Chapter 2

Observer-Based Robustness Improvement for FCS-MPCC Used in IMs

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This Chapter proposes a sliding mode (SM) disturbance observer based finite control set model predictive current control (FCS-MPCC) strategy to improve the control performance of induction motors. FCS-MPCC method is achieved based on the machine model, leading to the fact that the parameters have great impacts on the control performance, especially the steady-state characteristics. In this Chapter, the predicting model for induction motors (IMs) is established first. Simultaneously, a current-type flux observer is constructed according to the machine properties. Then, based on the predicting plant model (PPM), the disturbances caused by parameter mismatch are analyzed, posing the necessity of developing effective measures to compensate the disturbances. In this Chapter, a novel SM disturbance observer based on hyperbolic switching function is established to detect the real-time disturbances arising from parameter mismatch. Meanwhile, a Lyapunov function is constructed to analyze the stability of the observer and it is proven that there exist the internal gain factors to ensure the SM observer to be stable. Finally, the proposed disturbance observer is incorporated into the FCS-MPCC implementation process to eliminate the influence of parameter mismatch. The simulation is conducted on a three-phase IM to verify the performance of the proposed SM disturbance-observer-based FCS-MPCC strategy.

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2.1 Problem Descriptions

As illustrated in Chap. 1, FCS-MPC strategies have been widely used in the IM drives. Usually, the prediction process of an FCS-MPC controller is based on the machine model, leading to the fact that the system control performance is closely related to the machine's electrical parameters, including the winding resistance and inductance, etc. In practice, the machine parameter values for FCS-MPC are usually provided by the suppliers on the nameplate. However, the parameters vary greatly during operations due to the ambient conditions (e.g. temperature and magnetic field). On this ground there must exist errors between the offline parameters and the real-time ones, leading to current divergence and static errors [1]. In order to improve the robustness of predictive control against parameter mismatch, two different approaches have been developed. Firstly, some researchers regard the predictive errors caused by the mismatched parameters as disturbances, and then compensate them by using perturbation observers [2–4]. Secondly, the online parameter identification techniques are incorporated into the MPC to tackle the parameter mismatch problem [5–7]. Comparatively, the disturbance observers are able to detect not only the general disturbances caused by parameter mismatch but also the system nonlinearities and even external disturbances, so it is attracting more attentions at present. Paper [8] proposes a disturbance observer based on feedback compensation to solve the inductance and bus voltage variation problem. [9, 10] use sliding mode observers (SMO) that have the advantages of robustness against disturbances, low sensitivity to the system parameter variations and fast response to solve the parameter mismatch and uncertainty problems, laying the ground for the SMO based disturbance computation and compensation techniques. However, it needs to be mentioned that although the second order SMO with low chattering has been successfully applied in [9], the algorithm is complicated to implement in practice. Besides, the SMO is particularly designed for the deadbeat MPC, and there are few researches concerning the sliding mode disturbance observers used for the FCS-MPC applications. As far as the observer in [10] is concerned, it is only proposed for the mechanical load torque rather than electrical parameter estimation for the permanent magnet synchronous motors (PMSMs). Thus, the sliding mode electrical observers that are characterized by easier implementation are highly required for the FCS-MPC based IMs.

This Chapter proposes a sliding mode perturbation observer-based FCS model predictive current control (FCS-MPCC) for IMs to improve the robustness against the machine resistance and inductance mismatch phenomenon. It needs to be mentioned that the disturbance observer that uses a new constructed-function (CF) for chattering attenuation is innovatively used for IM FCS-MPCC situations. After establishing the mathematical model of the machine, the impacts of parameter mismatch on the control performance (static errors) of an FCS-MPCC controller is analyzed in detail. Then, a SMO based on CF is designed to obtain the system disturbance. Compared to the high order SMO in [9], the new observer is easier to achieve without using the differential-based reaching law. In order to ensure the new SMO to remain stable, a Lyapunov function is constructed and the stability conditions are calculated. Finally,

by integrating the estimated disturbance into the prediction model, the robust FCS-MPCC algorithm is achieved. Compared to the traditional FCS-MPCC algorithms, the current divergence and static errors will get suppressed in the resistance and inductance.

2.2 Implementation of FCS-MPCC and Impacts of Parameter Mismatch on Control Performance

A discrete PPM is the prerequisite for achieving an IM FCS-MPCC algorithm. In this section, the mathematical model of an IM is established firstly. To obtain the rotor flux used for feedback regulation, a novel numerical solution based current-type flux observer is presented secondly. Then, the implementation procedures are given in detail. Finally, the relationship between the control performance and parameter errors is theoretically discussed, posing the necessity to employ a disturbance observer for compensation.

