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Novel Analytical Weighting Factor Tuning Strategy based on State Normalization and Variable Sensitivity Balance for PMSM FCS-MPTC

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***Abstract*— This paper innovatively proposes a numerical weighting factor handling strategy for the PMSM finite control set (FCS) model predictive torque control (MPTC) method based on state normalization and variable sensitivity balance. Firstly, both the static and dynamic reasons why the weighting factors in relation to the flux and torque are essential for an FCS-MPTC controller are analyzed at length. Then, in order to eliminate the differences between the two targeting variables' static properties, a state normalization (SN) scheme is applied to the control system. Finally, aiming at the imparities of the dynamic characteristics between the flux and torque, the weighting factors are tuned based on balancing the variable sensitivity to voltage variations (VSTVV). The simulation and experimental results prove that the proposed weighting factor tuning technique is effective.**

***Index Terms*— Permanent magnet synchronous machine, model predictive torque control, weighting factor, variable sensitivity balance.**

I. INTRODUCTION

PERMANENT magnet synchronous machines (PMSM) are attracting increasing attention due to their advantages of high efficiency, high power and torque density and compact structure [1]-[3]. Meanwhile, in order to improve the control performance of the PMSMs, many high-performance control techniques have been developed, e.g., field-oriented control (FOC) and direct torque control (DTC) [4], [5]. In comparison with the FOC that takes the *d*, *q*-axis currents as the control targets in the inner loop, DTC that is characterized by controlling the flux and electromagnetic torque has shown dramatical dynamics and strong robustness in the real-world applications [6]. Usually, the traditional DTC methods need to employ two independent hysteresis controllers to determine the switch-control signals [7]. Whereas, the hysteresis-based controllers have the inherent disadvantages of variable switching frequency and high sampling requirement, resulting in high torque and flux ripples [8]-[10]. Currently, as the promising alternative control strategy with relatively lower harmonics, finite control set model predictive torque control (FCS-MPTC) has gained considerable amount of attention [11]-[14], [16]. Instead of hysteresis comparators, an FCS-MPTC-based controller adopts only one single model predictive controller (MPC) that incorporates a machine plant-based estimator and a cost function to regulate the flux and torque and generate control signals. Now, the most commonly used FCS-MPTC was proposed in [11], which is based on the maximum torque per ampere (MTPA) operation. In [12], the basic FCS-MPTC algorithm is improved with the deadbeat (DB) control theory. By means of this method, the optimal switching states can be selected without evaluating all the candidate voltage vectors so as to greatly reduce the calculation load. In order to further reduce the flux and torque ripples, [13] uses virtual vectors to extend the control set of a three-phase two-level inverter-fed PMSM drive. Literature [14] improves the machine control performance by compensating the cogging torque and introducing an extra term concerning the *d*-axis current errors into the cost function. Although the aforementioned FCS-MPTC algorithms have been successfully used in the PMSM drives, there still exits a challenge. The combination of flux and torque in a single cost function is not a straightforward task, and the weighting factors in relation to each control target should be employed to settle the differences and tune the importance between the two variables. Unfortunately, there are few analytical or numerical methods to design the parameters, and in [11]-[14], they are determined following the empirical approaches, which places great demand on the designers.

Many up-to-date researches have specially addressed the weighting factor issue of FCS-MPTC. [15] innovatively establishes the basic guidelines to reduce the uncertainty and improve the effectiveness of the tuning stage, but this method requires tedious test work, and the designed results are not universally suitable for the other systems with different parameters, such as inductance and resistance, and so forth.

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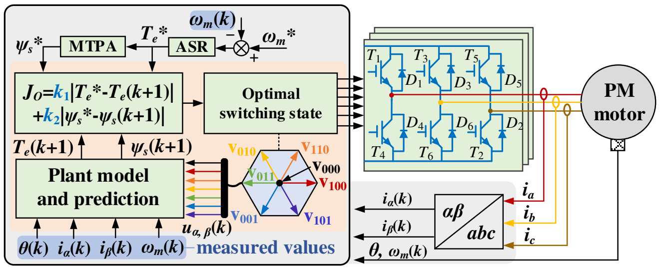

$i_{\alpha,\beta}$: α,β-axis currents, T_e: torque, **v**: candidate voltages, $u_{\alpha,\beta}$: α,β-axis control voltages, ω_m: speed , θ: position, i_a, i_b, i_c: phase currents, ψ_s: air-gap flux

Fig. 1. Structure of an FCS-MPTC drive system.

