Torque Ripple Suppression for IPMSM using FEA-based Model Predictive Direct Torque Control

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Abstract—The interest in model predictive direct torque control (MP-DTC) for high-performance dynamic control of electric drives has been growing. Unlike the conventional direct torque control (DTC), MP-DTC can achieve optimal voltage selection by predicting the control variables evaluations using a machine model. However, the model-machine mismatch can degrade the control performance significantly, especially for the interior permanent magnet synchronous machine (IPMSM) because of its highly nonlinear characteristics. Therefore, this paper describes an investigation of the MP-DTC algorithm that exploits the advantages of a finite element analysis (FEA) based model in representing the behavior of the IPMSM precisely, including the magnetic saturation and spatial harmonics effects, to suppress the torque pulsations and eliminate the steady-state torque error. Moreover, this approach optimizes the duty ratio simultaneously with the voltage vector selection to guarantee further torque ripple reduction under steady-state operation, especially at low speeds. Simulation results of an 80-kW IPMSM drive are presented to validate the model and the proposed control method.

Keywords—FEA-based model, permanent magnet synchronous motor (PMSM), model predictive control (MPC), direct torque control (DTC), torque ripple.

I. INTRODUCTION

Due to the rotor saliency, the interior permanent magnet synchronous machine (IPMSM) produces a reluctance torque in addition to the torque component produced by the magnets, exhibiting higher torque density, higher efficiency, and wide constant power range compared with the surface-mount PMSM (SPMSM) [1]. Therefore, it is more attractive for many applications, such as electric vehicles, aerospace, marine traction system [2]. On the other hand, that saliency introduces a higher torque ripple due to the intrinsic variation of the magnetic energy with the rotor position, and leads to the nonlinear torque-current characteristics that make the design of a high-performance control system more challenging [3]. The torque ripple is a critical issue for these applications as it can produce mechanical vibration and acoustic noise [4].

As a high-performance control scheme that can achieve a sufficiently high bandwidth, direct torque control (DTC) is utilized in [5, 6] to reduce the torque pulsations of PMSM. This method directly controls both the torque and the stator flux amplitude using a predefined switching table, from which

a voltage vector is selected based on the error between the reference and estimated values [7]. The torque estimator considers the ripple as a known external load that is predetermined using either an analytical model [4, 8] or finite element analysis (FEA) based model [6]. Although DTC can effectively mitigate the cogging torque, it contributes to the torque ripple because the switching table cannot ensure optimal voltage vector selection. Also, that vector is employed for the whole control cycle, which in many cases is undesired [9]. Hence, the model predictive DTC (MP-DTC) [10-14] and duty regulation-based DTC (DDTC) [15, 16] are introduced as alternatives.

Unlike the conventional DTC, MP-DTC utilizes a system model to predict the future states, i.e., torque and stator flux amplitude, under the different inverter's voltage vectors. Then, a cost function is employed to select the voltage vector that achieves the optimal solution [17]. As a result, MP-DTC can achieve better torque control performance than the conventional DTC [9]. To guarantee further reduction of torque ripple, the duty ratio regulation concept is applied with MP-DTC in [18] and [11] to insert a zero voltage vector next to an active voltage vector during each control period. However, the existing MP-DTC methods focus on reducing the torque ripple due to the control algorithm, and hence neglect the magnetic saturation and spatial harmonics effects of the machine in the prediction model. During practical implementation, this leads to machine-model mismatch that can degrade the control performance significantly and cause high steady-state error. Thus, accurate modeling of the machine is an essential requirement for MP-DTC.

With the high-accuracy offered by the FEA in evaluating the machine parameters, the modeling-accuracy can be ensured [19]. A high-accuracy and computationally efficient IPMSM model is presented in [20]. This model extracts the flux linkage data from FEA results at different currents and rotor positions to consider both the magnetic saturation, and the cogging torque. Therefore, this paper uses that model with an advanced MP-DTC approach that optimizes the voltage vector selection simultaneously with its working duration to minimize the torque pulsations and steady-state torque error of an 80 kW IPMSM drive system. The feasibility and effectiveness of the proposed method are confirmed by a comparison with the conventional MP-DTC techniques.

The rest of this work is organized as follows. Section II introduces the mathematical models of IPMSM and converter. The basic principle of the proposed control approach is described in Section III. In Section IV, the FEA-based model of an IPMSM prototype is presented. Section V shows the simulation results and verifications of the proposed method. Finally, conclusions are drawn in Section VI.

