Model Predictive Torque Control of a Hybrid Excited Axial Field Flux-Switching Permanent Magnet Machine

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This work was supported in part by the National Natural Science Foundation of China under Grant 51707156, in part by the China Postdoctoral Science Foundation under Grant 2018M633645XB, and in part by the Education Department Key Laboratory Project in Shaanxi Province of China under 19JS052.

ABSTRACT Hybrid excited axial field flux-switching permanent magnet (HEAFFSPM) machine is a novel stator excitation hybrid excited synchronous machine, which combines the advantages of the axial field flux-switching permanent machine and wound field machine. In this paper, two model predictive torque control (MPTC) methods with flux-adjusting strategy implementation for the HEAFFSPM machine, including the MPTC and MPTC with duty cycle control (MPTC-DCC) by optimizing the active voltage vector duration to reduce the torque and flux ripples, are proposed and comparatively investigated. Based on the theoretical analysis, a discrete-time model of the HEAFFSPM machine is established. Considering the flux-enhancing/-weakening strategies, the different multi-objective cost functions are designed. The multiple right weight coefficients are analyzed and chosen to optimize the operating performance of the drive system. The results indicate that the proposed MPTC-DCC method reduces the torque and flux ripples significantly compared with MPTC method, and the drive system has better steady performance. Meanwhile, the load capability in the whole speed region is improved and the constant power operating range is broadened by using the proposed flux-adjusting strategy.

INDEX TERMS Axial field, flux-switching, flux-adjusting, model predictive torque control, duty cycle control.

I. INTRODUCTION

Recently, stator permanent magnet (PM) axial field flux-switching PM (AFFSPM) machines have received wide attention. These machine combine the feature of the axial flux PM machine [1]–[5] and flux-switching machine [6]–[10], which exhibit a lot of advantages including short axial length, compact and robust structure, as well as high power/torque density, and so on [11]–[15]. However, the flux-regulation capability is not excellent enough, which limits its driving applications with wide speed-regulation requirement. As a result, in order to improve the flux-regulation performance of the AFFSPM machine, some hybrid excitation [16]–[20] topologies, demonstrated additional excellent merits such as low-speed large-torque capability, wide speed operating range, and strong overload capacity, were proposed in [21]–[23]. The hybrid excited AFFSPM (HEAFFSPM) machine is a novel stator excitation hybrid excited synchronous machine (HESM), which combines the characteristics of the AFFSPM machine and the wound field machine, and is an excellent candidate for variable-speed applications such as electric vehicles (EVs).

By regulating the amplitude and polarity of the excitation current in the field windings, hybrid excitation operating modes including PM, flux-enhancing, and flux-weakening can be implemented. Some control strategies based on the vector control (VC) method for the HESM have been reported in the scientific and technical literature. In [24], a torque and flux-weakening control method with open-loop speed for a hybrid excited FSPM motor was investigated. The load...
capability in the constant power region was improved and the range of speed regulation was broadened. However, the anti-load-disturbance performance of the control system was not outstanding and the speed smooth transition was not attained.

A closed-loop flux-weakening control strategy for a HESM according to independent regulation of the voltage amplitude and phase angle between the armature voltage and current was proposed in [25]. The optimal combination of \(d\)-axis and field current was found to improve the stability of the system and broaden the constant power operating region. In [26], a novel control strategy, based on the principle of the voltage error regulation method while the field current is controlled towards zero in the flux-weakening mode, for a hybrid excited FSPM machine was proposed. The torque response was improved and the speed range was extended independent on the precise parameters of the machine, but the field current was not utilized effectively in the constant power region.

In [27], a partitioned optimal current control method including the recursive algorithm for a HESM with no pole saliency was proposed. The minimal winding copper losses operation was performed to enhance the load capability in the entire speed region and broaden the wide speed operating range, but it was not suitable for the large saliency ratio HESM.

In [28], a novel minimum-copper-loss control strategy for a HEAFFSPM machine, which can operate in both flux-enhancing and flux-weakening conditions, was proposed. The reluctance torque was utilized completely while the operating efficiency was improved immensely. In recent years, a kind of model predictive torque control (MPTC) method is attracting a lot of attention in the academic and industry communities because it can observably improve the torque dynamic performance [29]–[31]. Zhang et al. presented a model predictive torque control method with optimal duty cycle control for induction motor [32], and the better steady-state performance under the whole speed region is achieved.