2.2.1 State-Space Model of IM

State-space model is explicit and easy to describe the general behaviors of a multi-variable system. In order to estimate the future current states, the electrical dynamics of IMs should be employed for analysis, and the differential equations in MT -axis frame are as follows, where the iron saturation and eddy current are assumed to be negligible.

$$\frac{di_{sM}}{dt} = -\frac{R_s}{L_s}i_{sM} + \omega_e i_{sT} - \frac{L_m}{L_s} \frac{di_{rM}}{dt} + \frac{L_m}{L_s} \omega_e i_{rT} + \frac{u_{sM}}{L_s} \quad (2.1)$$

$$\frac{di_{sT}}{dt} = -\omega_e i_{sM} - \frac{R_s}{L_s} i_{sT} - \frac{L_m}{L_s} \omega_e i_{rM} - \frac{L_m}{L_s} \frac{di_{rT}}{dt} + \frac{u_{sT}}{L_s} \quad (2.2)$$

$$\frac{di_{rM}}{dt} = -\frac{L_m}{L_r} \frac{di_{sM}}{dt} + \frac{L_m}{L_r} \Delta\omega i_{sT} - \frac{R_r}{L_r} i_{rM} + \Delta\omega i_{rT} \quad (2.3)$$

$$\frac{di_{rT}}{dt} = -\frac{\Delta\omega L_m}{L_r} i_{sM} - \frac{L_m}{L_r} \frac{di_{sT}}{dt} - \Delta\omega i_{rM} - \frac{R_r}{L_r} i_{rT} \quad (2.4)$$

$$T_e = pL_m(i_{sT}i_{rM} - i_{sM}i_{rT}) = p \frac{L_m}{L_r} \psi_r i_{sT} \quad (2.5)$$

where i_{sM} and i_{sT} are stator currents. u_{sM} and u_{sT} are stator voltage. ω_e and $\Delta\omega$ are the synchronous speed and slip speed, respectively. i_{rM} and i_{rT} are the rotor currents.

R_s and L_s represent the stator resistance and inductance, respectively. R_r and L_r are the rotor resistance and inductance. L_m is the mutual inductance between the stator and rotor windings. T_e is the electromagnetic torque. ψ_r is the rotor flux and p is the number of pole pairs. Substitute (2.3) and (2.4) into (2.1) and (2.2), respectively and then, discretize them in a time step of T (sampling time) to calculate the future states as follows:

$$i_{sM}^{k+1} = (1 - C_1 L_r R_s) i_{sM}^k + C_1 [(L_s L_r \omega_e^k - L_m^2 \Delta \omega^k) i_{sT}^k + (\omega_e^k - \Delta \omega^k) L_r L_m i_{rT}^k + L_m R_r i_{rM}^k + L_r u_{sM}^k] \quad (2.6)$$

$$i_{sT}^{k+1} = (1 - C_1 L_r R_s) i_{sT}^k + C_1 [(L_m^2 \Delta \omega^k - L_s L_r \omega_e^k) i_{sM}^k - (\omega_e^k - \Delta \omega^k) L_r L_m i_{rM}^k + L_m R_r i_{rT}^k + L_r u_{sT}^k] \quad (2.7)$$

where the superscripts $k+1$ and k represent the future and current states, respectively. C_1 is a constant, and it satisfies that $C_1 = \frac{T}{L_s L_r - L_m^2}$. In the process of prediction, L_m can be set to zero by ignoring the mutual coupling [11].

Differing from synchronous machines, the flux rotating speed in the IM is not in sync with the mechanical speed, leading to the fact that the measured speed and position using external sensors cannot be directly used for coordinate transformation and prediction. Simultaneously, because the rotor flux is induced by the magnetic field of the stator, the amplitude of the rotor flux should be regulated in an FCS-MPCC strategy. On these grounds it is crucial to accurately obtain the amplitude and phase angle of the rotor flux and the synchronous speed for IM control. Now, there exist two main flux observation methods, that is, current-type observer [12] and voltage-type observer [13]. Comparatively, the latter approach accuracy is low over the low-speed range due to the internal integrators. Therefore, a current-type observer is adopted in this Chapter. As in [12], according to (2.1)–(2.5) and the flux descriptions, the rotor flux can be derived as:

$$\psi_r = \frac{L_m i_{sM}}{T_r s + 1} \quad (2.8)$$

where T_r is the electrical time constant of the rotor windings, and it equals $\frac{L_r}{R_r}$. And the slip speed is:

$$\Delta \omega = \frac{L_m i_{sT}}{T_r \psi_r + 1} \rightarrow \omega_e = p \omega_r + \Delta \omega \quad (2.9)$$

where ω_r represents the rotor speed. It can be noted that once the rotor flux is only related to the M -axis current, and once ψ_r is calculated, the slip speed can be obtained subsequently. Further, the phase angle θ of the rotor flux, which is used for coordinate transformation, can be calculated by:

$$\theta = \int \omega_e dt = \int (p\omega_r + \Delta\omega) dt \quad (2.10)$$

It can be seen from (2.8) that the relationship between the rotor flux and M -axis current can be treated as a first-order inertia element. In this chapter, in order to calculate ψ_r , the method based on solving the differential equation is adopted, namely,

$$\psi_r(t) = L_m i_{sM} (1 - e^{-\frac{t}{T_r}}) \quad (2.11)$$

In the control period between t_k and t_{k+1} , where $0 \leq t \leq T$, i_{sM}^k can be directly substituted into (2.11) to calculate ψ_r at any moment. Considering that the rotor flux shifts constantly, we can treat the typical value at $t_k + 0.5T$ as the output of the flux observer within the current cycle, that is,

$$\psi_r^k = L_m i_{sM}^k (1 - e^{-\frac{T}{2T_r}}) \quad (2.12)$$

When an FCS-MPCC algorithm is implemented, the candidate control voltages applied to the stator windings should be directly substituted into the predicting model one by one to predict the next-step states. In terms of a two-level inverter, a total of seven phase voltage vectors that are denoted as are among the alternatives:

