s \boldsymbol{R}_s (\boldsymbol{K}_s)^{-1} \boldsymbol{i}_{qd0} + \boldsymbol{K}_s p(\boldsymbol{K}_s)^{-1} \boldsymbol{\lambda}_{qd0} + \boldsymbol{K}_s (\boldsymbol{K}_s)^{-1} p\boldsymbol{\lambda}_{qd0} \end{aligned} \tag{4}$$

where $\boldsymbol{\lambda}_{qdo}$ and $\boldsymbol{i}_{qdo}$ are the flux linkage and current vectors under the rotary reference frame, $\boldsymbol{R}_s$ is the stator winding resistance matrix, and p is the differential operator (=d/dt).

After mathematical calculations, the voltage equations under dq-axis reference frame can be written as:

$$\begin{cases} u_d = R_s i_d - \omega_e \lambda_q + p\lambda_d \\ u_q = R_s i_q + \omega_e \lambda_d + p\lambda_q \end{cases} \tag{5}$$

where ω_e is the PMSM speed in electrical radian per second.

Similarly, for the R_c branch in the per-phase ECM, the voltage equation can be described as:

$$\boldsymbol{u}_{abc} = \boldsymbol{R}_s \boldsymbol{i}_{abc} + \boldsymbol{R}_c \boldsymbol{i}_{cabc} \tag{6}$$

Apply the reference frame transformation:

$$\begin{aligned} \boldsymbol{u}_{qd0} &= \boldsymbol{K}_s \boldsymbol{u}_{abc} = \boldsymbol{K}_s \boldsymbol{R}_s (\boldsymbol{K}_s)^{-1} \boldsymbol{i}_{qd0} + \boldsymbol{K}_s \boldsymbol{R}_c (\boldsymbol{K}_s)^{-1} \boldsymbol{i}_{cqd0} \\ &= \boldsymbol{R}_s \boldsymbol{i}_{qd0} + \boldsymbol{R}_c \boldsymbol{i}_{cqd0} \end{aligned} \tag{7}$$

where $\boldsymbol{i}_{abc}$ and $\boldsymbol{i}_{cabc}$ are the phase current and the core loss current matrixes under the three-phase stationary reference frame, whereas $\boldsymbol{i}_{cqdo}$ is the core loss current matrix under the rotary reference frame, and $\boldsymbol{R}_c$ is the equivalent core loss resistance matrix of the PMSM.

Then, the mathematical models of the PMSM considering the core loss resistance under the *d-q* axis reference frame have been established.

For the claw pole PMSM with SMC core, the parameters in the per-phase ECM can be determined by theoretical calculation [11-13], as listed in Table I.

TABLE I
Parameters in the PMSM ECM

Parameter	Value
Stator resistance R_s	0.302 Ω
Equivalent core loss resistance R_c	0.0702n (Ω); n is the motor speed (r/min)
Synchronous inductance L_s	5.24 mH
Permanent magnet flux λ_f	0.026 Wb
Number of pole pairs P	10
Rated voltage	64 V

Notice that the equivalent core loss resistance is a function of the speed, and hence the PMSM performance in the entire working speed range can be accurately predicted.

III. Establishment of the Drive System with Improved DPCC

The DPCC is based on the predictive model of the PMSM to predict voltage references to generate proper switch signals via space vector pulse-width-modulation module for the inverter, and then drive the PMSM. Correspondingly, the model parameter mismatch of DPCC is an obvious problem that has attracted widespread attention from scholars all over the world. Establishing an accurate predictive model of PMSM can address the aforementioned problem fundamentally. The block diagram of the drive system with the improved DPCC is illustrated in Fig. 2. A PI controller which regulates the mechanical speed loop of the PMSM, and a DPCC which adjusts the d-q axis current loop are included in the proposed drive system. The reference d-q axis currents are derived from the speed error in the PI controller. In this application, the i_d=0 control strategy is adopted to realize the maximum torque per ampere drive.