In this paper, based on a HEAFFSPM machine illustrated in Fig.1, two MPTC methods including the MPTC and MPTC with duty cycle control (MPTC-DCC) by inserting a null vector along with the selected active voltage vector to achieve torque and flux ripples reductions are proposed. In section II, the topology is analyzed and the mathematic model is deduced. In section III, the proposed MPTC methods with flux-regulation strategy including flux-enhancing/ -weakening in the entire region are investigated comparatively. The drive system is established based on the MPTC and the implementation procedure is analyzed. The operating performance of the machine under the proposed MPTC-DCC is investigated and evaluated in comparison with adopting the MPTC method by simulations and experiments in section IV and V, respectively.

II. TOPOLOGY AND MATHEMATIC MODEL

A. TOPOLOGY

The topology of 3-phase 12/10-poles HEAFFSPM machine, composed of two same stators and one rotor, is shown in Fig. 1. The stator contains 6 ‘E’-shaped laminated segments, 6 PMs with interlaced magnetizing, concentrated armature and excitation windings. The PMs are embedded in the ‘E’-shaped laminated segments, and the excitation windings are coiled in the middle teeth which can provide magnetic circuit isolation between phase and phase. The polarity of the opposite PMs in the two stators is reversed. There are neither PMs nor windings in the rotor, which improves the robustness while makes heat-dissipation easier. The parallel hybrid excitation can flexibly regulate the air-gap field and avoid the risk of irreversible demagnetization.

B. OPERATING PRINCIPLE

Based on the 2-D magnetic field distribution shown in Fig. 2, the operating principles are analyzed as follows. The PM and excitation flux routes are described by the black and green line, respectively. Firstly, when the load is lower than the rated electromagnetic torque, the machine operates under the PM mode. There is only PM excitation source, and the 2-D magnetic field distribution is shown in Fig. 2(a). Furthermore, when the load is larger than the rated torque or starting, the positive DC excitation current is injected to produce large torque. At the moment, the direction of PM and excitation fluxes is consistent to increase flux, and the machine operates under flux-enhancing mode, as depicted in Fig. 2(b). Finally, when the operating speed is higher than the based speed, the machine operates under flux-weakening mode. The negative DC excitation current is applied to broaden the constant power operating region. As demonstrated in Fig. 2(c), the PM and excitation fluxes are in the opposite direction. Due to the flux-switching feature, the pole number is equal to the number of pole pairs.
The dynamic model of the HEAFFSPM machine in the α-β reference frame can be obtained as
\[
\begin{align*}
\frac{di_α}{dt} &= \frac{1}{L_α}(u_α - R_αi_α + ω_εψ_{exc} \sin θ) \\
\frac{di_β}{dt} &= \frac{1}{L_β}(u_β - R_βi_β - ω_εψ_{exc} \cos θ) \\
\frac{dψ_α}{dt} &= u_α - R_αi_α \\
\frac{dψ_β}{dt} &= u_β - R_βi_β
\end{align*}
\] (1)

The electromagnetic torque can be derived as
\[
T_e = \frac{3}{2}β(ψ_α i_β - ψ_β i_α)
\] (2)

The reference flux is generated by the self-adaptation method in the following sections.

The electromagnetic torque can be obtained from (3).

III. MODEL PREDICTIVE TORQUE CONTROL
In this paper, two MPTC methods with flux-regulation strategy implementation, to enhance the load capability and extend the range of constant power operating region, are proposed for a HEAFFSPM machine. Meanwhile, through optimizing vector selection, the duty cycle control is achieved to reduce the torque and flux ripples. As depicted in Fig.3, the drive system based on the proposed control method is established. It can be seen that the real torque and flux is obtained using a torque-flux observer. Moreover, the reference torque is produced by an external speed control loop. The reference flux is generated by the self-adaptation method on account of the flux-regulation strategy including the flux-enhancing in constant torque region and the flux-weakening in constant power region. The drive signal for the excitation power convertor is produced on the basis of the current hysteresis band PWM (CHBPWM). The detailed implementation process of the proposed MPTC method will be analyzed in the following sections.