$$\mathbf{v}_{s_a s_b s_c} = \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \frac{U_{dc}}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} s_a \\ s_b \\ s_c \end{bmatrix} \quad (2.13)$$

where $[s_a, s_b, s_c]^T$ is the switching states. They are $[0, 0, 0]^T$, $[1, 0, 0]^T$, $[1, 1, 0]^T$, $[0, 1, 0]^T$, $[0, 1, 1]^T$, $[0, 0, 1]^T$ and $[1, 0, 1]^T$, which can also be denoted as $v_1, \dots, v_7$. U_{dc} is the DC-bus source voltage. $[u_a, u_b, u_c]^T$ are the terminal phase voltages. By the use of transformation, the control voltage sets used for prediction can be expressed as:

$$\begin{bmatrix} u_{sM}^k \\ u_{sT}^k \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos \theta & \frac{\sqrt{3} \sin \theta - \cos \theta}{2} & \frac{-\sqrt{3} \sin \theta - \cos \theta}{2} \\ -\sin \theta & \frac{\sin \theta + \sqrt{3} \cos \theta}{2} & \frac{\sin \theta - \sqrt{3} \cos \theta}{2} \end{bmatrix} \cdot \mathbf{v}_{s_a s_b s_c} \quad (2.14)$$

The block diagram of the FCS-MPCC implementation is shown in Fig. 2.1. At the k th period, the FCS-MPCC implementation procedures are:

- (a) Measurement: the phase currents and speed are measured by using current and position sensors.
- (b) abc/MT transformation: the measured phase currents are transformed to the MT -axis currents according to the rotor position estimated in the last period.

Fig. 2.1 Block diagram of the FCS-MPCC implementation

- (c) Observation: use the immediate currents to calculate the rotor flux, slip speed, synchronous speed and position.
- (d) Prediction: use the immediate speed and currents to estimate the future current states i_{sM}^{k+1} and i_{sT}^{k+1} for all the seven candidate voltage vectors.
- (e) Evaluation: substitute the seven the predicted values into the cost function (2.15) and determine the optimal voltage vector and the corresponding switching states.

$$J = |i_{sM}^* - i_{sM}^{k+1}| + |i_{sT}^* - i_{sT}^{k+1}| \quad (2.15)$$

where i_{sT}^* and i_{sM}^* are the reference currents.

- (f) Actuation: apply the optimum switching state to the drive system.

2.2.2 Impacts of Parameter Mismatch on Performance

Paper [1] analyses the sources (inductance and flux disturbance, etc.) of the current static errors for PMSM drives, laying the ground for theoretically analyzing IMs, though it neglects the impact of the winding resistance. This part will comprehensively explain the impacts of resistance, mutual and self-inductance mismatch on the FCS-MPC static errors.

The measured resistance and inductance used for FCS-MPCC controller are denoted as R_{s0} , L_{s0} , L_{r0} and L_{m0} . Taking the M -axis current as an example, the estimated value at t_k is denoted as i_{sM0}^{k+1} , and the predicting model can be written as:

$$\begin{aligned} i_{sM0}^{k+1} = & (1 - C_{1_0}L_{r0}R_{s0})i_{sM}^k + C_{1_0}[(L_{s0}L_{r0}\omega_e^k - L_{m0}^2\Delta\omega^k)i_{sT}^k \\ & + (\omega_e^k - \Delta\omega^k)L_{r0}L_{m0}i_{rT}^k + L_{m0}R_{r0}i_{rM}^k + L_{r0}u_{sM}^k] \end{aligned} \quad (2.16)$$

where C_{1_0} relies on the offline inductance values. Further, the estimation error Δi_{sM} can be deduced by subtracting (2.16) from (2.6) as follows:

$$\begin{cases} \Delta i_{sM} = i_{sM}^{k+1} - i_{sM0}^{k+1} = \Delta k_1 i_{sM}^k + \Delta k_2 i_{sT}^k + \Delta k_3 i_{rT}^k + \Delta k_4 i_{rM}^k + \Delta k_5 i_{rM}^k \\ \Delta k_1 = C_{1_0} L_{r0} R_{s0} - C_1 L_r R_s \\ \Delta k_2 = C_{1_0} (L_s L_r \omega_e^k - L_m^2 \Delta \omega^k) - C_{1_0} (L_{s0} L_{r0} \omega_e^k - L_{m0}^2 \Delta \omega^k) \\ \Delta k_3 = C_{1_0} (\omega_e^k - \Delta \omega^k) L_r L_m - C_{1_0} (\omega_e^k - \Delta \omega^k) L_{r0} L_{m0} \\ \Delta k_4 = C_{1_0} L_m R_r - C_{1_0} L_{m0} R_{r0} \\ \Delta k_5 = C_{1_0} L_r - C_{1_0} L_{r0} \end{cases} \quad (2.17)$$

According to (2.17), it can be noted that the static error is proportional to the control period T . Usually, the switching period is small (e.g., 0.1 ms), so the current static error will be pretty small unless the parameter mismatch phenomenon is severe. Obviously, the higher the magnitude of Δk_n ($n = 1, 2, 3, 4, 5$) is, the larger the current static error becomes. This represents that parameter mismatch will greatly reduce the steady-state estimation accuracy of an FCS-MPCC controller. Unluckily, as for the traditional FCS-MPCC algorithms ($L_{m0} = 0$), there always exists disturbance caused by parameter mismatch. Moreover, it can be seen that the estimation errors are highly related to the machine speed, so the control performance might decrease visibly in the high-speed range.

