Letters

Flux Observation Transfer-Based Inductance Identification Technique for Precise FCS-MPCC Used in Surface-Mounted PMSMs

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***Abstract*—To eliminate the side impacts of inductance mismatch on the accuracy of finite control set model predictive current control (FCS-MPCC) scheme used for surface-mounted permanent magnet synchronous motors, this letter proposes a new flux observation transfer-based inductance identification strategy. First, a flux observer based on sliding mode theory is developed, with its stability analyzed. Second, the flux estimation errors are discussed, obtaining the relationship between the estimated flux and the inductance variations. On this basis, the inductance is detected using the flux information. Then, the estimated inductance is used to achieve the precise FCS-MPCC method. Finally, experiment is conducted on a three-phase SPMSM prototype to validate the proposed techniques.**

***Index Terms*—Flux observation, inductance identification, model predictive control (MPC), surface-mounted permanent magnet synchronous motor (SPMSM).**

I. Introduction

Due to the advantages of high-torque density, high-power density and compact structure, etc., surface-mounted permanent magnet synchronous motors (SPMSM) are widely adopted in industry such as electric vehicles and servo systems [1], [2]. In these applications, the motors require to track the reference signals quickly and precisely [3]. To achieve this goal, high-performance control strategies are in need.

Finite-control set model predictive control (FCS-MPC) that can be divided into model predictive current control (MPCC) [3], model predictive torque control [4], model predictive power control [5], and model predictive speed control (MPSC) [6] is a strategy based on optimal control theory. It utilizes a predicting plant model (PPM) to calculate the future states of the motor for candidate voltage vectors, which will further be evaluated by a cost function to opt for the manipulated variable. Compared to the traditional proportional integral controllers, FCS-MPC can discard the integral delay effect so as to have superior dynamics. However, because the FCS-MPC relies on machine model, it is parameter-dependent. In practice, it is not easy to ensure the machine inductance used for control to comply with the real ones because first, magnetic saturation exists, and second, the offline-measured inductance only represents the average value rather than the real-time one that is relevant to the rotor position. Once the inductance mismatches, the prediction accuracy of the PPM drops, resulting in steady-state errors and degraded dynamics [7].

Many up-to-date studies have developed effective techniques to reduce or eliminate the side impacts of inductance mismatch, among which the most direct way is online inductance identification. For instance, [8] and [9] develop inductance observers based on extended Kalman filter and model reference adaptive system to detect the winding inductance, respectively. Nevertheless, the existing inductance observers have two disadvantages. First, their bandwidth is low, thereby being weak in tracking the real-time inductance [10]. Second, they are unable to check and improve the accuracy of the estimated inductance. To solve the low-bandwidth issue, sliding mode (SM) variable structure theory that is well-known for its rapidity (high bandwidth) can be used for parameter identification [11]. But as explained in [12], the inductance information is contained in the denominators of the SPMSM model, leading to the fact that the estimation accuracy of an SM inductance observer (SMIO) used to directly calculate the inductance would degrade. This happens because the offline-measured inductance needs to be used to construct the observer.

This letter proposes a novel concept of flux observation transfer-based inductance identification to achieve precise FCS-MPCC for the SPMSMs. The main novelties and significance of the proposed method can be summarized as follows.

1) The rationale behind the proposed inductance identification concept is to use stable rotor flux (RF) to calibrate the mutable inductance.
2) In the proposed method, SM variable structure theory is utilized in a new way. In detail, instead of directly developing an SMIO, an SM flux observer (SMFO) is established to estimate the RF first. Then, after deriving the relation of the estimated flux and the inductance variations, the errors between the pre-measured RF that nearly sees

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no change during operation for a healthy motor and the estimated RF are used to calculate the real inductance.

3) In comparison with the existing inductance identification strategy, the new one can accomplish self-check and self-improvement in accuracy. With accurate inductance, both stable and dynamic performance of the FCS-MPCC method can be improved.

II. Proposed Strategies

A. Modeling of SPMSM

The electrical property of SPMSM in q-axis reference frame, which can be used for the proposed inductance identification scheme, is described as follows:

$$\frac{di_q}{dt} = -p\omega_m i_d - \frac{R_s}{L_s} i_q - \frac{\psi_f}{L_s} p\omega_m + \frac{u_q}{L_s} \tag{1}$$

where i_d, i_q are stator d, q-axis currents, u_q is q-axis control voltage, L_s is the real-time winding inductance, ω_m is angular speed, R_s and p are winding resistance and the number of pole pairs, respectively, ψ_f is the real-time flux linkage. Here, a reasonable assumption that the resistance R_s can be obtained accurately by using offline or online methods should be made considering the main purpose of this letter mainly is to tackle the inductance mismatch problem.