Similarly, the weighting factors are obtained by carrying out numerous experiments on a specific test bench in [16]. Although fuzzy-decision-making strategy is promising to solve the problem, it is hard to design the effective membership functions [17]. In terms of [18] and [19], the weighting factors are completely removed by rebuilding the cost function. However, they contribute few to directly tuning the weighting factors analytically. This paper will explain the deeper reasons why weighting factors must be adopted in the cost function of FCS-MPTC. In the process, a brand-new concept "variable sensitivity to voltage variation (VSTVV)" is proposed, and a direct weighting factor handling strategy that can be used in different PMSM systems is discussed. Both simulation and experiment are conducted on a three-phase surface-mounted PMSM to verify the effectiveness of the proposed methods.

II. NECESSITY OF WEIGHTING FACTORS

As is shown in Fig.1, the implementation procedures of a typical FCS-MPTC algorithm can be summarized as follows: firstly, an automatic speed regulator (ASR) is used to control the speed and generate the reference torque T_e^*. Then, the targeting air-gap flux ψ_s^* can be calculated according to the MTPA control theory in [11]. As for the MPTC controller, the measured currents, position, speed and the seven manipulated voltages are substituted into the plant model to predict the next step's torque $T_e(k+1)$ and flux $\psi_s(k+1)$. For the purpose of tracking both torque and flux, the errors between $T_e(k+1)$ and T_e^* together with the errors between ψ_s^* and $\psi_s(k+1)$ are evaluated by a cost function so as to select the best control voltage vector to be applied. In the process, the cost function serves as one of the most crucial components for optimization, and it can be expressed as:

$$J_O = k_1 \left| T_e^* - T_e(k+1) \right| + k_2 \left| \psi_s^* - \psi_s(k+1) \right| \tag{1}$$

where k_1 and k_2 are the weighting factors.

There are two reasons why the weighting factors k_1 and k_2 are essential for the multi-objective FCS-MPTC controller. 1) *Static reason*: the nature (units and amplitude range) of the torque and air-gap flux is diverse. Firstly, the unit of torque is Nm while it is Wb for flux, indicating that the two parameters are intrinsically different. Secondly, for the sake of cost and volume reduction, the magnitude of the flux of a PMSM is usually designed to be dozens of times smaller than that of the torque. For instance, in [20], the rated torque and flux are 5.5 Nm and 0.0734 Wb, respectively. Hence, the static properties of the torque and flux contribute to the employment of weighting factors. 2) *Dynamic reason*: the magnitude of the torque and flux variations corresponding to the same voltage alteration during a short period is different. In other words, the sensitivity of the torque and flux (response variables) to the voltage (manipulated variables) variations is different, and the phenomenon is called VSTVV in this paper. Intuitively, the variable with higher VSTVV will dominate the evaluation process if no weighting factors are used, leading to that the variable with lower VSTVV plays an unimportant role in selecting the best switching state. Obviously, this is unreasonable, but few researches have focused on the dynamic characteristics of the torque and flux.

III. PROPOSED WEIGHTING FACTOR HANDLING TECHNIQUE

Aiming at the static differences between the flux and torque, a state normalization (SN) method is developed at first. Then, the VSTVV of the two variables is analysed numerically on account of the PMSM model. Finally, the weighting factors can be tuned after balancing the discrepancies of their VSTVV.

A. Implementation of SN

SN is a methodology that expresses the state variables (current, speed and voltage) as the fractions of the base quantities. After implementing SN, the representations of all variables become uniform in the form of per unit values (unit is pu and magnitude ranges from -1 to 1). In this paper, the base quantities of the state variables are designed as follows. Firstly, the base voltage U_0 is selected as the maximum line-to-line voltage (dc-lind voltage U_{dc}):

$$U_0 = U_{dc} \tag{2}$$

Then, the base current I_0 is:

$$I_0 = \frac{2P_{rated}}{\sqrt{3}U_{dc}} \tag{3}$$

where P_{rated} is the rated power of the PMSM. The base speed ω_{m0} equals the value of angular velocity, at which the machine can generate 1 pu voltage between its terminals. According to the relationship between the back electromotive force (EMF) and the speed, the base speed is approximated as:

$$\omega_{m0} = \frac{U_{dc}}{\sqrt{3}C'_e\psi_f} \tag{4}$$

where C'_e is the voltage constant, ψ_f is the permanent magnet flux. The SN implementation is as follows:

$$i_{\alpha n} = \frac{i_\alpha}{I_0}, i_{\beta n} = \frac{i_\beta}{I_0}, u_{\alpha n} = \frac{u_\alpha}{U_0}, u_{\beta n} = \frac{u_\beta}{U_0}, \omega_{mn} = \frac{\omega_m}{\omega_{m0}} \tag{5}$$

where $i_{\alpha n}$, $i_{\beta n}$, $u_{\alpha n}$, $u_{\beta n}$ and ω_{mn} are the normalized α, β-axis currents, control voltages and speed, respectively. i_α, i_β and ω_m are the measured values. u_α, u_β are the real control voltages.