Overall, if the perturbation caused by parameter mismatch is not compensated, the static current errors will inevitably appear, lowering the control performance of a predictive controller [5]. Even worse, the system will become unstable when the parameter deviations are very large. Therefore, it is necessary to introduce a perturbation observer to detect the real-time disturbance caused by the parameter mismatch and compensate the FCS-MPCC algorithms.

2.3 Proposed Sliding Mode Disturbance Observer

The conventional sliding mode observers are achieved by the use the sigum function, which is shaped like Fig. 2.2a. However, due to the inertia of a real system, its response speed is much slower than the expected property (steep trend) near the sliding mode surface (SMS). Hence, chattering arises inevitably. The reason why the SMO in [9] is complicated is that a high order sliding mode surface is adopted to suppress

Fig. 2.2 Properties of switching functions. **a** Signum function; **b** Hyperbolic function

the chattering effects. In this section, a simpler SMO based on hyperbolic function shaped like Fig. 2.2b is proposed. It deserves to be mentioned that the switching function is pretty new, and because it is continuous and differentiable (modest trend) near the SMS, the chattering phenomenon can be attenuated.

2.3.1 Sliding Mode Disturbance Observer

Denote the M , T -axis disturbances caused by parameter mismatch as f_M and f_T , respectively. In virtue of the measured parameters, the IM model containing the disturbances can be rewritten as:

$$\frac{di_{sM}}{dt} = -\frac{R_{s0}}{L_{s0}}i_{sM} + \omega_e i_{sT} + \frac{u_{sM}}{L_{s0}} + f_M \quad (2.18)$$

$$\frac{di_{sT}}{dt} = -\omega_e i_{sM} - \frac{R_{s0}}{L_{s0}}i_{sT} + \frac{u_{sT}}{L_{s0}} + f_T \quad (2.19)$$

According to the sliding mode theory, the disturbance observer can be constructed as:

$$\frac{di_{sM}^*}{dt} = -\frac{R_{s0}}{L_{s0}}i_{sM}^* + \omega_e i_{sT} + \frac{u_{sM}}{L_{s0}} + k_M F(\bar{i}_{sM}) \quad (2.20)$$

$$\frac{di_{sT}^*}{dt} = -\omega_e i_{sM} - \frac{R_{s0}}{L_{s0}}i_{sT}^* + \frac{u_{sT}}{L_{s0}} + k_T F(\bar{i}_{sT}) \quad (2.21)$$

where i_{sM}^* and i_{sT}^* are estimated stator currents. $\bar{i}_{sM}$ and $\bar{i}_{sT}$ represent the errors between the estimated and real currents, and $\bar{i}_{sM} = i_{sM}^* - i_{sM}$, $\bar{i}_{sT} = i_{sT}^* - i_{sT}$. k_M and k_T are the gain factors. $F(\bar{i}_{sM})$ and $F(\bar{i}_{sT})$ are the hyperbolic function, that is,

$$\begin{bmatrix} F(\bar{i}_{sM}) \\ F(\bar{i}_{sT}) \end{bmatrix} = \begin{bmatrix} \frac{e^{m \cdot \bar{i}_{sM}} - e^{-m \cdot \bar{i}_{sM}}}{e^{m \cdot \bar{i}_{sM}} + e^{-m \cdot \bar{i}_{sM}}} \\ \frac{e^{m \cdot \bar{i}_{sT}} - e^{-m \cdot \bar{i}_{sT}}}{e^{m \cdot \bar{i}_{sT}} + e^{-m \cdot \bar{i}_{sT}}} \end{bmatrix} \quad (2.22)$$

where m is a constant for boundary layer (as in Fig. 2.2b) regulation, and it should be less than one but larger than zero. By carefully looking at the switching function, three main features can be witnessed. Firstly, when the estimated errors approach zero, the values of the function are zero as well. Secondly, the upper and lower output are 1 and -1 , respectively. Finally, the boundary layer needs to be in accord with the system properties by adjusting m . In practice, this parameter can be obtained by using the trial-and-error method. In this chapter, $m = 0.78$. If the system reaches a

Fig. 2.3 Block diagram of proposed SMO

stable state, the actual disturbances can be obtained by the following equations:

$$\begin{bmatrix} f_M \\ f_T \end{bmatrix} = \begin{bmatrix} k_M F(\overline{i_{sM}}) \\ k_T F(\overline{i_{sT}}) \end{bmatrix} \quad (2.23)$$

The block diagram of the proposed observer is shown in Fig. 2.3.