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II. MODEL OF IPMSM AND INVERTER

The electrical dynamic behavior of the IPMSM can be represented in the rotor reference frame (dq) using the flux linkage-based model as [19]

$$\begin{cases} v_d = i_d R_s + \frac{d\psi_d}{dt} - \omega_e \psi_q \\ v_q = i_q R_s + \frac{d\psi_q}{dt} + \omega_e \psi_d \end{cases} \quad (1)$$

$$\begin{cases} \psi_d = L_d i_d + \psi_{pm} \\ \psi_q = L_q i_q \end{cases} \quad (2)$$

$$T_e = \frac{3p}{2} (\psi_d i_q - \psi_q i_d) + T_{cog} \quad (3)$$

where $V_d, V_q, i_d, i_q, \psi_d, \psi_q, L_d, L_q$ are the dq-components of the stator voltage, current, flux linkage, and inductance, respectively; ω_e is the electrical angular speed of the rotor; T_e is the electromagnetic torque; T_{cog} is the cogging torque; ψ_{pm} is the permanent magnet flux; p is the number of pole pairs; R_s is the stator winding resistance.

The two-level voltage source inverter (2L-VSI) provides eight voltage vectors to feed the IPMSM [21]. These voltage vectors can be expressed, using the switching states of the inverter's legs ($S_1, S_2, S_3 \in \{0, 1\}$), as [14]

$$V_i = \frac{2V_{dc}}{3} (S_1 + aS_2 + a^2S_3) \quad (4)$$

where $i \in \{0, 1, \dots, 7\}$ is the voltage vector index; V_{dc} is the DC-link voltage, and $a = e^{j2\pi/3}$.

III. PROPOSED MP-DTC METHOD FOR IPMSM

Fig. 1 shows the overall control diagram of the proposed method. First, the torque (T_e^k) and the stator flux amplitude (ψ_s^k) need to be estimated from the measured current signals. Then, a prediction model is used to determine the future values (T_e^{k+1} and ψ_s^{k+1}) under each voltage vector. Finally, a cost function evaluates these predictions to select the optimal voltage vector and its duty ratio (V_x and D_x) that force the torque and the stator flux to follow their references (T_e^{ref} and ψ_s^{ref}). A detailed description of this diagram is presented next.

A. Flux and Torque Estimation

The stator flux ψ_s^k can be estimated based on either the voltage or the current equations, i.e., (1) or (2), respectively. The former is preferred because of its robustness against inductance variations with the magnetic saturation [15]. For precise torque estimation, the torque maps versus the dq-currents at different rotor positions are determined by the FEA, as will be seen in Section IV.

B. Prediction model

The future values of stator flux amplitude ψ_s^{k+1} can be obtained by discretizing (1) using forward Euler approximation as follows [14]:

$$\begin{cases} \psi_d^{k+1} = \psi_d^k + T_s (v_d^k - i_d^k R_s + \omega_e^k \psi_q^k) \\ \psi_q^{k+1} = \psi_q^k + T_s (v_q^k - i_q^k R_s - \omega_e^k \psi_d^k) \\ \psi_s^{k+1} = \sqrt{(\psi_d^{k+1})^2 + (\psi_q^{k+1})^2} \end{cases} \quad (5)$$

where k is the sampling instant, and T_s is the sampling period.

In the conventional methods, according dq-flux linkages ψ_d^{k+1} and ψ_q^{k+1} , constant parameters (i.e., ψ_{pm}, L_d and L_q) are employed to determine the current as

$$\begin{cases} i_d^{k+1} = (\psi_d^{k+1} - \psi_{pm})/L_d \\ i_q^{k+1} = \psi_q^{k+1}/L_d \end{cases} \quad (6)$$

Fig. 1. Block diagram of the proposed MP-DTC method

Fig. 2. The FEA-based IPMSM model

Then, the torque T_e^{k+1} is predicted by (3), neglecting the cogging torque. Consequently, the prediction model cannot represent the machine behavior accurately.

Therefore, in the proposed approach, the dq-flux linkages and the electromagnetic torque are extracted from the FEA at different currents (i_d, i_q) and rotor positions (θ_e) to include the magnetic saturation, spatial harmonics effects, and the cogging torque in the model. As shown in Fig. 2, for a given voltage, the d- and q- axis flux linkages (ψ_d, ψ_q) are calculated using (5). Subsequently, the d- and q-axis currents are obtained from 3D-lookup tables with ψ_d, ψ_q , and θ_e as inputs. Finally, the electromagnetic torque is acquired by (3) also in a form of a 3D-lookup table with i_d, i_q , and θ_e as inputs. This model can be implemented by inverting the solution of currents versus the flux linkages [20], as will be described later.