C. MATHEMATICAL MODEL
The dynamic model of the HEAFFSPM machine in the α-β reference frame can be obtained as

\[
\begin{align*}
i_α(k + 1) &= \frac{T_s}{L_α}[u_α(k) - R_αi_α(k) + ω_εψ_{exc} \sin θ] + i_α(k) \\
i_β(k + 1) &= \frac{T_s}{L_β}[u_β(k) - R_βi_β(k) - ω_εψ_{exc} \cos θ] + i_β(k)
\end{align*}
\] (3)

\[
\begin{align*}
ψ_α(k + 1) &= T_s[u_α(k) - R_αi_α(k)] + ψ_α(k) \\
ψ_β(k + 1) &= T_s[u_β(k) - R_βi_β(k)] + ψ_β(k)
\end{align*}
\] (4)

The electromagnetic torque can be predicted as
\[
T_e(k + 1) = \frac{3}{2}β[ψ_α(k + 1)i_β(k + 1) - ψ_β(k + 1)i_α(k + 1)]
\] (5)

where \(T_s\) is the sampling period. \(i_α(k + 1), i_β(k + 1)\) are the \(α\)- and \(β\)-axis current predicted value at the \(k + 1\) instant. \(ψ_α(k + 1), ψ_β(k + 1)\) are the \(α\)- and \(β\)-axis flux predicted value at the \(k + 1\) instant. \(T_e(k + 1)\) is the torque predicted value at the \(k + 1\) instant.

A. TORQUE AND FLUX ESTIMATION
A stator flux observer for the machine is designed based on the current model avoiding the integral element to improve the estimated performance, which is indicated as

\[
\begin{align*}
ψ_α &= L_αi_α + (ψ_{pm} + M_f i_γ) \cos θ \\
ψ_β &= L_βi_β + (ψ_{pm} + M_f i_γ) \sin θ
\end{align*}
\] (6)

The amplitude of the stator flux can be written as
\[
ψ_s = \sqrt{ψ_α^2 + ψ_β^2}
\] (7)

The electromagnetic torque can be obtained from (3).
B. REFERENCE CURRENT AND FLUX CALCULATION

In this paper, the reference stator flux is adaptively given through using the flux-regulation strategies including the flux-enhancing and flux-weakening.

According to the hybrid excited principle and characteristic of the HEAFFSPM machine, the flux-enhancing strategy on account of load condition is applied in the low speed region and the flux-weakening strategy based on the speed operating range is adopted in the high speed region, as shown in Fig.4.

The electromagnetic torque equation of the HEAFFSPM machine in the $d$-$q$ reference frame can be described as

$$ T_e = \frac{3}{2} p i_q \left[ \psi_{pm} + (L_d - L_q) i_d + M_f i_f \right] \tag{9} $$

There are two operating conditions based on the load in the low speed region. Firstly, under light load, the $d$-axis current $i_d$ and the excitation current $i_f$ are controlled to achieve zero. According to eq. (9), the reference current under light load condition can be obtained as

$$ \begin{cases} i_{dref} = 0 \\ i_{qref} = \frac{2 T_e}{3 p \psi_{pm}} \quad (T_L \leq \frac{3}{2} p \psi_{pm} i_q N) \\ i_{fref} = 0 \end{cases} \tag{10} $$

Secondly, under heavy load, the $i_d$ is remained to zero and the $i_f$ is used for flux-enhancing to improve the load capability. Similarly, by eq. (9), the reference current under heavy load condition can be gotten as

$$ \begin{cases} i_{dref} = 0 \\ i_{qref} = \frac{2 T_e - 3 p \psi_{pm} i_q N}{3 p M_f i_q N} \quad (T_L > \frac{3}{2} p \psi_{pm} i_q N) \\ i_{fref} = i_{qref} \end{cases} \tag{11} $$