2.3.2 Stability Analysis

In order to construct Lyapunov function for stability analysis, the sliding mode surfaces of M , T -axis currents are denoted as S_M and S_T , respectively. They should satisfy the following conditions:

$$\mathbf{S} = \begin{bmatrix} S_M \\ S_T \end{bmatrix} = \begin{bmatrix} \overline{i_{sM}} \\ \overline{i_{sT}} \end{bmatrix} = 0 \quad (2.24)$$

The Lyapunov function V is as follows:

$$V = \frac{1}{2} \mathbf{S} \cdot \mathbf{S}^T = \frac{1}{2} \overline{i_{sM}}^2 + \frac{1}{2} \overline{i_{sT}}^2 \quad (2.25)$$

No doubt that the value of V is larger than zero. Only by proving that the derivative of V is less than zero can we conclude that the proposed observer is stable. Take the time derivative of (2.25) and it can be deduced that:

$$\frac{dV}{dt} = \overline{i_{sM}} \cdot \frac{d\overline{i_{sM}}}{dt} + \overline{i_{sT}} \cdot \frac{d\overline{i_{sT}}}{dt} \quad (2.26)$$

Substitute (2.18)–(2.21) into (2.26), and then we can obtain that:

$$\frac{dV}{dt} = -\frac{R_{s0}}{L_{s0}}\overline{i_{sM}}^2 - \frac{R_{s0}}{L_{s0}}\overline{i_{sT}}^2 + (k_M F(\overline{i_{sM}}) - f_M)\overline{i_{sM}} + (k_T F(\overline{i_{sT}}) - f_T)\overline{i_{sT}} \quad (2.27)$$

Obviously, the values of the first and second terms are less than zero. Therefore, in order to make the system stable, the following equations need to be satisfied:

$$\begin{cases} (k_M F(\overline{i_{sM}}) - f_M)\overline{i_{sM}} < 0 \\ (k_T F(\overline{i_{sT}}) - f_T)\overline{i_{sT}} < 0 \end{cases} \quad (2.28)$$

According to the signs (positive or negative) of the M, T -axis current errors, (2.28) can be further derived as:

$$\begin{cases} k_M < \frac{f_M}{F(\overline{i_{sM}})}, & \text{if } \overline{i_{sM}} > 0 \\ k_M < -\frac{f_M}{F(\overline{i_{sM}})}, & \text{if } \overline{i_{sM}} < 0 \end{cases} \rightarrow k_M < -\left| \frac{f_M}{F(\overline{i_{sM}})} \right| \quad (2.29)$$

$$\begin{cases} k_T < \frac{f_T}{F(\overline{i_{sT}})}, & \text{if } \overline{i_{sT}} > 0 \\ k_T < -\frac{f_T}{F(\overline{i_{sT}})}, & \text{if } \overline{i_{sT}} < 0 \end{cases} \rightarrow k_T < -\left| \frac{f_T}{F(\overline{i_{sT}})} \right| \quad (2.30)$$

Combing (2.29) and (2.30), the observer stability condition can be summarized as:

$$k_M, k_T < \min\left(-\left| \frac{f_M}{F(\overline{i_{sM}})} \right|, -\left| \frac{f_T}{F(\overline{i_{sT}})} \right| \right) \quad (2.31)$$

Because $F(\overline{i_{sM}})$ and $F(\overline{i_{sT}})$ are between -1 and 1, theoretically, even by making the magnitudes of k_M and k_T extremely large, the observer cannot always keep stable, especially when $\overline{i_{sM}}$ and $\overline{i_{sT}}$ are near zero. But in the real applications, the current estimation errors will fluctuate mostly around the sliding surfaces with small variations with the range of tolerance [14]. Define the smallest tolerance as η ,

$$\eta = \min(|\overline{i_{sM}}|, |\overline{i_{sT}}|) \quad (2.32)$$

Then, the minimum switching function value is:

$$\min F = \frac{e^{m \cdot \eta} - e^{-m \cdot \eta}}{e^{m \cdot \eta} + e^{-m \cdot \eta}} \quad (2.33)$$

Hence, the observer gain can be set as:

$$k_M = k_T = \min\left(-\left|\frac{f_M}{\min F}\right|, -\left|\frac{f_T}{\min F}\right|\right) \quad (2.34)$$

In theory, there exist k_M and k_T making the observer stable as long as the disturbance values are not exaggeratedly large (where the system is unstable). During the control process, although $\hat{i}_{sM}$ and $\hat{i}_{sT}$ are possible to be less than the pre-set value of η , the proposed SMO can re-converge again once their values increase. Hence, although the proposed observer is asymptotically stable, the disturbances can be estimated.

After estimating the disturbances caused by the parameter mismatch using the proposed SMO, the disturbances can be directly incorporated the FCS-MPCC PPM for compensation. By applying Euler implementation to (2.18) and (2.19), the predicting model used in practice is:

$$\hat{i}_{sM}^{k+1} = \frac{L_{s0} - T R_{s0}}{L_{s0}} \hat{i}_{sM}^k + T \omega_e \hat{i}_{sT}^k + \frac{T u_{sM}^k}{L_{s0}} + T f_M^k \quad (2.35)$$

$$\hat{i}_{sT}^{k+1} = -T \omega_e \hat{i}_{sM}^k + \frac{L_{s0} - T R_{s0}}{L_{s0}} \hat{i}_{sT}^k + \frac{T u_{sT}^k}{L_{s0}} + T f_T^k \quad (2.36)$$

where f_M^k and f_T^k are the disturbances at t_k observed by the SMO. The implementation (simulation) diagram of the improved FCS-MPCC method is depicted in Fig. 2.4. As to this controller, although the offline parameters are still used for future state prediction, the disturbances can be removed.

Fig. 2.4 Implementation diagram of the proposed SMO based FCS-MPCC

2.4 Verifications

Simulation is conducted on a three-phase IM whose real parameters and structure are assumed to be consistent with those in Table 2.1 to verify the effectiveness of the proposed sliding mode disturbance observer-based FCS-MPCC. Considering that the disturbances principally affect the static errors during control, the steady-state control performance is mainly discussed in this section, though the dynamics are given. In simulation, the control frequency is set to 10 kHz.