Once the normalized variables are used for control in the FCS-MPTC, the observed and estimated torque and flux will be in the normalized form. Now, the imparity in the magnitude and units of them can be removed. Whereas, the VSTVV of the targeting objectives has not been considered, which is illustrated in the next part.

B. VSTVV Balance

a) Analysis on VSTVV of flux and torque

It deserves to be mentioned that the VSTVV analysis of the torque and flux is independent of the form of variables due to the definition of VSTVV, so for the sake of simplicity, the PMSM model described as the normal form in the rotating frame is used for VSTVV analysis. Without considering the mutual inductance effects, the expressions of flux, q-axis current and torque for a surface-mounted machine are:

$$\frac{\mathrm{d}\boldsymbol{\psi}_{\mathbf{s}}}{\mathrm{d}t} = -\mathbf{i}_{\mathbf{s}} R_s + \mathbf{u}_{\mathbf{s}} \tag{6}$$

$$\frac{\mathrm{d}i_{sq}}{\mathrm{d}t} = \frac{1}{L_s}(u_{sq} - i_{sq}R_s - p\omega_m\psi_f) \tag{7}$$

$$T_e = \frac{3}{2}p\psi_f i_{sq} \tag{8}$$

where $\boldsymbol{\psi}_{\mathbf{s}}$, $\mathbf{i}_{\mathbf{s}}$ and $\mathbf{u}_{\mathbf{s}}$ are the d, q-axis flux [ψ_{sd}, ψ_{sq}]$^{\mathrm{T}}$, current [i_{sd}, i_{sq}]$^{\mathrm{T}}$ and control voltage [u_{sd}, u_{sq}]$^{\mathrm{T}}$, respectively. L_s and R_s are the stator winding inductance and resistance, respectively. p represents the number of pole pairs. When the forward Euler discretization is applied to (6) and (7) in a time step of T (sampling period), the discrete model is derived as:

$$\boldsymbol{\psi}_{\mathbf{s}}(k+1) = (\mathbf{u}_{\mathbf{s}}(k) - \mathbf{i}_{\mathbf{s}}(k)R_s)\cdot T + \boldsymbol{\psi}_{\mathbf{s}}(k) \tag{9}$$

$$i_{sq}(k+1) = \frac{T}{L_s}u_{sq}(k) - \frac{Tp\psi_f}{L_s}\omega_m(k) + (1 - \frac{TR_s}{L_s})i_{sq}(k) \tag{10}$$

And the torque can be observed by:

$$T_e(k+1) = \frac{3}{2}p\psi_f i_{sq}(k+1) \tag{11}$$

Before leaving (9)-(11), it should be noted that the common factor that influences both flux and torque is the q-axis control voltage. Therefore, the main purpose of VSTVV balance in this paper is to analyze the impact of the variation of u_{sq} on T_e and ψ_s. Assume that the voltage applied at the present moment is $\mathbf{u}_s(k)$ together with a disturbance of $\triangle\mathbf{u}_s(k)$ ([$\triangle u_{sd}(k)$, $\triangle u_{sq}(k)$]$^{\mathrm{T}}$) occurs, where $\triangle u_{sd}$=0 since only the q-axis voltage is considered. According to (9) and (10), the flux and current variations caused by the disturbance voltage within T are:

$$\Delta\boldsymbol{\psi}_{\mathbf{s}}(k+1) = \Delta\mathbf{u}_{\mathbf{s}}(k)\cdot T \tag{12}$$

$$|\Delta i_{sq}(k+1)| = \frac{T}{L_s}|\Delta u_{sq}(k)| \tag{13}$$

Equation (11) illustrates that the torque is a consequence of the q-axis current, so the torque variation can be described as:

$$\Delta T_e(k+1) = \frac{3}{2}p\psi_f\frac{T}{L_s}|\Delta u_{sq}(k)| \tag{14}$$

And the amplitude of $\triangle\boldsymbol{\psi}_{\mathbf{s}}(k+1)$ is as follows:

$$\Delta\boldsymbol{\psi}_{\mathbf{s}}(k+1) = |\Delta u_{sq}(k)|\cdot T \tag{15}$$

It can be noted that the VSTVV of torque and flux is different and they are closely related to T. However, the quotient ς of $\triangle T_e(k+1)$ and $|\triangle\boldsymbol{\psi}_{\mathbf{s}}(k+1)|$ is only related to the machine parameters, that is:

$$\varsigma = \frac{\Delta T_e(k+1)}{\Delta\boldsymbol{\psi}_{\mathbf{sr}}(k+1)} = \frac{3p\psi_f}{2L_s} \tag{16}$$

b) Weight factor tuning

In order to balance the sensitivity differences between the two variables, the weighting factors can be set as:

$$k_1 = 1,\ k_2 = \varsigma \tag{17}$$

Then, the magnitude of the torque and flux variations caused by the same voltage change within one switching period will stand at the same level.

