Speed identification and control for permanent magnet synchronous motor via sliding mode approach

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In this paper, speed identification and control problems are simultaneously considered for a permanent magnet synchronous motor (PMSM) based on the sliding mode technique. To eliminate the mechanical sensors, an observer is designed to identify the speed of PMSM based on a variable-structure model reference adaptive system, in which a sigmoid function with an adaptive gain is applied to replace the conventional signum function to cope with the chattering problem caused by the discontinuous switch function. Then, a sliding mode speed regulator is developed to overcome the limitations of traditional proportion integration scheme. Desired flexibility, adaptability and high precision are obtained and the stability of the closed-loop system is guaranteed by the proposed strategy. The results of simulation by MATLAB/Simulink indicate that the speed could be estimated and adjusted precisely, and the dynamical property of system is evidently improved.

Keywords: variable-structure MRAS; speed identification; sliding mode regulator; PMSM

1. Introduction

Recently years, the permanent magnet synchronous motor (PMSM) has been widely employed in our life and industrial control because of its several inherent advantages. Generally speaking, high-precision and high-resolution sensors are necessary to obtain accurate position and speed information to control PMSM precisely. While, speed or position sensors require the additional mounting space, increase the cost and the complexity of the system as well as reduce the reliability of the system. In addition, these sensors cannot be used or installed in some serious industrial environments. Therefore, a lot of researchers have paid their considerable attentions to sensorless control of PMSM and many excellent control techniques have been explored. Here, we introduce several significant sensorless control methods. The earliest one is the stator flux estimation method which is with simple structure and quick dynamic response (French & Acarnley, 1996; Senju, Shimabukuro, & Uezato, 1995). However, the accuracy of the results cannot be guaranteed since it is essentially an open-loop method. Subsequently, the model reference adaptive system (MRAS) method has widely been applied in the estimation of rotor position and speed in PMSM drives (Maiti, Chakraborty, Hori, & Ta, 2008; Maiti, Chakraborty, & Sengupta, 2009) due to its easy implementation, the shortcoming of which is that the estimated results depend greatly on motor parameter correctness. The extended Kalman filter is also an important choice (Islam, Husain, & Fardoun, 2009; Kaux & Fadel, 2005). On the one hand, it is less influenced by measurement noise and requires less accuracy of parameters, on the other hand, it is hard to apply in practical engineering on account of computationally intensive and time consuming. The sliding mode estimate and control problems for all kinds of systems have extensively been researched for a long time (Comanescu & Xu, 2006; Eom, Kang, & Lee, 2008; Han, Choi, & Kim, 2000; Kang, Kim, Hwang, & Kim, 2004) and employed in PMSM motor control problems. The robustness of this method is attractive, however the serious chattering phenomenon due to the discrete switch control influences its application.

The MRAS method first proposed by C. Schauder has been widely used in motor control owing to its advantages, such as simple structure and easy to implement via programmable digital devices (Schauder, 1992). The unknown speed of rotor can be estimated by the adaptive law of this method to track the reference model according to error between the state variables of the reference model and the adjustable model. However, the MRAS method heavily depends on the accuracy of the model parameters and the variation of the reference model would reduce the precision of this method. Consequently, a kind of MRAS approach combined with the idea of sliding mode control has been exploited for speed identification of motors, see, e.g. Yan, Lin, Li, and Li (2009), Young, Sang, and Young (2003), and Kojabadi and Ghribi (2006). In the above-mentioned articles, the signum function is applied as the switching

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function suffering from chattering. Due to the chattering, the estimated signals of the observer contain high frequency oscillation components which can excite high frequency dynamic performance. Thus, this cannot meet the control requirements of high-performance applications.