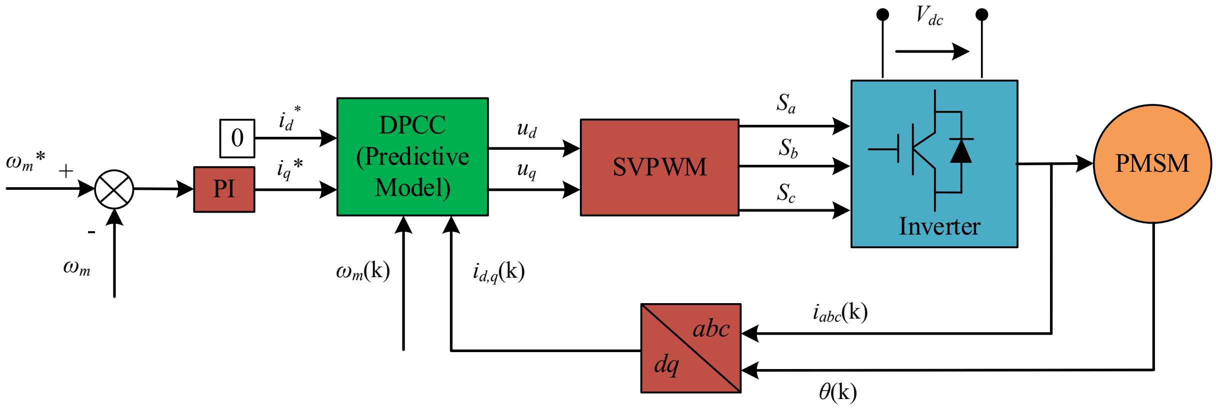

Fig. 2. Schematic diagram of the DPCC drive system.

The current equations considering the core loss of the PMSM in the DPCC can be written as:

$$\begin{bmatrix} \frac{di_{od}}{dt} \\ \frac{di_{oq}}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{R_c R_s}{L_s(R_c+R_s)} & \omega_e \\ -\omega_e & -\frac{R_c R_s}{L_s(R_c+R_s)} \end{bmatrix} \begin{bmatrix} i_{od} \\ i_{oq} \end{bmatrix} + \begin{bmatrix} \frac{R_c}{L_s(R_c+R_s)} & 0 \\ 0 & \frac{R_c}{L_s(R_c+R_s)} \end{bmatrix} \begin{bmatrix} u_d \\ u_q \end{bmatrix} + \begin{bmatrix} 0 \\ -\frac{\omega_e \lambda_f}{L_s} \end{bmatrix} \tag{8}$$

$$\begin{cases} i_d = i_{od} - \frac{L_s \omega_e}{R_c} i_{oq} \\ i_q = i_{oq} + \frac{L_s \omega_e}{R_c} i_{od} + \frac{\omega_e \lambda_f}{R_c} \end{cases} \tag{9}$$

where i_d and i_{od} are the d-axis current and magnetizing current, and i_q and i_{oq} are the q-axis current and magnetizing current, respectively. λ_f is flux linkage generated by the PMs.

Assuming that the control system has very small sampling period T_s, the PMSM's discrete current predictive model can be obtained according to the first-order Taylor series as:

$$\boldsymbol{i}(k+1) = \boldsymbol{Ai}(k) + \boldsymbol{Cu}(k) + \boldsymbol{D}(k) \tag{10}$$

where

$$\boldsymbol{i}(k) = \begin{bmatrix} i_d(k) \\ i_q(k) \end{bmatrix}, \boldsymbol{u}(k) = \begin{bmatrix} u_d(k) \\ u_q(k) \end{bmatrix} \tag{11a}$$

$$\boldsymbol{A} = \begin{bmatrix} 1-\frac{T_s R_c R_s}{L_s(R_c+R_s)} & T_s\omega_e \\ -T_s\omega_e & 1-\frac{T_s R_c R_s}{L_s(R_c+R_s)} \end{bmatrix} \tag{11b}$$

$$\boldsymbol{C} = \begin{bmatrix} \frac{T_s R_c}{L_s(R_c+R_s)} & 0 \\ 0 & \frac{T_s R_c}{L_s(R_c+R_s)} \end{bmatrix} \tag{11c}$$

$$\boldsymbol{D} = \begin{bmatrix} 0 \\ -\frac{T_s \omega_e \lambda_f}{L_s} \end{bmatrix} \tag{11d}$$

The PMSM voltage in the following modulation period is predicted as:

$$\boldsymbol{u}(k+1) = \boldsymbol{C}^{-1}\left[\boldsymbol{i}^*(k) - \boldsymbol{A}\left(\boldsymbol{Ai}(k) + \boldsymbol{Cu}(k) + \boldsymbol{D}(k)\right) - \boldsymbol{D}(k+1)\right] \tag{12}$$

where $\boldsymbol{i}^*(k)$ is the reference currents.