C. Voltage Vector Selection and Duty Ratio Regulation

In the conventional methods, the prediction model is used to get T_e^{k+1} and ψ_s^{k+1} for each voltage vector represented by (4). After that, a cost function is utilized to evaluate the error between the predicted values and the reference signals to select the optimal voltage vector. The working duration of that voltage vector is then determined based on a control objective, such as minimizing the mean torque error over one control period [15]. However, changing the working duration makes the selected voltage vector non-optimal as it is equivalent to varying the voltage amplitude. As a result, the torque ripple reduction cannot be ensured, especially at low speeds [11]. Therefore, the proposed method simultaneously optimizes the duty ratio with the voltage vector selection.

With the aim of minimizing the rms value of the torque ripple over each control cycle, the duty ratio of the active voltage vectors (i.e., $i \in \{1, 2, \dots, 6\}$) can be calculated as [15]

$$D_i^k = \frac{2(T_e^{ref} - T_e^k) - \Delta T_{e0}}{2\Delta T_{ei} - \Delta T_{e0}}, \quad D_i^k \in [0, 1] \quad (7)$$

where ΔT_{e0} and ΔT_{ei} are the torque deviations ($T_e^{k+1} - T_e^k$) due to the zero and active voltage vectors, respectively, if applied for the whole control cycle. The prediction model can be utilized to determine T_e^{k+1} using V_i as inputs.

Once the duty ratio is determined for each voltage vector, the values of T_e^{k+1} and ψ_s^{k+1} are obtained using $D_i V_i$ as inputs to the prediction model. Then, the cost function (G) is used to evaluate the voltage vectors and their duty ratio to select those of them that achieve the minimum error in the torque and the stator flux amplitude, according to the following expression:

$$G = \left(\frac{T_e^{ref} - T_e^{k+1}}{T_n} \right)^2 + \lambda \left(\frac{\psi_s^{ref} - \psi_s^{k+1}}{\psi_n} \right)^2 + f(i_s^{k+1}) \quad (8)$$

where T_n , ψ_n are the nominal values of the torque and stator flux, respectively; λ is the weighting factor of the stator flux error term; $f(i_s^{k+1})$ represents the hard constraints to limit the stator current to its peak value ($i_{s\ peak}$) as follows:

$$f(i_s^{k+1}) = \begin{cases} \infty & \text{if } |i_s^{k+1}| > i_{s\ peak} \\ 0 & \text{if } |i_s^{k+1}| \leq i_{s\ peak} \end{cases} \quad (9)$$

The flow chart shown in Fig. 3 summarizes the algorithm of proposed MP-DTC with the duty ratio regulation.

IV. FEA-BASED IPMSM MODEL

In this section, the FEA-based model is demonstrated for an 80-kW IPMSM prototype with the specifications listed in Table I. This machine has 48 slots and 4 pole pairs with N42UH magnets. Fig. 4 shows a complete view of the machine and its cross-section.

A. Model Implementation

First, the FEA is used to determine the dq-flux linkage components and electromagnetic torque at different operating points by varying i_d , i_q , and θ_e in the ranges of $[-400, 400]$ A, and $[0, 30]$ electrical degrees with steps of 40A, and 1 degree, respectively. The raw data determined by the FEA is processed using Matlab to generate 3D-lookup tables for the d- and q-axis flux linkage and the torque, as shown in Fig. 5.

In order to reverse the flux-linkage maps, minimum and maximum values of ψ_d and ψ_q are obtained, and the intervals are subdivided into n divisions ($n = 50$). The inverse solution then can be obtained using the curve fitting tool in Matlab. Fig. 6 depicts the d- and q-axis current maps versus the flux linkages.

Once the inversion of these maps has been accomplished, a validation is carried out by selecting different sets of i_d , i_q , and θ_e and use the original flux linkage maps to compute ψ_d and ψ_q which are employed to calculate new sets of i_d and i_q using the inversed maps. Fig. 7 shows the % error in d- and q-axis currents at $i_d = -100$ A and different rotor positions. It can be noticed that the maximum current error is 0.7%. The error at different values of i_d were also checked, and they show similar small magnitudes which are not presented for the sake of space.

