Composite Decoupling Control of PMSM Based on Extended State Observer

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Abstract. In order to solve the problem that the dynamic decoupling performance of the traditional decoupling method is reduced due to the parameter disturbance of permanent magnet synchronous motor (PMSM), a composite decoupling control method based on extended state observer (ESO) is proposed in this paper. In this method, voltage drop across stator resistance, cross coupling terms, internal uncertain and external load torque are taken as disturbances. The disturbance is observed in real time by using the extended state observer and compensated to the output end of the current controller, so as to realize the current decoupling control of the system and achieve the purpose of precise control of the current loop. The results of theoretical analysis show and simulation show that the composite decoupling control strategy based on extended state observer has better dynamic decoupling effect.

1. Introduction

Permanent magnet synchronous motor is widely used in various fields. However, if the compensation is not ideal, the performance of the motor control system will be reduced due to the cross-coupling term between the two subsystems of d and q axis. In Chunpeng Li[1], the change of inductance parameters and the error of voltage were taken as the system disturbances, and the disturbance observer was adopted for observation and combined with the deviation decoupling control. In Yanwei Huang[2], interference observer is introduced into internal model control, and voltage error caused by coupling, changes in load torque and motor parameters are regarded as interference of the system. In Thieli S.Gabbi[3], disturbance observer is introduced on the basis of current decoupling control. The coupling term of the motor and the voltage error are regarded as the interference of the system, and the observer is used to observe and these interference. In Rachid[4], based on the model predictive control, the designed disturbance observer is introduced to realize the dynamic decoupling of the system and improve the prediction accuracy under the condition of parameter change.

Although the decoupling control of current loop is realized in the above papers, only the variation of parameter is observed as disturbance. And in this paper, the composite decoupling control based on extended state observer, voltage drop across stator resistance, cross coupling terms, internal uncertain and external load torque are taken as disturbances, real-time observation and compensation using the
extended state observer, and combined with deviation decoupling, so as to realize the compensation of
coupling terms, achieve the goal of dynamic decoupling.

2. Deviation decoupling control

The composite decoupling control proposed in this paper combines the deviation decoupling with the
extended state observer. The deviation decoupling is to introduce the external decoupling branch at the
position of given value and feedback value of the current loop, so as to cancel the influence of the
coupling term and realize the decoupling control of the system. The structure of decoupling control is
shown in ‘figure 1’:

![Figure 1 Deviation decoupling structure diagram](diagram)

From ‘figure 1’, the relationship between the given current value and the feedback value can be
obtained as follows:

\[
\begin{bmatrix}
    i_d(s) \\
    i_q(s)
\end{bmatrix}
= \begin{bmatrix}
    C_{dd}(s) & C_{dq}(s) \\
    C_{qd}(s) & C_{qq}(s)
\end{bmatrix}
\begin{bmatrix}
    i_d(s) \\
    i_q(s)
\end{bmatrix}
\]

(1)

and:

\[
C_{dq}(s) = -C_{qd}(s) = \frac{G(s)\omega L - G_1(s)(R + Ls)}{[R + Ls + G(s)]^2 + [G_1(s) + \omega L]^2}
\]

\[
C_{dd}(s) = C_{qq}(s) = \frac{G(s)[R + Ls + G(s)] + G_1(s)[G_1(s) + \omega L]}{[R + Ls + G(s)]^2 + [G_1(s) + \omega L]^2}
\]

\[
G_1(s) = \frac{\omega L G(s)}{R + Ls}
\]

\[\hat{L}\]

\[L\]

\[C_{dd}(s)\] and \[C_{qq}(s)\] represent the direct transfer function of the d-axis and q-axis current
controllers; Where \[C_{dq}(s)\] and \[C_{qd}(s)\] represent the transfer function of the dynamic decoupling term of
the d-axis and q-axis current controllers; \[G(s)\] represents the transfer function of the proportional
integral controller; \[G_1(s)\] represents the transfer function of the decoupling controller; \[\hat{L}\] represents the
estimated value of d-axis and q-axis inductance \[L\]; It can be obtained by the formula, when the
estimated inductance value is equal to the actual value, when \[\hat{L} = L\], \[C_{dq}(s) = -C_{qd}(s) = 0\] indicates
that the dynamic decoupling term of the current controller is zero, and the system is completely
decoupled; If the estimated inductance value is different from the actual inductance value, \[\hat{L} \neq L\], the
transfer function of the coupling term is none zero, indicating that the system is not completely
decoupled.
3. Eso-based composite decoupling control