The classical proportion integration differentiation (PID) controller is an important technique to adjust motor current, speed and position in PMSM vector control strategy (Swierczynski & Kazmierkowski, 2002). However, PID control is not very effective because of the non-linearity characteristics of PMSM. As to this problem, many advanced control methods have been developed to enhance the robustness of the system, such as adaptive control (Li & Liu, 2009; Mohamed, 2006), fuzzy control (Cheng & Tzou, 2004), and neural network approach (Orlowska-Kowalska, Dybkowski, & Szabat, 2010), especially, sliding mode variable-structure control (Kawamura, Itoh, & Sakamoto, 1994). The sliding mode variable-structure control was first proposed by the former Soviet Union scholars Emelyanov and Utkin in the 1960s (Utkin, 1977). In the years since then, it has attracted a great number of researchers and a lot of academic achievements have been published, see, e.g. Hu, Wang, and Gao (2012a), Hung, Gao, and Hung (1993), Hu, Wang, Niu, and Stergioulas (2012), Hu, Wang, and Gao (2012b), Niu, Jia, and Huang (2012a), and Niu, Jia, and Huang (2012b). This method is an important controller design method in control area, such as robot manipulators, aircraft, electrical motors and automotive engines, and at present, it has become an independent research branch. It is not necessary for this method to know accurate mathematical model of the system and their possible varying ranges. In addition, a great advantage of the sliding mode control is that once the sliding mode takes place, the system performance becomes insensitive to the system parameter variations and external disturbances. However, in the traditional variable-structure control, the discontinuity signum function is used as the control function and hence a serious chattering problem is given rise to reduce the accuracy. In this paper, in order to reduce system chattering phenomenon, a continuous sigmoid function with an adaptive gain is chosen.

Summarizing the discussion made by far, in this paper, we aim to employ a MRAS method combined with the idea of sliding mode control to deal with the speed identification problem for a type of PMSM without position sensors. On the other hand, a speed regulator is developed by the sliding mode control method to make up the shortcomings of speed proportion integration (PI) regulator to a certain extent. The main contributions are as follows: (1) a sigmoid function is applied in the variable-structure MRAS method instead of the conventional signum function which easily leads to chattering problem; (2) the fixed constant gain of the control law is replaced by an adaptive gain according to the motor speed to weaken the chattering phenomenon; and (3) both the speed observer and speed controller are constructed by the sliding mode control method. Finally, the effectiveness and feasibility of this method are illustrated by simulation experiments.

2. Model description

In this paper, based on the assumptions: (i) saturation, eddy currents and hysteresis losses are neglected; (ii) the back emf is sinusoidal; (iii) there is no damping windings on the rotor; and (iv) the permanent magnet conductivity is zero, we have the following PMSM model in the synchronously rotating reference frame:

$$\frac{di_d}{dt} = \frac{R}{L} i_d + \omega i_q + \frac{u_d}{L}$$  \hspace{1cm} (1)

$$\frac{di_q}{dt} = \frac{R}{L} i_q - \omega i_d - \frac{\psi_f}{L} \omega + \frac{u_q}{L}$$  \hspace{1cm} (2)

$$\frac{d\omega}{dt} = \frac{3p^2 \psi_f}{2J} i_q - \frac{B}{J} \omega - \frac{p}{J} T_L,$$  \hspace{1cm} (3)

where $i_d$, $i_q$, and $u_d$, $u_q$ are $d$-axis and $q$-axis stator currents and stator voltages, respectively, $R_s$ is the stator phase resistance, $L$ is the stator phase inductance, $\psi_f$ is the permanent magnet rotor flux linkage, $\omega$ is the electrical rotor angular velocity, $p$ is the number of pole pairs, $J$ is the rotor equivalent inertia, $B$ is the viscous friction coefficient, and $T_L$ is the load torque.

It is easy to see that Equations (1) and (2) can be rewritten as

$$\frac{d}{dt} \left[ \frac{i_d + \psi_f}{L} \right] = \begin{bmatrix} \frac{R}{L} & \omega \\ -\omega & -\frac{R}{L} \end{bmatrix} \begin{bmatrix} i_d + \psi_f \\ i_q \end{bmatrix}$$

$$+ \begin{bmatrix} \frac{u_d + \psi_f}{L} \\ u_q \end{bmatrix}.$$  \hspace{1cm} (4)

Set $i_d' = i_d + (\psi_f/L)$, $i_q' = i_q$, $u_d' = u_d + (R\psi_f/L)$ and $u_q' = u_q$, we can obtain

$$\frac{d}{dt} \begin{bmatrix} i_d' \\ i_q' \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & \omega \\ -\omega & -\frac{R}{L} \end{bmatrix} \begin{bmatrix} i_d' \\ i_q' \end{bmatrix} + \frac{1}{L} \begin{bmatrix} u_d' \\ u_q' \end{bmatrix}.$$  \hspace{1cm} (5)