B. Model verification

The FEA-based model is implemented in Simulink and verified by experimental results. The IPMSM prototype is drive by a dynamometer, and the no-load test is performed to capture the back-EMF waveforms. Fig. 8 compares the Simulink-, FEA-, and experiment- line-to-line back-EMF at an operating speed of 3000 rpm. It can be noticed that the predicted

Fig. 3. Flow chart of the proposed MP-DTC with duty ratio regulation

Fig. 4. The IPMSM prototype: (a) cross-section; (b) complete view

TABLE I. DESIGN PARAMETERS OF IPMSM PROTOTYPE

Electrical parameters	Value	Mechanical parameters	Value
Rated power (kW)	80	Stator outer diameter (mm)	290
Rated torque (Nm)	400	Rotor outer diameter (mm)	193
Peak torque (Nm)	600	Axial length (mm)	200
Base speed (rpm)	3000	Number of slots	48
Max. speed (rpm)	10000	Number of pole pairs	4
DC-link voltage (V)	540	Number of turns per coil	12
Peak current (A)	400	Air gap length (mm)	1

back EMF using the Simulink model matches that of the FEA results, but the measured back EMF has a lower ripple because the rotor of the real machine prototype is skewed to reduce the interaction between the magnets and the stator teeth. The rotor skewing is ignored in the simulation to illustrate how the control method can eliminate the torque ripples caused by these interactions.

Besides, to verify the torque prediction at different operating points, the currents ($i_d = 0$ A, $i_q = 0$ A) and ($i_d = -300$ A, $i_q = 200$ A) are given to FEA, and the resulting d- and q-axis flux linkages are then fed to the Simulink model to extract the torque waveforms that are compared in Fig. 9. It can be noticed that the torque waveforms coincide at zero currents, while the difference at the other operating point can be neglected. Thus, it can be stated that the implemented FEA-based provides high accuracy for machine variables prediction.

Fig. 5. Flux linkage and torque maps versus dq-current components

Fig. 6. Current maps versus d- and q-axis flux linkages

Fig. 7. % error in i_q prediction due to lookup tables inversion at $i_d = -100$ A and different rotor positions

Fig. 8. Simulink-, FEA-, and measured line-to-line back EMF waveforms 3000 rpm.

Fig. 9. Simulink- and FEA-torque waveforms at: (a) $i_d = 0$ A, $i_q = 0$ A, and (b) $i_d = -300$ A, $i_q = 200$ A

V. SIMULATION RESULTS

In this section, the MATLAB/Simulink environment is used to verify the feasibility of the proposed MP-DTC method by comparing its performance with the conventional scheme. The machine under test is driven by a speed source (as a virtual dynamometer) and operates in torque control mode. A two-level VSI is used to feed that machine, whose switching states are decided by the control algorithm. The stator currents and the rotor position are used as feedback signals for the control algorithm. Park's and Clarke's transformations are utilized to get d- and q-axis stator voltages as inputs of the FEA-based model. The DC supply voltage is maintained at 540 V, and the sampling frequency is decided to be 40 kHz. The weighting factor of the cost function (8) is set to 1 to make the torque and stator flux control equally important.

The performance of the proposed MP-DTC without duty ratio regulation is first compared with that of the conventional method (with constant parameters of $\psi_{pm} = 0.1837$ Wb, $L_d = 0.6$ mH, and $L_q = 1.33$ mH) to show the benefits of employing the FEA-based model for predictions. Fig. 10 compares the torque, stator flux amplitude, and stator phase current when the machine runs at two different speeds of 500 and 3000 rpm with a demanded torque of 0 and 400 Nm, respectively.

As can be noticed in Fig. 10, the proposed MP-DTC reduces the torque ripple considerably for all operating conditions because the FEA-based model can predict the electromagnetic variables of the machine accurately, including the cogging torque and the magnetic saturation impact on the flux linkage. As a result, the harmonics in the stator phase current increases. On the other hand, the conventional method shows

Fig. 10. Simulation results of estimated torque, stator flux amplitude, and stator phase current at different operating points: (a) 500 rpm and no load; (b) 3000 rpm and 400 Nm.

Fig. 11. Simulation results of estimated torque, stator flux amplitude, stator phase current, and duty ratio at different operating points: (a) 500 rpm and no load; (b) 3000 rpm and 400 Nm.

a significant steady-state error in the torque under heavy loading conditions because of the inaccurate current predictions using (6) that neglects the inductance variation with the magnetic saturation.