IV. Comparison of Proposed and Traditional DPCC

Initially, the motor is at standstill and with no-load. A step command of rated speed (1800 r/min) from standstill is provided. In the drive system, the parameters of the PI controller are fixed as K_p=10 and K_i=0.24 both for the traditional DPC control and the improved DPCC. Fig. 3 depicts the rotor speed response of the two cases. It is found that the rise time with the traditional DPCC is 0.091 s, and after a short period of oscillation, the motor speed can follow the preset speed without steady-state error, as shown by the blue line. The red line describes the rotor speed response with the improved DPCC, and the rise time is 0.085 s and also can follow the preset speed without steady-state error. The dynamic speed response of the drive system with the improved DPCC is faster than that of the traditional one.

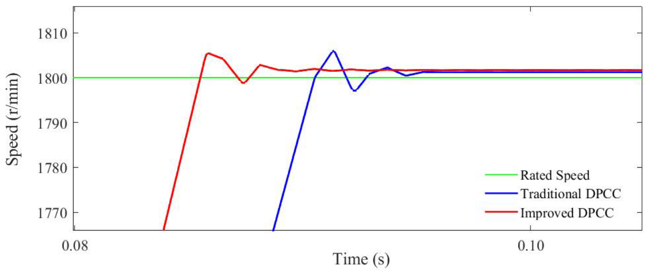

Fig. 3. Comparison of rotor speed response between the drive systems with the traditional and improved DPCCs.

After the rotor speed reaches the steady-state, a torque step command of 1 Nm from no-load at 0.12 s is applied. The corresponding torque characteristics for both the traditional and improved DPCCs are presented in Fig. 4. With the traditional DPCC, after a short period of oscillation, the speed offset of the drive system changes from zero to a negative value, i.e., the steady-state speed is less than the preset speed (1800 r/min), depicted by the blue line. With the improved DPCC, the rotor speed enters the steady-state after 0.005 s of oscillation, and can still follow the preset speed accurately. It can also be seen that the torque robustness of the drive system with the improved DPCC is better than the traditional DPCC when the motor load torque changes suddenly.

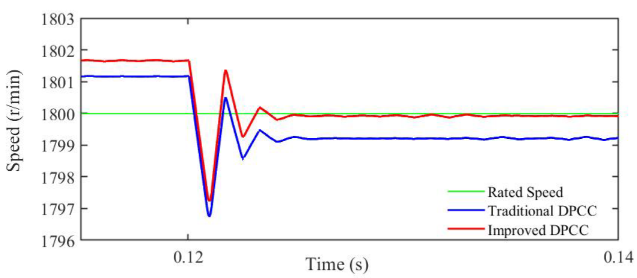

Fig. 4. Comparison of torque response between the drive systems with the traditional and improved DPCC.

Fig. 5 illustrates the phase current response of the drive system with the improved DPCC during the control process mentioned above. After the phase currents are stabilized, their amplitude is 2.379 A, and the phase currents are quite sinusoidal.

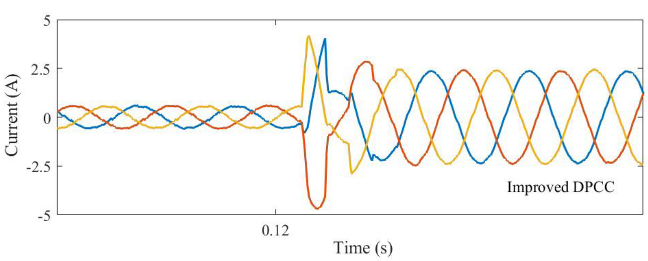

Fig. 5. Phase current response of the drive system with the improved DPCC.