By comparing the PPM (2.35) and (2.36) with the comprehensive ones (2.6) and (2.7), without considering the disturbance terms, the rotor parameters (rotor inductance and resistance) are removed totally when the mutual effect is ignored. On this ground the rotor parameters can be treated to be one hundred percent (100%) mismatched in terms of an FCS-MPCC algorithm. As for the stator inductance and resistance, they are inclined to encounter mismatch problems during control as well. For the sake of comprehensiveness, two typical cases are analyzed in this part. *Case 1*: the measured stator inductance and resistance are 90% lower than the actual ones. *Case 2*: the measured stator inductance and resistance are 50% higher than the actual ones. For each case, different working conditions (40 rad/s, 80 rad/s and 110 rad/s under load and no-load) are taken into account.

2.4.1 Case 1

(a) FCS-MPCC without disturbance observer

Figure 2.5 shows the dynamic speed and torque performance characteristics of the FCS-MPCC controller without using any disturbance observers. According to the dynamics in Fig. 2.5, the simulation setup can be described as follows. Between 0 and 3 s, the machine speeds up from 0 to 40 rad/s, after which the reference speed is set as 80 rad/s. Between 6 and 12 s, the machine is expected to be controlled to remain 110 rad/s, and at 12 s, the motor decelerates to 80 rad/s. Finally, from 15 s, the speed

Table 2.1 Measured IM parameters and structure

Parameters	Value	Unit
Stator inductance L_s	0.12	H
Stator resistance R_s	0.065	Ω
Mutual inductance L_m	0.075	H
Rotor inductance L_r	0.095	H
Rotor resistance R_r	0.05	Ω
Friction coefficient F	0.003	–
Rated load T_{L_rated}	4.5	Nm
Rated speed ω_{r_rated}	110	rad/s

Fig. 2.5 Speed and torque dynamic performance of machine

reference is set to 40 rad/s. In terms of the external load, before and after 12 s, it is set to 0 and 4.5 Nm, respectively. Before leaving Fig. 2.5, it should be noticed that firstly, the machine has fast dynamics regardless of acceleration and deceleration. Specifically, the rise time for the acceleration processes (0–40 rad/s, 40–80 rad/s and 80–110 rad/s) is nearly 1.85 s, 0.65 s and 0.45 s, respectively. The deceleration is a little faster than the acceleration process. In detail, the settling time is about 0.3 s.

Figure 2.6 depicts the steady-state performance of the FCS-MPCC at the speed of 40 rad/s under no-load (between 2.5 s and 3 s) and rated load (between 17 s and 17.5 s) conditions. In the no-load conditions, the speed can remain at 42 rad/s, so the static error rate (*SER*) is 5%. As far as the rotor flux is concerned, the *SER* is 2.4%. Comparatively, the speed and flux *SER* is 3% and 8.2%, respectively. This is interesting that the static error for speed decreases, but it increases for the flux after the external load is imposed on the rotor shaft. This happens mainly because that the flux is more closely related to the load (current) than the speed. Because currents are not the final control targets, we just give the current ripples of the i_{sM} and i_{sT} . Comparatively speaking, the M , T -axis current ripples (*CR*) under load (3.1 A and 1.3 A) are slightly higher than those under no load (2.4 A and 1.25 A).

The steady-state performance of the system when the machine runs at 80 rad/s is illustrated in Fig. 2.7. Compared to Fig. 2.6, the magnitude of the speed static error increases to 3.2 rad/s and 1.8 rad/s under no-load and load conditions. This

Fig. 2.6 Steady-state performance at speed of 40 rad/s with rotor parameter 100% and stator parameter 90%-lower mismatch. **a** No-load condition; **b** Rated load condition

Fig. 2.7 Steady-state performance at speed of 80 rad/s with rotor parameter 100% and stator parameter 90%-lower mismatch. **a** No-load condition; **b** Rated load condition

complies with the conclusion in this chapter. In terms of the rotor flux, the *STR* witnesses a dramatical growth regardless of the load conditions. i_{sM} and i_{sT} are very similar to those in the situation that the machine speed is 40 rad/s, and they are 2.2 A and 1.28 A when the machine rotates without external load, 3.0 A and 1.42 A with rated load imposed on the shaft. Figure 2.8 demonstrates the control performance over higher speed range (11 rad/s), it can be seen that the magnitudes of the static errors experience an upward trend in comparison with the low-speed cases, while the currents nearly remain at the similar level. Overall, the traditional FCS-MPCC that ignores the mutual coupling has marked static errors over the full-speed range.

(b) FCS-MPCC with SM disturbance observer

Figure 2.9 a, b show the estimated disturbances using the proposed SMO when the machine rotates at 40 rad/s under no load and load, respectively. At the moment,

Fig. 2.8 Steady-state performance at speed of 110 rad/s with rotor parameter 100% and stator parameter 90%-lower mismatch. **a** No-load condition; **b** Rated load condition

Fig. 2.9 Steady-state estimated disturbances using the proposed SMO at the speed of 40 rad/s. **a** No-load condition; **b** Rated load condition

the observed disturbances have not been incorporated into the FCS-MPCC implementations. It can be seen when the machine runs without load, the M -axis disturbance (around -5) is much smaller than the T -axis one (-31). However, in the load condition, the M -axis witnesses a sharp increase to about -180 , while the T -axis disturbance is about -210 . Although the estimated values are pretty large, when they are substituted into (2.35) and (2.36) for prediction, they need to multiply by the sampling period (0.001 s). Therefore, the estimated values are reasonable. Overall, these results represent that the disturbances caused by rotor and stator parameter mismatch is closely related to the load states.