To verify the effectiveness of optimizing the duty ratio simultaneously with the voltage vector selection, the simulation results of the proposed MP-DTC are compared with those of two other algorithms. 1) MP-DTC without duty ratio regulator. 2) MP-DTC that calculates the duty ratio after the selection of the optimal voltage vector [18]. These two algorithms

TABLE II. QUANTITATIVE EVALUATION OF THE CONTROL METHODS UNDER DIFFERENT SPEEDS AND LOADING CONDITIONS

Index	Speed (rpm)	Torque (Nm)	MP-DTC based Control Methods			
			Conv.	I	II	Proposed
T_{ripple} (Nm)	500	0	7.15	3.09	1.92	0.41
	3000	400	33.58	5.42	3.63	0.88
T_{sse} (Nm)	500	0	6.97	5.11	5.16	4.29
	3000	400	32.36	7.87	13.67	7.21
ψ_{sse} (mWb)	500	0	0.86	0.15	2.44	0.06
	3000	400	166.2	0.32	3.81	0.08
ψ_{ripple} (mWb)	500	0	2.31	2.37	3.30	2.01
	3000	400	169.3	3.19	13.87	4.37
ψ_{ripple} (mWb)	500	0	1.95	2.14	1.91	0.51
	3000	400	4.72	2.51	2.93	0.96
ψ_{ripple} (mWb)	500	0	2.26	2.32	2.34	2.02
	3000	400	4.34	3.05	5.97	5.70

will respectively be designated as MP-DTC I and MP-DTC II for convenience. Fig. 11 compares the torque, stator flux amplitude, stator phase current, and duty ratio when the machine runs at the same operating points mentioned before.

At low speed (i.e., 500 rpm), as shown in Fig. 11(a), the MP-DTC II achieved less torque ripple than MP-DTC I, but it causes a higher steady-state torque error. The proposed MP-DTC exhibits the best steady-state behavior in terms of the torque ripple, steady-state torque error, and flux ripple.

It can be seen in Fig. 11(b) that the proposed MP-DTC achieved the lowest torque ripple at high speed (i.e., 3000 rpm), while it increases the flux ripple because the duty ratio regulation gives higher priority for torque ripple minimization. Also, the MP-DTC II deteriorates the overall steady-state performance because the cost function optimization considers applying the voltage vector for the whole control cycle. Thus, changing the duty ratio after the optimization process cannot ensure that the applied voltage vector is optimal.

Table II gives a quantitative evaluation for the control methods in terms of the steady-state torque error, the torque ripple, and the stator flux ripple. The steady-state torque error is detected by comparing the reference torque with the average value of the developed torque, while the ripple is calculated by

$$y_{ripple} = \sqrt{\frac{1}{m} \sum_{k=1}^m (y(k) - y_{av})^2} \quad (10)$$

where y can be the torque or the stator flux amplitude, $y(k)$ is the instantaneous value, y_{av} is the average value, and m is the number of samples.

According to Table II, the MP-DTC methods that employ the FEA-based model prediction (i.e., I, II, and proposed) improve the steady-state performance remarkably compared with the conventional scheme, especially under heavy loading conditions. Minimum reductions of 58%, 91%, and 29% are achieved for the torque ripple, steady-state torque error, and flux ripple, respectively, at full load. Among these methods, the proposed MP-DTC exhibits the lowest torque ripple, steady-state torque error, and flux ripple by an average of 77%, 67%, and 68%, respectively, at low speed (i.e., 500 rpm). This steady-state performance improvement becomes insignificant compared with MP-DTC I with the speed increase, which implies that the duty ratio regulation is more effective at low speeds. Also, it can be noticed that MP-DTC II degrades steady-state performance. These simulation results prove the necessity of employing an accurate prediction model and optimizing both the voltage vector selection and its duty ratio

simultaneously to improve the torque control performance of PMSM drives, especially at low speeds and heavy loads.

VI. CONCLUSION

Because the model predictive-based direct torque control technique requires high accuracy for the implemented machine model, this paper proposes utilizing the FEA-based modeling approach for predicting the machine variables. The FEA-based model is implemented in Matlab/Simulink and verified by both FEA results and experiments. The proposed MP-DTC achieved effective torque ripple suppression and eliminated the steady-state torque ripple with an average of 58% and 90%, respectively, compared with the conventional method that uses the constant-parameters model. Also, this paper investigated the MP-DTC with the duty ratio regulation. The optimization of the duty ratio is essential to be carried out simultaneously with the voltage vector selection to avoid steady-state performance degradation. Moreover, the duty ratio regulation is more beneficial for torque ripple mitigation at low speeds compared with that at high speeds. The practical implementation of the proposed method will be presented in future work.

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