IV. VERIFICATIONS

Simulation and experiment are carried out to verify the proposed weighting factor handling strategy on a three-phase surface-mounted PMSM whose parameters are: bus voltage U_{dc} =60 V, rated speed ω_{rated}=700 rpm and rated load torque T_{rated} = 5 Nm, phase resistance R_s = 0.6383 Ω, flux linkage ψ_f=0.085 Wb, inductance L_s=2 mH, the number of pole pairs p=4, viscous coefficient B=0.0035, rotor inertia J=0.013 kg·m^2 and T_s =0.1 ms. The FCS-MPTC algorithm is implemented on a DSP TMS320X28335 control board. The simulation and experimental setup are as follows: the machine speeds up from standstill to 200 rpm (low speed) between 0 and 5 s, after which it stabilizes in the next 5 s. At 5 s, the rated load is imposed on the shaft suddenly, and from 1 s, the reference speed ω_m^* is set as 700 rpm (high speed). At 15 s, the load is removed, and from 20 s, the speed decreases to 50 rpm (ultra-low speed). Fig.2 and Fig.3 show the simulation and experimental results, respectively. On the one hand, the system illustrates marked steady-state performance. Firstly, the machine speed can remain stable at the setpoint regardless of that the machine is loaded or not. Secondly, as far as the torque is concerned, the output torque T_e can accurately track the load T_l with slight fluctuations. Thirdly, it can be seen that the air-gap flux magnitude levels off at 0.085 Wb under the no-load conditions, while it increases by about 0.008 Wb with load. On the other hand, dramatical dynamic performance can be witnessed in Fig.2 and Fig.3. Firstly, the rise time is short (within 0.4 s) during acceleration and deceleration, and there is only a small speed overshoot (less than 2%) that can be witnessed. Then, the speed slightly fluctuates once a load is suddenly applied to or removed from the motor, indicating that the system has strong robustness against the load variations. Moreover, during acceleration, both the torque and flux experience a sharp

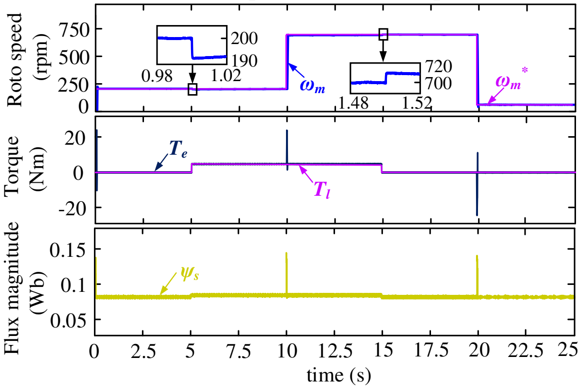

Fig. 2. Simulation results using the proposed weighting factor handling strategy.

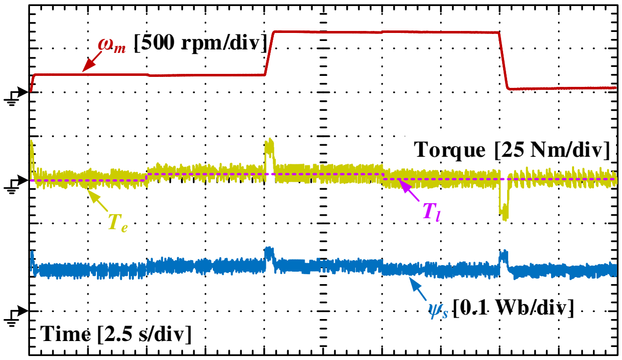

Fig. 3. Experimental results using the proposed weighting factor handling strategy.

increase to about 24 Nm and 0.14 Wb, respectively. But when the machine decelerates, the torque quickly drops while the flux sees an instantaneously upward trend. These indicate that the proposed weighting factor handling strategy can ensure the PMSM system to work with high performance.

V. CONCLUSION

This paper develops a novel analytical weighting factor tuning strategy for the FCS-MPTC method. At first, the reasons for which the weighting factors are required in the cost function of an FCS-MPTC controller are detailedly analyzed. It is found that apart from the differences of the nature between the flux and torque, the VSTVV is another key factor that impacts greatly on the weighting factors. On these ground the weighting factor handling strategy based on two sequential procedures (SN and VSTVV balance) is introduced. By using the proposed tuning method, the numerical values of the weighting factors can be obtained. Simulation and experimental results show that the calculated parameters are effective.

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