B. Flux Observation

The prerequisite for achieving the proposed inductance identification method is to observe the RF that will be further transferred to inductance. Hence, this part presents an SMFO that is seldom studied before with its stability analyzed.

1) Structure of SMFO: Based on the SM variable structure theory, the SMFO should be designed as (2) by virtue of (1)

$$\frac{di_q^*}{dt} = -p\omega_m i_d - \frac{R_s}{L_s} i_q^* - \frac{\lambda F(\overline{i_q})}{L_s} p\omega_m + \frac{u_q}{L_s} \tag{2}$$

where i_q^* is the estimated current, λ is gain coefficient of the observer, $\overline{i_q}$ is the error between the estimated current and the real one, namely, $\overline{i_q} = i_q^* - i_q$, and $F(\overline{i_q})$ is signum function

$$F(\overline{i_q}) = \begin{cases} 1, & \text{if} \overline{i_q} \geq 0 \\ -1, & \text{if} \overline{i_q}, < 0 \end{cases}. \tag{3}$$

When the observer reaches the equilibrium state, the estimated flux linkage ψ_f^* can be represented as:

$$\psi_f^* = \lambda F(\overline{i_q}). \tag{4}$$

2) Stability Analysis: A Lyapunov function needs to be established to analyze the stability of the SMFO. First, define a sliding surface $\mathbf{S}$ as

$$\mathbf{S} = \left[\overline{i_q}\right]. \tag{5}$$

Then, the Lyapunov function $\mathbf{V}$ can be constructed as

$$\mathbf{V} = \frac{1}{2}\mathbf{S}\cdot\mathbf{S}^T = \frac{1}{2}\left[\overline{i_q}^2\right]. \tag{6}$$

Third, taking the derivative of (6) and substituting (1) and (2) into the result, it can be deduced that

$$\frac{d\mathbf{V}}{dt} = \left[\frac{d\overline{i_q}}{dt}\overline{i_q}\right] = \left[-\frac{R_s}{L_s}\overline{i_q}^2 + \frac{(\psi_f - \lambda F(\overline{i_q}))}{L_s} p\omega_m \overline{i_q}\right]. \tag{7}$$

Theoretically, in order to ensure the observer to remain stable, the following conditions require to be satisfied

$$\mathbf{V} > 0, \quad \frac{d\mathbf{V}}{dt} < 0. \tag{8}$$

Obviously, based on (6), $\mathbf{V} > 0$. Hence, only when the second condition is satisfied can we conclude that the SMFO is stable. From (7), it can be seen that the first term is less than zero, so what is needed is that

$$\frac{(\psi_f - \lambda F(\overline{i_q}))}{L_s} p\omega_m \overline{i_q} < 0. \tag{9}$$

Based on the sign of $\overline{i_q}$, (9) can be further simplified as

$$\begin{cases} (\psi_f - \lambda)\omega_m < 0, & \text{if} \overline{i_q} \geq 0 \\ (\psi_f + \lambda)\omega_m > 0, & \text{if} \overline{i_q} < 0 \end{cases}. \tag{10}$$

Assuming that the machine rotates in the anticlockwise direction ($\omega_m > 0$), the condition making the SMFO stable is

$$\lambda > \psi_f. \tag{11}$$

Overall, λ should be set as a positive constant that is larger than the maximum RF in practice.

C. Relationship Between Flux and Inductance Variations

Practically, the offline-measured inductance L_{s_mea} rather than the accurate inductance should be adopted to construct the observer (2). Assume there exist inductance variations $\triangle L_s$, that is

$$L_{s\_\text{mea}} = L_s + \Delta L_s. \tag{12}$$

When substituting L_{s_mea} into (2) and subtracting the result from (1), the flux estimation error $\psi_{f\text{err}}$ caused by the inductance variations can be obtained as

$$\psi_{f\_\text{err}} = \psi_f^* - \psi_f = -i_d \Delta L_s - \frac{R_s}{p\omega_m}\overline{i_q} - \frac{1}{p\omega_m}\left(L_s\frac{d\overline{i_q}}{dt} - \Delta L_s \frac{di_q^*}{dt}\right). \tag{13}$$