When the HEAFFSPM machine operates in the high speed region, considering the steady state operation and neglecting the resistance terms, the voltage constrain is given as

$$ (-\omega_e L_q i_q)^2 + \left\{ \omega_e [\psi_{pm} + M_f i_f] + L_d i_d \right\}^2 \leq (U_{dc}/\sqrt{3})^2 \tag{12} $$

where $i_{dref}$, $i_{qref}$, $i_{fref}$ are the $d$, $q$-axis and excitation reference currents, respectively. $T_L$ is the load torque and $i_{qN}$ is the $q$-axis rated current.
In the high speed region, the excitation current $i_f$ is used for flux weakening firstly. According to eq. (9) and (12), the reference current can be obtained as

$$
\begin{align*}
    \text{i}_{d.ref} &= 0 \\
    \text{i}_{f.ref} &= \frac{\sqrt{\left(\frac{U_{dc}}{\sqrt{3}\omega_e}\right)^2 - (L_qi_{q.ref})^2 - \psi_{pm}}}{M_f} \\
    \text{i}_{q.ref} &= \frac{2T_e}{3p(\psi_{pm} + M_fi_{f.ref})}
\end{align*}
$$

When the excitation current achieves the rated value, to extend sequentially the speed operating range, the $d$-axis current is applied to further weaken flux. Based on eq. (9) and (12), the reference current can be expressed as

$$
\begin{align*}
    \text{i}_{f.ref} &= -i_{fN} \\
    \text{i}_{d.ref} &= \left[\sqrt{\left(\frac{U_{dc}}{\sqrt{3}\omega_e}\right)^2 - (L_qi_{q.ref})^2 - \psi_{pm}} - M_fi_{fN}\right] \\
    \text{i}_{q.ref} &= \frac{2T_e}{3p(\psi_{pm} + (L_d - L_q)i_{d.ref} - M_fi_{fN})}
\end{align*}
$$

where $i_{fN}$ is the rated excitation current.

In the $d$-$q$ reference frame, the stator flux equation of the HEAFFSPM machine can be described as

$$
\begin{align*}
    \psi_d &= \psi_{pm} + L_di_d + M_fi_f \\
    \psi_q &= L_qi_q
\end{align*}
$$

**FIGURE 6.** Simulation results based on the MPTC. (a) Speed. (b) Torque (0–5 s). (c) Torque (1.5–1.6 s). (d) Stator flux (0–5 s). (e) Stator flux (1.5–1.6 s). (f) Armature current $i_a$ (0–5 s). (g) Armature current $i_a$ (1.5–1.6 s). (h) Excitation current.
The reference stator flux can be expressed as

$$\psi_{sref} = \sqrt{\psi_{dref}^2 + \psi_{qref}^2}$$

$$= \sqrt{(\psi_{pm} + L_d i_{dref} + M_f i_{fref})^2 + (L_q i_{qref})^2}$$ (16)

Substituting (10), (11), or (13), (14) into (16), the reference stator flux in the whole speed operating region can be obtained.

C. VECTOR SELECTION AND DUTY RATION CALCULATION

1) MPTC

MPTC: Based on the discrete-time model including (4), (5) and (6), eight basic voltage vectors available ($u_0, u_1, \ldots, u_7$) will be employed to predict the stator flux $\psi_s(k + 1)$ and torque $T_e(k + 1)$ at the $k + 1$ sampling instant. A cost function, expressed as the linear combination of the torque error and flux error, will be evaluated for each voltage vector. The one minimizing the cost function will be selected as the optimal voltage vector, which is concluded as

$$J = \left| T_{eref} - T_e(k + 1) \right| + \lambda \left| \psi_{sref} - |\psi_s(k + 1)| \right|$$ (17)

where $\lambda$ denotes the weighting factor for the stator flux.

2) MPTC-DCC

The implementation flow chart of the proposed MPTC with duty cycle control is shown in Fig. 5. The active voltage vector is firstly selected from the MPTC as in 1). The duty ratio of
the active voltage vector is gotten based on the principle of the deadbeat torque control.

Setting the derivative of (3) with respect to the time $t$ and combining (1), (2), the following equation can be obtained as

$$\frac{dT_e}{dt} = \frac{3}{2}\frac{\sigma}{p}(\frac{d\psi_\alpha}{dt}i_\beta + \frac{d\psi_\beta}{dt}i_\alpha - \frac{d\psi_\beta}{dt}i_\alpha - \frac{d\psi_\alpha}{dt}i_\beta)$$

$$= s_0 + s_i$$

(18)

where $s_0$, $s_i$ are the torque slopes of the zero voltage vector ($u_0$, $u_7$) and the active voltage vector $u_i$ ($i = 1, 2, ..., 6$), respectively.