Equation (5) can be expressed in a compact matrix form as

$$\frac{d}{dt} x = Ax + bu,$$  \hspace{1cm} (6)

where

$$A = \begin{bmatrix} -\frac{R}{L} & \omega \\ -\omega & -\frac{R}{L} \end{bmatrix}, \quad x = \begin{bmatrix} i_d' \\ i_q' \end{bmatrix}, \quad b = \frac{1}{L}, \quad u = \begin{bmatrix} u_d' \\ u_q' \end{bmatrix}.$$
the reference model is the actual motor. Then, define the estimator as
\[
\frac{d}{dt} \hat{x} = \hat{A} \hat{x} + b u,
\]
where \( \hat{\omega}, \hat{i}_d', \) and \( \hat{i}_q' \) are the estimate of \( \dot{i}_d' \) and \( \dot{i}_q' \), respectively and
\[
\hat{A} = \begin{bmatrix} -\frac{R}{L} & \frac{1}{L} \\ -\frac{1}{L} & -\frac{R}{L} \end{bmatrix}, \quad \hat{x} = \begin{bmatrix} \hat{i}_d' \\ \hat{i}_q' \end{bmatrix}.
\]

The estimate error is defined as \( e = x - \hat{x} \), and from Equations (6) and (7), we have
\[
\frac{d}{dt} e = A x - \hat{A} \hat{x} = A e + \Delta \omega Q \hat{x},
\]
where
\[
\Delta \omega = \omega - \hat{\omega}, \quad Q = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}.
\]

In this paper, our main aim is to design an observer to identify the speed variable for the considered PMSM model (1) based on a variable-structure MRAS method and a regulator to control the motor speed by using a sliding mode control approach.

3. Design of speed identifier and regulator

3.1. Speed identifier design

Design the following sliding mode surface:
\[
S = e^T Q \hat{x} = i_d' \hat{i}_q' - \hat{i}_d i_q',
\]
then, the dynamics of the sliding mode function is expressed as
\[
\dot{S} = e^T Q \hat{x} + e^T Q \dot{x} = (\omega - \hat{\omega}) x^T \dot{x} - \frac{2R}{L} e^T Q \hat{x} + e^T Q b u.
\]

The following sigmoid function is chosen as the switching function:
\[
F(S) = \frac{2}{1 + e^{-aS}} - 1,
\]
where \( a \) is a positive constant used to regulate the slope of the sigmoid function. Hence, the speed identifier (i.e. the sliding mode control law) is written as
\[
\dot{\hat{\omega}} = M F(S).
\]

Remark 1 In the conventional sliding mode variable-structure control, the following constant switching control law is most commonly used:
\[
\dot{\hat{\omega}} = M \text{sgn}(S),
\]
where \( \text{sgn}(S) \) is the signum function, see, e.g. Lei, Li, and Lei (2009) and Wang, Zhang, and Zhang (2008). According to this constant switching control law, the stator current error \( e \) is fed into the Bang–Bang control, which easily causes a severe chattering problem since the Bang–Bang control with a signum switching function is a discontinuous control. In this paper, the signum function is replaced by a continuous sigmoid function to reduce the chattering phenomenon.

In the following theorem, the reachable performance and the stability of the error states in terms of the designed speed identifier is discussed.

**Theorem** Consider the stator current error system (8) and the sliding mode surface (9). The estimated speed converge to the reference value accurately according to the designed speed identifier (12). The reachable condition is satisfied and the stator current error system is stabilized, as long as
\[
M > \left| \frac{\omega - (x^T \dot{x})^{-1} \left( \frac{2R}{L} e^T Q \hat{x} - e^T Q b u \right)}{1} \right|.
\]
is satisfied.

**Proof** Choose the following Lyapunov function:
\[
V(S) = \frac{1}{2} S^2.
\]
From Equations (10) and (12), we have
\[
\dot{V}(S) = S \dot{S} = S \left( \omega x^T \dot{x} - MF(S)x^T \dot{x} - \frac{2R}{L} e^T Q \hat{x} + e^T Q b u \right).
\]

Because \( x^T \dot{x} > 0 \), if there is a big enough positive integer \( M \) to satisfy Equations (14), we have \( \dot{V}(S) < 0 \). This complete the proof.