As for the observer, $\overline{i_q}$ equals zero when it gets stable. Then, (13) can be rewritten as

$$\psi_{f\_\text{err}} = \Delta L_s \left(\frac{1}{p\omega_m}\frac{di_q^*}{dt} - i_d\right). \tag{14}$$

D. Proposed Flux Observation Transfer-Based Inductance Identification Strategy

1) Inductance Identification: Based on the relationship between the flux and inductance variations, the inductance can be identified by using

$$L_s^* = L_{s\_\text{mea}} - \Delta L_s = L_{s\_\text{mea}} - \frac{p\omega_m(\psi_f^* - \psi_f)}{\frac{di_q^*}{dt} - p\omega_m i_d} \tag{15}$$

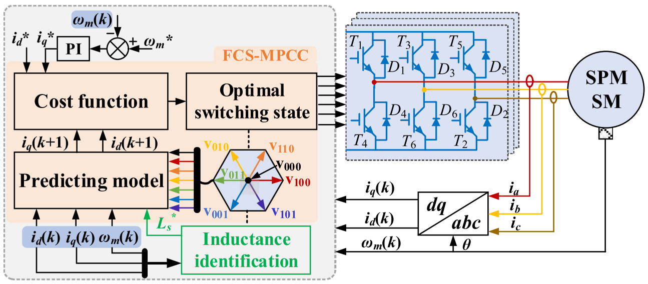


Fig. 1. Structure of FCS-MPCC method.

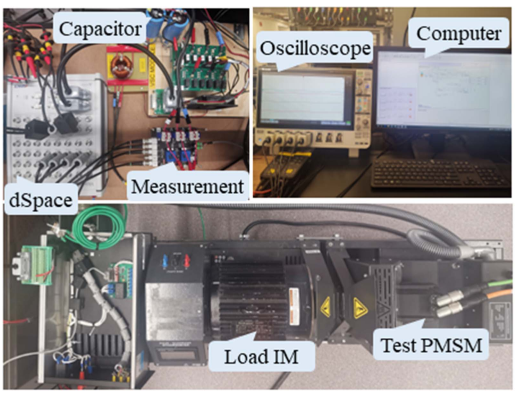


Fig. 2. Experimental test bench used for verifications.

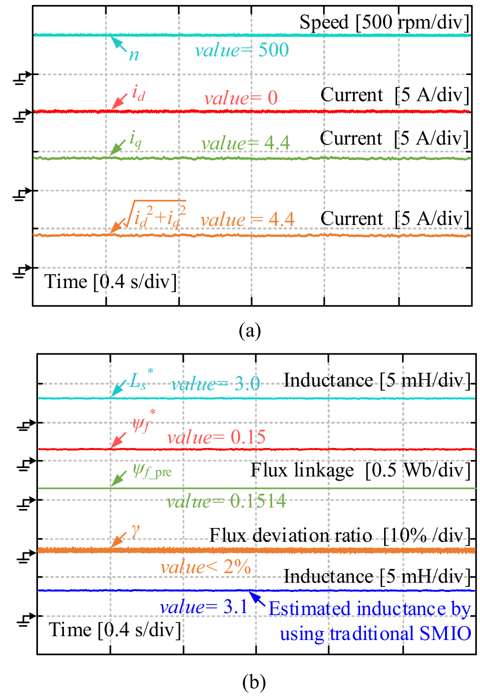


Fig. 3. Steady-state performance with no inductance mismatch issue. (a) Speed and current performance. (b) Results of estimated inductance and flux linkage.

where L_s^* is the estimated inductance. In terms of the proposed strategy, two aspects need to be addressed. First, the inductance identification issue is transferred to a flux observation issue. As long as ψ_f^* is calculated by using the SMFO, the measured inductance together with the flux information contributes to the inductance identification process. Second, it is necessary to know the RF ψ_f in advance. Considering that for a healthy motor (without demagnetization), the RF generated by the permanent magnets sees few changes in practice, it can be pre-measured ($\psi_{f\text{-pre}}$) by using the back electromotive strategy that is parameter-independent when the motor is assembled [13], [14].

2) Accuracy Check and Improvement: After obtaining L_s^*, it will be substituted into (2) to calculate the flux linkage again by using resampling states (current, speed and rotor position, etc.). Denote the re-estimated flux linkage as $\psi_{f\_re}{}^*$ and the flux deviation ratio γ can be defined as

$$\gamma = \frac{|\psi_{f\_\text{re}}^* - \psi_{f\_\text{pre}}|}{\psi_{f\_\text{pre}}} \times 100\%. \tag{16}$$

When ratio γ is no larger than the presetting threshold such as 2% in this letter, the accuracy of the estimated inductance L_s^* is considered to be high. Otherwise, iterative algorithm should be employed to improve its accuracy. Specifically, the estimated L_s^* are substituted into (2) and (15) (replacing L_{s_mea}) to recalculate the inductance.