After incorporating the SMO into the FCS-MPCC control process, the control performance characteristics at the speed of 40 rad/s are shown in Fig. 2.10. Compared to the results in Fig. 2.6, the speed and flux static errors have been dramatically reduced regardless of the working conditions. In detail, the SER for speed and rotor flux is 0.5% and 0.057% respectively under no load, and it is 0.75% and 0 respectively in the load conditions. These represent that the proposed observer is able to improve the system control performance. Apart from the static errors, the current ripples experience a visible decrease as well. In simulation, the M - and T -axis current ripples become 0.6 and 0.55 A under no load.

Figure 2.11a, b show the estimated disturbances at the speed of 80 rad/s and Fig. 2.11c, d depict the control performance after compensation. Obviously, the disturbances are much larger than those in Fig. 2.9, so it is further proven that

Fig. 2.10 Steady-state performance of the machine when incorporating the proposed SMO at the speed of 40 rad/s. **a** No-load condition; **b** Rated load condition

Fig. 2.11 Steady-state performance of the machine when incorporating the proposed SMO at the speed of 80 rad/s. **a** No-load-condition disturbances; **b** Rated-load-condition disturbances; **c** No-load-condition performance; **d** Rated-load-condition performance

the disturbances are highly related to the machine speed. Similar as the results in Fig. 2.10, the control performance after compensation. Obviously, the disturbances are much larger than those in Fig. 2.9, so it is further proven that the disturbances are proportionally related to the machine speed. Similar as the results in Fig. 2.10, the speed and flux static errors are nearly zero. In terms of the M , T -axis currents, the ripples are about 0.5 A, which is truly small. Therefore, the steady-state control performance has been improved greatly when adopting the proposed observer.

In Fig. 2.12, the no-load-condition and rated-load-condition disturbances and the steady-state control performance at the speed of 110 rad/s are demonstrated. The disturbances become larger than the lower speed cases. In detail, the M -axis disturbance is about 50, while the T -axis disturbance is -780 under no load, but they become around -275 and -1180 when the external load is imposed on the rotor shaft. After the SMO is adopted for disturbance observation and compensation, the speed and flux static errors become very small (SER for speed and flux is 0.4% and 0 respectively under no load).

In order to clearly reveal the superiority of the proposed SMO based FCS-MPCC, Table 2.2 summarizes the speed and flux static errors and the M -axis current ripples before and after employing the disturbance observer. it deserves to be mentioned that aiming at the case in which the rotor parameters and stator parameters are 100 and 90% mismatched, the proposed FCS-MPCC has great capability.

Fig. 2.12 Steady-state performance of the machine when incorporating the proposed SMO at the speed of 110 rad/s. **a** No-load-condition disturbances; **b** Rated-load-condition disturbances; **c** No-load-condition performance; **d** Rated-load-condition performance

Table 2.2 Comparison of static errors and M -axis current ripple before and after employing SMO

Speed (rad/s)	Speed static error (rad/s)		Flux static error (Wb)		Ripples of i_{sM} (A)	
	Before	After	Before	After	Before	After
40	2	0.2	0.002	0.0005	2.4	0.6
	1.2	0.3	0.007	0	3.1	0.5
80	3.2	0.1	0.005	0	2.2	0.55
	1.8	0.1	0.01	0	3.0	0.5
110	3.5	0.5	0.006	0	2.5	0.35
	2.5	0	0.007	0.0003	3.3	0.55

2.4.2 Case 2

(a) FCS-MPCC without disturbance observer

When the stator parameters provided by the suppliers (used for control) are 50% higher than the actual ones, the dynamic speed and torque performance without using any disturbance observers are shown in Fig. 2.13. The simulation setup is the same to that in Fig. 2.5, but the dynamics are a little different. In detail, the rise time for the acceleration processes (0–40 rad/s, 40–80 rad/s and 80–110 rad/s) is 0.98 s, 0.5 s and 0.28 s, respectively, and the settling time for deceleration is even shorter. These represent that the milder the parameter mismatch phenomenon is, the better the

Fig. 2.13 Speed and torque dynamic performance of machine

dynamics become. Considering that the disturbances caused by parameter mismatch influence the system dynamics, the proposed disturbance observer based FCS-MPCC strategy is significant to improve not only the system steady-state performance but also the dynamic performance.

In Fig. 2.14, the steady-state control performance at the speed of 40 rad/s is shown. Compared to Fig. 2.6, the speed and flux *SER* has decreased greatly when the parameter mismatch issue gets milder. In detail, the speed and flux *SER* under no load are 2.5% and 1.2% respectively, and they are 2 and 1.2% under load. In terms of the current ripples, they are 1.4 A and 1.05 A for the *M* and *T* axis respectively in the no-load condition.