V. Conclusion

This paper establishes an improved DPCC with a novel predictive model to enhance the performance of the PMSM drive system. In the improved DPCC, the predictive model of PMSMs with predictable core loss is adopted to generate more accurate predictive control variables. Then, the dynamic speed response and the torque robustness of the drive system with this improved DPCC are enhanced effectively. At the same time, the phase currents of the drive system with the improved DPCC can maintain a good sinusoid. This predictive model can be further extended to analyze the robustness when other kinds of disturbance, such as parameter variation during operation, and this approach would also be effective to enhance the accuracy of the predictive control variables in other kinds of model predictive control.

References

[1] X. Sun, C. Hu, G. Lei, Z. Yang, Y. Guo, and J. G. Zhu, "Speed sensorless control of SPMSM drives for EVs with a binary search algorithm-based phase-locked loop," *IEEE Trans. Veh. Technol.,* vol. 69, no. 5, pp. 4968-4978, 2020.

[2] X. Sun, C. Hu, J. G. Zhu, S. Wang, W. Zhou, G. Lei, K. Li, B. Zhu, and Y. Guo, "MPTC for PMSMs of EVs with multi-motor driven system considering optimal energy allocation," *IEEE Trans. Magn.,* vol. 55, no. 7, pp. 1-6, 2019.

[3] X. Sun, *et al.*, "An improved model predictive current control for PMSM drives based on current track circle," *IEEE Trans. Ind. Electron.*, vol. 68, no. 5, pp. 3782-3793, May 2021.

[4] B. D. S. G. Vidanalage, S. Mukundan, W. Li, and N. C. Kar, "An overview of PM synchronous machine design solutions for enhanced traction performance," in *Proc. 2020 Int. Conf. on Electrical Machines (ICEM)*, 2020, vol. 1, pp. 1697-1703.

[5] Y. Guo, J. G. Zhu, P. A. Watterson, and W. Wu, "Development of a PM transverse flux motor with soft magnetic composite core," *IEEE Trans. Energy Convers.,* vol. 21, no. 2, pp. 426-434, 2006.

[6] G. Lei, J. G. Zhu, Y. Guo, K. Shao, and W. Xu, "Multiobjective sequential design optimization of PM-SMC motors for six sigma quality manufacturing," *IEEE Trans. Magn.,* vol. 50, no. 2, pp. 717-720, 2014.

[7] G. Lei, J. G. Zhu, Y. G. Guo, J. F. Hu, W. Xu, and K. R. Shao, "Robust design optimization of PM-SMC motors for six sigma quality manufacturing," *IEEE Trans. Magn.,* vol. 49, no. 7, pp. 3953-3956, 2013.

[8] R. S. Dastjerdi, M. A. Abbasian, H. Saghafi, and M. H. Vafaie, "Performance improvement of permanent-magnet synchronous motor using a new deadbeat-direct current controller," *IEEE Trans. Power Electron.,* vol. 34, no. 4, pp. 3530-3543, 2019.

[9] X. Zhang, B. Hou, and Y. Mei, "Deadbeat predictive current control of permanent-magnet synchronous motors with stator current and disturbance observer," *IEEE Trans. Power Electron.,* vol. 32, no. 5, pp. 3818-3834, 2017.

[10] L. Springob and J. Holtz, "High-bandwidth current control for torque-ripple compensation in PM synchronous machines," *IEEE Trans. Ind. Electron.,* vol. 45, no. 5, pp. 713-721, 1998.

[11] X. Ba, Y. Guo, J. Zhu, and C. Zhang, "An equivalent circuit model for predicting the core loss in a claw-pole permanent magnet motor with soft magnetic composite core," *IEEE Trans. Magn.,* vol. 54, no. 11, article 8105506, 2018.

[12] Y. Guo, J. Zhu, P. Watterson, W. Holliday, and W. Wu, "Improved design and performance analysis of a claw pole permanent SMC motor with sensorless brushless DC drive," in *Proc. 5th Int. Conf. on Power Electron. & Drive Syst.*, 2003, vol. 1, pp. 704-709.

[13] Y. Guo, J. G. Zhu, P. Watterson, and W. Wu, "Development of a claw pole permanent magnet motor with soft magnetic composite core," *Australian J. Elec. & Electronic Eng.,* vol. 2, no. 1, pp. 21-30, 2005.