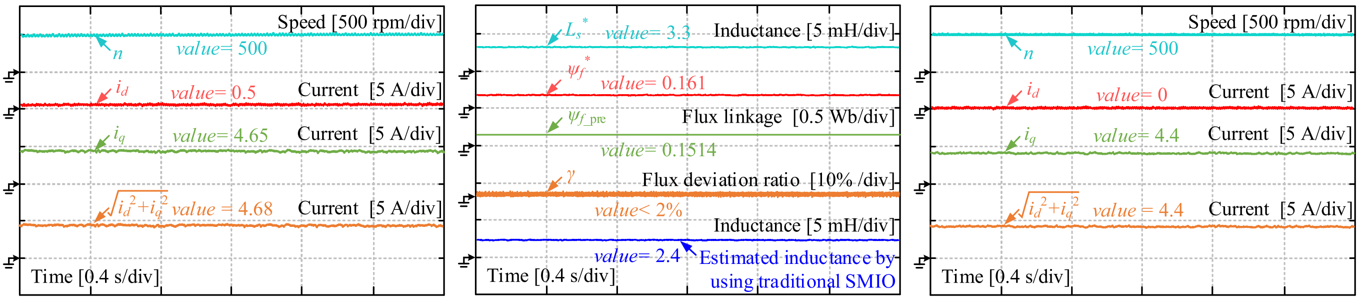
After estimating the inductance, it is used to achieve the FCS-MPCC algorithm presented in [7] (see Fig. 1), eliminating the impacts of inductance mismatch to ensure high performance.

TABLE I
MOTOR AND CONTROL PARAMETERS

Parameter	Value	Unit
stator winding resistance R_s	0.54	Ω
measured inductance $L_{s\ \text{mea}}$	3.1	mH
the number of pole pairs p	5	-
DC-bus voltage U_{dc}	100	V
pre-measured flux linkage $\psi_{f\ \text{pre}}$	0.1514	Wb
sampling time T_s	0. 1	ms

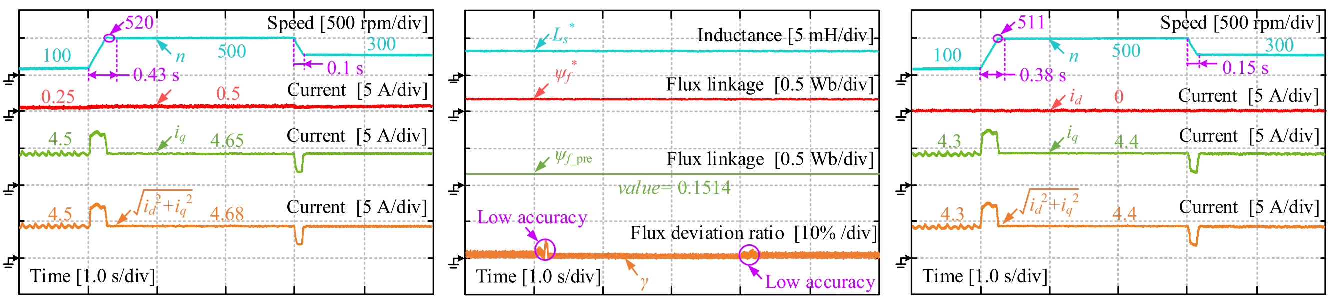
III. VERIFICATION RESULTS

To verify that the proposed flux observation transfer-based inductance identification and FCS-MPCC methods, experiment is conducted on an SPMSM prototype of which inductance can be accurately measured by an inductance measurement meter. More parameters of the system are given in Table I. The experimental test bench is shown in Fig. 2. Specifically, the proposed algorithms are implemented on a dSPACE control board, and the control frequency is 10 kHz. An induction motor (IM) working under the torque control mode is coupled to the test PMSM to provide the required load. By using the digital-to-analog conversion function of the dSPACE, all experimental results can be measured by Tektronix 5 Series MSO oscilloscope. For the sake of comprehensiveness, both steady-state and dynamic performance is presented. Besides, the estimation results of a traditional SMIO established based on the theory in [12] are presented for the purpose of comparison. It deserves to be mentioned when implementing the inductance identification



(a) (b) (c)

Fig. 4. Steady-state performance with inductance mismatch issue. (a) Speed and current performance using mismatched inductance. (b) Results of estimated inductance and flux linkage. (c) Speed and current performance using the inductance estimated by the proposed method.