Figures 2.15 and 2.16 illustrates the steady-state control performance at the speed of 80 rad/s and 110 rad/s, respectively. Similarly, as the speed increases, the magnitude of the static errors will become larger while the *SER* of them decreases. Interestingly, by contrast with Case 1, the flux fluctuations reduced markedly when the parameter mismatch phenomenon becomes wilder. At 80 rad/s, the speed and flux static errors are 1.5 rad/s and 0.002 Wb in the no-load condition, and 1.2 rad/s and 0.001 Wb, respectively. The reason why the control performance gets slightly better under load is that the impacts of disturbances caused by parameter mismatch are uncertain at different working states. In other words, At 110 rad/s, the static errors

Fig. 2.14 Steady-state performance at speed of 40 rad/s with rotor parameter 100% and stator parameter 50%-higher mismatch. **a** No-load condition; **b** Rated load condition

Fig. 2.15 Steady-state performance at speed of 80 rad/s with rotor parameter 100% and stator parameter 50%-higher mismatch. **a** No-load condition; **b** Rated load condition

Fig. 2.16 Steady-state performance at speed of 110 rad/s with rotor parameter 100% and stator parameter 50%-higher mismatch. **a** No-load condition; **b** Rated load condition

for speed and flux are 1.7 rad/s and 0.001 Wb under no load, and they are 1.3 rad/s and 0.0012 Wb under load, respectively. As far as the M , T -axis current ripples are concerned, they are nearly 1.6 A and 1.1 A respectively regardless of the load and speed states.

Overall, the impacts of parameter mismatch are significant to both the dynamic and steady-state control performance of FCS-MPCC strategies, and meanwhile, the mismatch degree is proportionally relevant to the system performance. That is, the more severe the parameter mismatch phenomenon is, the worse the system performance becomes.

(a) FCS-MPCC with SM disturbance observer

It needs to be mentioned that the effective disturbance compensation techniques are still needed in the less-severe parameter mismatch situations. This part shows

the control performance of the FCS-MPCC method based on the proposed SM perturbation observer.

Figure 2.17 illustrates the disturbances caused by parameter mismatch before compensation and the steady-state control performance after compensation when the machine runs at 40 rad/s. It can be noticed that the disturbances are smaller than those in Fig. 2.9, and they are the M -axis disturbance is about -4 than the T -axis one is -22 under no load. In the load condition, the M -axis disturbance also increases sharply to about -170 , while the T -axis disturbance is about -200 . Figure 2.17c, d show that the speed and flux static errors are nearly zero despite of no-load or load situations. In addition, the current ripples become half of the values before compensation. Consequently, the proposed SMO is able to effectively deal with the disturbances in the system.

Figures 2.18 and 2.19 show control performance at the speed of 80 rad/s and 110 rad/s, respectively. Obviously, the higher the speed is, the larger the disturbances turn out to be. Over these medium- and high-speed ranges, the speed and flux static errors approaches zero as well after compensation. Meanwhile, the current ripples are smaller than the results when the SM disturbance observer is not employed.

For the sake of intuitiveness, Table 2.3 illustrates the speed and flux static errors and the M -axis current ripples before and after using the disturbance observer to compensate the disturbances caused by parameter mismatch. Aiming at the case where the rotor parameters and stator parameters are 100 and 50% mismatched, the proposed FCS-MPCC is also effective to improve the system control performance.

Fig. 2.17 Steady-state performance of the machine when incorporating the proposed SMO at the speed of 40 rad/s. **a** No-load-condition disturbances; **b** Rated-load-condition disturbances; **c** No-load-condition performance; **d** Rated-load-condition performance

Fig. 2.18 Steady-state performance of the machine when incorporating the proposed SMO at the speed of 80 rad/s. **a** No-load-condition disturbances; **b** Rated-load-condition disturbances; **c** No-load-condition performance; **d** Rated-load-condition performance

Fig. 2.19 Steady-state performance of the machine when incorporating the proposed SMO at the speed of 110 rad/s. **a** No-load-condition disturbances; **b** Rated-load-condition disturbances; **c** No-load-condition performance; **d** Rated-load-condition performance

Table 2.3 Comparison of static errors and M -axis current ripple before and after employing SMO

Speed (rad/s)	Speed static error (rad/s)		Flux static error (Wb)		Ripples of i_{sM} (A)	
	Before	After	Before	After	Before	After
40	1	0	0.001	0.0003	1.4	0.5
	0.8	0.15	0.001	0.0001	1.5	0.5
80	1.5	0.1	0.002	0.0001	1.55	0.54
	1.2	0	0.001	0	1.6	0.5
110	1.7	0.5	0.001	0.0002	1.61	0.37
	1.3	0	0.0012	0.0002	1.63	0.55

2.5 Summary

In order to improve the robustness of the FCS-MPCC methods in the IM applications, this Chapter proposes a new SMO to diagnose and compensate the real-time disturbances caused by parameter mismatch. The main contributions of this chapter are as follows.

- (1) After establishing the predicting model for IMs, the M, T-axis disturbances caused by parameter mismatch are analyzed theoretically for the traditional FCS-MPCC strategy. It is found that, apart from the parameter deviations, the disturbances are also closely related to the machine working states, such as speed and currents.
- (2) In order to eliminate the impacts of the disturbances, a SMO observer based on hyperbolic function is developed. It deserves to be mentioned that the hyperbolic function is pretty novel, and the stability analysis procedures introduced in this chapter for this kind of SMO is new.
- (3) After incorporating the SM disturbance observer into the FCS-MPCC control implementations, the speed and flux static errors are significantly reduced. Meanwhile, the current ripples witness a visible decrease. These prove that the proposed FCS-MPCC strategy is effective in IM applications.

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