According to the principle of the deadbeat torque control, the predictive torque at the $k+1$ instant should reach the reference value $T_{eref}$ when the selected voltage vector $u_i$ is applied for a fraction of control period.

$$T_e(k+1) = T_{eref} = T_e(k) + s_{op}T_s + s_{op}(T_s - \gamma T_s)$$

(19)

IV. SIMULATION

The simulation analysis is carried out to verify the proposed control method and the operating performance of the HEAFFSPM machine. The parameters of the prototype under investigation are listed in Table 1.

A speed command of $n = 600$ r/min with 2 N·m load is given. The load is increased to 7 N·m at 1 s and decreased
to 2 N·m at 2 s, respectively. The given speed is increased to 1500 r/min at 3s. Fig.6 presents the results based on the MPTC.

As seen in Fig.6, the dynamic response of the HEAFFSPM machine in the whole speed operating region is exhibited. At start, the armature current is quickly increased while the excitation current achieves the rated value 3 A to produce a large torque for expediting the starting process. This moment, the stator flux increases to 0.13 Wb. After steady operation, due to the load of 2 N·m, the flux-enhancing strategy is not activated and the excitation current $i_f$ is zero. The stator flux is about 0.1 Wb. The load command is increased to 7 N·m at 1 s, and is larger than the rated torque. The armature current reaches the rated value and the flux-enhancing strategy using the excitation current is activated. After steady operation, the $i_f$ is about 2.1 A and the stator flux is 0.12 Wb. At 2 s, the load command decreases to 2 N·m. The armature current can satisfy the load requirement. Hence, the flux-enhancing strategy is not utilized. The $i_f$ and stator flux are zero and 0.1 Wb, respectively. As a result, the MPTC with flux-enhancing strategy is implemented. The load capability and anti-load-disturbance performance in the low speed region are improved. At 3 s, the given speed command is increased to 1500 r/min. The HEAFFSPM machine operates in the high speed region after 750 r/min at 3.05s. The flux-weakening strategy is activated, and the $i_d$ and $i_f$ are harmoniously controlled to broaden the constant power operating range. The stator flux is decreased continuously, and is achieved 0.041 Wb when the machine operates at 1500 r/min steadily. The response time is about 0.95 s. At the moment, the $i_f$ reaches $-3$ A. Therefore, the flux-weakening strategy utilized the negative excitation current is verified and the wide constant power operating range is achieved. According to the above analysis, the proposed MPTC with flux-adjusting strategy implementation including the flux-enhancing/-weakening in the whole speed operating range is validated.

Under the same operating condition, the simulation results based on the MPTC-DCC are shown in Fig.7. Like the results based on the MPTC shown in Fig.6, under the MPTC-DCC, the hybrid excitation operation can be also implemented. The excitation current $i_f$ is utilized for flux-enhancing at start and heavy load condition in the low speed region, and for flux-weakening in the high speed region. At 3.92 s, the speed achieves 1500 r/min. The response time is 0.92 s. As seen from Fig. 6(a), (b) and Fig. 7(a), (b), there is a little difference in dynamic response under the MPTC and MPTC-DCC. They show strong anti-load-disturbance capability and fast dynamic performance. With the changed armature and excitation current, the stator flux trends increase or decrease. Meanwhile, as the stepped load, the electromagnetic torque is increased or decreased. Comparing Fig. 6(b), (c) and 7(b), (c), it is seen that the torque ripple is decreased under the MPTC-DCC. The drive system shows better steady-state performance. As seen in Fig. 6(d), (e) and 7(d), (e), the stator flux ripple is reduced sharply under the MPTC-DCC method. Similarly, the harmonic components of the armature and excitation current are smaller under the MPTC-DCC by the comparison of Fig. 6(f), (g), (i) and Fig. 7(f), (g), (i). The flux-adjusting strategy including flux-enhancing/-weakening is achieved. Under the MPTC-DCC, the drive system demonstrates better dynamic and steady-state performance and stronger anti-load-disturbance capability. The low-speed large-torque characteristics and wide constant power operating range of the machine are verified.