(a) (b) (c)

Fig. 5. Dynamic performance with inductance mismatch issue. (a) Speed and current performance using mismatched inductance. (b) Results of estimated inductance and flux linkage. (c) Speed and current performance using the inductance estimated by the proposed method.

algorithms, the d-axis current is set as 0.5 A, while it is 0 when the FCS-MPCC is implemented.

A. Steady-State Performance

Fig. 3 shows the steady-state performance when no inductance mismatch issue occurs. The rotor speed n is 500 r/min, and the load is 4 N·m. The d-axis current, q-axis current and the magnitude of the overall current ($\sqrt{i_d^2 + i_q^2}$) are 0, 4.4 A and 4.4 A, respectively. Without the parameter mismatch issue, the estimated inductance and flux linkage, which are calculated by the proposed observers, are 3.0 mH and 0.15 Wb, respectively, tracking the real ones well. Comparatively, the output of the traditional SMIO is 3.1 mH, which shows high accuracy under this working status. Overall, the new inductance estimation strategy shows as good performance as the traditional one, proving that it is effective practically. In Fig. 4(a) and (b), the inductance mismatch issue occurs. In detail, the inductance used for FCS-MPCC and SMFO algorithms is 1.24 mH. Although the speed and load are the same, the system performance sees obvious differences. First, the d-axis current cannot track the reference zero, while it becomes 0.5 A. Second, the q-axis current and the current magnitude become larger (4.65) A. These represent that the inductance mismatch issue would result in higher current and low efficiency. Moreover, the estimated flux linkage relying on the mismatched inductance is 0.161 Wb, 6.3% higher than the real value. But the estimated inductance is pretty accurate (3.3 mH). Comparatively, the accuracy of the traditional SMIO decreases when the parameter mismatch issue occurs. This is consistent with the conclusion in [12], and this is the reason why that research employs complex numerical algorithms to increase the estimation accuracy. Fig. 4(c) presents the system performance when the estimated inductance is used for the FCS-MPCC algorithm, proving that the estimated inductance can make the stator current stand at a normal level.

B. Dynamic Performance

Since the estimation accuracy of the traditional SMIO is low when the parameter is mismatched in the stable states, it cannot be improved in the dynamic process. Hence, this part mainly presents the dynamics of the proposed technologies when the inductance becomes inaccurate. Fig. 5(a) and (b) illustrate the system dynamics and parameter estimation results with inductance mismatch issue, respectively, and Fig. 5(c) shows the dynamics when using the estimated inductance for control. The experimental setups are as follows. Between 0 and 1.0 s, the motor rotates at 100 r/min (low speed) under 4 N·m. Then, the motor speeds up to 500 r/min (high speed), and at 4.0 s, the speed reference is set as 300 r/min (medium speed). Two interesting phenomena should be addressed. First, when the inductance mismatch issue occurs, the speed overshoot and settling time are 20 r/min and 0.43 s during acceleration, respectively, which are higher than those (11 r/min and 0.38 s) in Fig. 5(c). This indicates that the system dynamics are related to the inductance. Second, although the estimated inductance and flux linkage in Fig. 5(b) seem to be stable, the flux deviation ratio is slightly higher than 2% during acceleration and deceleration, illustrating that the proposed estimation strategies are more effective in the stable states.

IV. Conclusion

This letter proposes an improved FCS-MPCC method for SPMSMs, which has high control performance because a novel flux observation transfer-based inductance identification method is developed to solve the inductance mismatch issue. The main contributions can be summarized as follows.

1) Instead of directly identifying the inductance, the RF is estimated first and then used for inductance calculation. This is a new approach based on the concept of transfer.
2) An SMFO that can accurately detect the flux linkage is developed, with its stability analyzed.
3) The estimated inductance is incorporated into the FCS-MPCC algorithm, improving its control performance. Experimental results prove that the proposed strategies are effective, especially in the stable states.

In the future, what deserves further investigation includes the following two aspects. First, SPMSMs are mainly focused on in this letter. It is valuable to extend the proposed strategies to the interior permanent magnet synchronous motors and IMs, etc. Second, the purpose of this letter is to clearly introduce the flux observation transfer-based inductance detection method, while some complex factors (e.g., saturation and nonlinearity, etc.) that influence the parameter identification accuracy are not considered, which require improvement.

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