3.1. Design of the ESO

During the actual operation of the motor, the parameters will be mismatched to some extent due to the change of temperature. In this paper, the stator resistance $R$, d-axis inductance $L_d$, q-axis inductance $L_q$, internal uncertainty disturbance and external disturbance are regarded as total disturbance. Let’s call it $d_d$ and $d_q$:

\[
\begin{align*}
\dot{d}_d &= \Delta R_i + \Delta L_d \frac{di_d}{dt} - \omega_e \Delta L_q i_q + \varepsilon_d \\
\dot{d}_q &= \Delta R_i + \Delta L_q \frac{di_q}{dt} - \omega_e (\Delta L_d i_d + \Delta \psi_f) + \varepsilon_q
\end{align*}
\]  

(2)

$\Delta R$, $\Delta L_d$, $\Delta L_q$ and $\Delta \psi$ represent the deviation between the actual value and the rated value of the corresponding parameter respectively; $\varepsilon_d$ and $\varepsilon_q$ represent the external disturbance and the equivalent unmodeled part respectively. ESO corresponding to d-axis and q-axis are designed respectively, voltage drop across stator resistance, cross coupling terms, internal uncertain and external load torque are taken as total disturbances and represented by $f_d$ and $f_q$. Since ESO of d-axis and q-axis have the same form, taking d-axis as an example. The total disturbance term was observed as the system's extended state variable. In order to obtain the observed value of the expansion state variable, the ESO of axis d was designed as follows:

\[
\begin{align*}
e_d &= \hat{i}_d - i_d \\
\hat{i}_d &= f_d - \beta_1 f_d (e_d, \alpha_1, \delta_1) + b_u u_d \\
f_d &= -\beta_2 f_d (e_d, \alpha_2, \delta_2)
\end{align*}
\]  

(3)

$u_d$ represents the input of the d-axis observer, $i_d$ is the output of the D-axis observer, $\hat{i}_d$ represents the estimated output of the d-axis observer, $\hat{f}_d$ represents the disturbance estimate of the d-axis observer. In addition, from equation (3) that d-axis ESO is not disturbed by q-axis, and the two observers are independent of each other and do not interfere with each other, which is beneficial to realize decoupling control.

3.2. Composite decoupling control based on ESO

In the design process of the control system, $b_d = 1/L_d$, $\gamma_d$ and $\gamma_q$ are regarded as the disturbance items in the d-axis and q-axis subsystems respectively, which are observed and compensated by the observer. By combining observer and deviation decoupling, the ESO-based composite decoupling structure of PMSM can be obtained, as shown in “figure. 2”:

![Figure 2 ESO-based composite decoupling structure diagram](image)
The control block diagram in ‘figure. 2’ can be mathematically expressed as follows:

\[
\begin{align*}
(i_d^* - \hat{i}_d)K_p - \frac{\hat{f}_d}{b_d} &= - \frac{f_d}{b_d} + \frac{i_d}{b_d} + \frac{i_q}{b_q} s \\
(i_q^* - \hat{i}_q)K_p - \frac{\hat{f}_q}{b_q} &= - \frac{f_q}{b_q} + \frac{i_d}{b_q} + \frac{i_q}{b_q} s
\end{align*}
\]

(4)

When the observer work perfectly, \(i_d = \hat{i}_d, i_q = \hat{i}_q, f_d = f_d, f_q = f_q\). Then equation (4) can be re-expressed as:

\[
\begin{align*}
\hat{i}_d &= \frac{K_p b_d}{s + K_p b_d} i_d \\
\hat{i}_q &= \frac{K_p b_q}{s + K_p b_q} i_q
\end{align*}
\]

(5)

Because the proportional control coefficient \(K_p > 0\) and \(b_d > 0\), the output of the closed-loop control system can track the input, it is convergent, and the system is stable.