The armature current THD at 1~2 s and the torque ripple at different speed and load based on the MPTC and MPTC-DCC are analyzed, as shown in Fig. 8.

It is seen that the armature current THD is much smaller and the torque ripple is much lower under the MPTC-DCC method. The simulation results are consistent.
with the theoretical analysis. The validity of the proposed control methods including the MPTC and MPTC-DCC is verified.

V. EXPERIMENTAL VERIFICATION

This section presents the experimental results related to the validity of the proposed control method and the operating performance of the machine. The experimental platform for a 3-phase 12/10-pole HEAFFSPM machine is established, as shown in Fig. 9. The two-level inverter is used for the PM and excitation power converter, and the switching frequency is 10 kHz. The sampling frequencies on the basis of the MPTC and MPTC-DCC are 20 kHz and 10 kHz, respectively. The DC motor used for the load motor is connected with a HEAFFSPM machine controlled based on MicroLabBox by a torque sensor. The load measured by the torque sensor is transferred to the controller and is used for the flux-regulation strategies. The parameters of the investigated prototype machine have been given in Table 1.

With a speed command of 500 r/min, the no-load is given at first. The load increases and decreases 5 N-m at 7 s and 16 s respectively and the speed increases to 1500 r/min at 20 s. The experimental results under the MPTC are shown in Fig. 10.

The flux-enhancing current $i_f$ of 3 A is used to provide a large toque for starting. After steady operation, the $i_f$ return to zero because of the no-load operation and the stator flux is 0.1 Wb. At 7 s, the load increases 5 N-m and the flux-enhancing strategy is activated again to satisfy load requirement. The $i_f$ reaches 1.8 A and the flux is about 0.14 Wb at the steady-state. At 16 s, the load decreases 5 N-m, the $i_f$ and flux are zero and 0.1 Wb, respectively. Hence, the flux-enhancing operation is achieved and the load capability in the low speed region is improved. There is a ripple in the speed at suddenly increasing and decreasing load. But it rapidly recovers to the given value after the closed-loop regulation. The drive system based on the MPTC exhibits strong anti-load-disturbance capability. The speed command increases to 1500 r/min at 20 s and the machine operates in the high speed region above the 750 r/min. To broaden the range of speed-regulation, the $i_f$ and $i_d$ are together used for flux-weakening. At steady-state, the $i_d$ achieves 3 A and the flux decreases to 0.04 Wb. Thus, the flux-weakening operation is achieved. The experimental results are consistent with the simulation analysis and the validity of the proposed MPTC is validated.

The experimental results based on the MPTC-DCC with the same condition are shown in Fig. 11. The torque and flux ripples at different speed and load based on the MPTC and MPTC-DCC are analyzed, as shown in Fig. 12.

Under the MPTC-DCC, the hybrid excitation operation on account of the excitation current including the flux-enhancing strategy, the different multi-objective cost functions are designed. The multiple right weight coefficients are analyzed and chosen to optimize the operating performance of the drive system. The results show that all the two methods present strong anti-load-disturbance capability and fast dynamic performance. Compared with the MPTC method, the torque and flux ripples are significantly reduced under the MPTC-DCC, and the drive system exhibits better steady-state performance. The low-speed large-torque capability and wide constant power operating range of the machine are achieved, and the proposed MPTC-DCC is verified.

VI. CONCLUSION

In this paper, two MPTC methods with flux-adjusting implementation including the MPTC and MPTC–DCC by optimizing the active voltage vector duration to reduce the torque and flux ripples for the HEAFFSPM machine are proposed and comparatively investigated. Based on the theoretical analysis, a discrete-time model of the HEAFFSPM machine is established. Considering the flux-enhancing/-weakening strategy, the different multi-objective cost functions are designed. The multiple right weight coefficients are analyzed and chosen to optimize the operating performance of the drive system. The results show that all the two methods present strong anti-load-disturbance capability and fast dynamic performance. Compared with the MPTC method, the torque and flux ripples are significantly reduced under the MPTC-DCC, and the drive system exhibits better steady-state performance. Meanwhile, the load capability in the whole speed region is improved and the constant power operating range is broadened by using the proposed flux-adjusting strategy.

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