4. Comparison of simulation results

In order to verify the effectiveness and feasibility of the composite decoupling control strategy based on extended state observer, the models of internal model control decoupling system, deviation decoupling control system and composite decoupling control are built in MATLAB/Simulink, and the d-axis current and speed waveforms of these three control strategies are analyzed. For comparison, PI controller of speed loop are tuned with same parameters, in which the proportional coefficient is 0.35 and the integral coefficient is 50. The motor is operated under sudden load increase and decrease, which increases from no-load to full load in 0.2 seconds and decreases from full load to no-load in 0.3 seconds. By studying the dynamic process of d-axis current when q-axis current changes, the dynamic decoupling effect of current loop of three control strategies is reflected. And permanent magnet synchronous motor parameters are: \(R_s=0.958\Omega, L_d=5.25\text{mH}, L_q=12\text{mH}, \phi_f=1.0962\text{Wb}\).

4.1. With matched motor parameter

The given speed of the motor is 1000r/min, and the load is increased and decreased suddenly under the condition with matched motor parameter ‘figure.3’ shows the d-axis currents of the three control strategies respectively. It can be seen from the waveform that the decoupling effect of the three current subsystems is good when the motor parameters of the three are matched. That is, when system load suddenly change its amplitude at 0.2s and 0.3s, and the d-axis current has almost no fluctuation and is not affected by the change of motor parameter. According to the speed waveform in ‘figure.4’, the recovery time of the three control strategies is almost the same when the motor is loading and unloading, but composite decoupling control presented in this paper exhibits the smallest dynamic speed drop among the three, that is the best dynamic performance.
4.2. With mismatched motor parameter

A. When the actual value of the motor parameter inductance is 0.7 times the rated value, given is still 1000r/min, the motor is operated under same abrupt load and unloading as 4.1. ‘Figure. 5’ shows the d-axis current of the three control strategies. It can be seen that the d-axis current controlled by internal mode decoupling fluctuates obviously when the sudden loading and unloading at 0.2s and 0.3s. The amplitude of d-axis current fluctuation of the deviation decoupling control is less than that of the internal mode decoupling control. In the composite decoupling control, the d-axis current fluctuates within the amplitude of 0.5A, and the overall trend is a straight line. When the load changes, the current does not exceed the fluctuation amplitude of the mutation. According to the speed waveform in ‘figure.6’, the recovery time of the three control strategies is almost the same when the motor is loading and unloading, but composite decoupling control presented in this paper exhibits the smallest dynamic speed drop among the three, that is also the best dynamic performance.

B. When the actual value of the motor’s inductance is 1.3 times the rated value, the given speed again is 1000r/min, the motor is operated under same abrupt load and unload as 4.1. ‘Figure.8’ shows the $i_d$ of the three control policies. It can be seen that at 0.2s and 0.3s, the d-axis current controlled by internal mode decoupling fluctuates significantly, and the decoupling effect is not ideal. The q-axis current controlled by deviation decoupling basically appear small fluctuation. However, the current waveform controlled by composite decoupling has almost no fluctuation, and the decoupling effect is better. According to the speed waveform in ‘figure. 9’, the composite decoupling control still maintains the optimal dynamic performance.
5. Conclusion
Through the above theoretical analysis and simulation results, the following conclusions can be drawn: in the case of motor parameters matching, the internal mode decoupling control and the deviation decoupling control have the same dynamic performance, and the dynamic performance of the composite decoupling presented in this paper is better than the former two. All three control methods can fully compensate the coupling terms of the current subsystem. When motor parameters do not match, the dynamic performance of composite decoupling control is better than the former two. And the internal model decoupling control can not fully realize the dynamic decoupling of the system, and the decoupling effect of composite decoupling control is better than that of deviation decoupling control. In the design of the observer, the variation of parameters, internal disturbance and external disturbance are taken as the observation compensate, which not only improves the robustness under system parameter disturbance, but also improves the immune performance to external disturbance of the whole system.

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