However, it will increase the chattering noise when \( M \) is too large. In particular, it does not need a large gain when the motor velocity is small at the beginning of motor starting. Hence, the adaptive law about \( M \) is designed as
\[
M = m \omega_{a},
\]
where \( m \) is a positive constant, \( \omega_{a} \) is determined heuristically and can be written as
\[
\omega_{a} = \begin{cases} 10, & \hat{\omega} \leq 10, \\
\hat{\omega}, & \hat{\omega} > 10,
\end{cases}
\]
where \( \hat{\omega} \) is the estimated speed.

Consequently, we can get the algorithm block diagram of sliding mode MRAS speed identification that is shown in Figure 1.
3.2. Speed controller design

Choose the state variables of PMSM system as follows:

\[ x_1 = \omega^* - \omega, \]
\[ x_2 = \dot{x}_1 = -\dot{\omega}, \]

where \( \omega \) is the estimated speed and \( \omega^* \) is the reference speed.

From Equation (3), we can obtain

\[ \dot{x}_1 = -\dot{\omega} = -\frac{p}{J} \left[ \frac{3}{2} p \psi_f i_q - T_L \right], \]
\[ \dot{x}_2 = -\ddot{\omega} = -\frac{3 p^2}{2 J} \dot{\psi}_f i_q. \]  

(20)

Ignore the influence of damping coefficient \( B \), and set \( a = -\left( \frac{3 p^2 \psi_f}{2 J} \right) \), \( d = \dot{i}_q \), Equation (20) can be expressed as

\[ \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ -a \end{bmatrix} d. \]

(21)

The typical sliding mode surface is chosen as follows:

\[ S = cx_1 + x_2, \quad c > 0 \]

(22)

Moreover, in order to improve the dynamic performance of the system in normal movement stage, we choose variable exponential rate reaching law (Zhang & Panda, 1999)

\[ \dot{S} = -\eta |X| \text{sgn}(S) - kS, \quad X = x_1, \]
\[ \lim_{t \to \infty} |X| = 0, \quad k > \eta > 0. \]

(23)

With the above variable exponential rate reaching law, the performance of reaching segment is improved, the system reaches the sliding surface quickly and the chattering of the system is also eliminated when the state is close to the sliding mode surface. Then, the state of the system can be guaranteed to converge to the origin finally.

From the partial derivative of Equations (22) and (23), the output of the speed controller can be obtained

\[ i_q = \frac{1}{d} \int (\eta |X| \text{sgn}(S) + kS + cx_2) \, dt. \]

(24)

To reduce the chattering phenomenon of the system when the speed is stable, the smoothing function is utilized in switching controller to replace the discontinuous signum function

\[ \text{sgn}(S) = \frac{S}{|S| + \sigma}, \]

where \( \sigma \) is a small positive constant.

In order to verify the stability of the aforementioned sliding mode controller, the Lyapunov function is chosen as

\[ V = \frac{S^2}{2}, \]

and the sliding mode exists if

\[ \dot{V} = SS \leq 0. \]

(27)

From Equation (23), we have

\[ \dot{S} = S(-\eta |X| \text{sgn}(S) - kS). \]

(28)

Obviously Equation (28) is less than or equal to zero because of \( k > \eta > 0 \). Thus, the system is guaranteed to enter into the sliding mode and be stable.

Finally, the block diagram of whole motor system is shown in Figure 2. Among the block diagram, the speed feedback value and rotor electrical angle value are obtained from the sliding mode MRAS speed observer, and the speed controller is sliding mode controller.

Remark 2 The algorithm structure of the speed observer has been described in detail in Figure 1 and Figure 2 shows each step of the whole motor system which is based on sensorless vector control combining with sliding mode control theory. Then, the following simulation model in Section 4 is established according to Figures 1 and 2. From the simulation results, the proposed strategy has the characteristic of quick convergence, also its estimated precision is highly. Moreover, nowadays, along with the quick development of digital signal processors, complex control strategies can be possible implemented.

4. Simulation results

In this paper, the simulation model is established under the circumstance of MATLAB/Simulink according to the
established mathematic model, and the simulation model is shown in Figure 3.

The parameters of this motor control system in Figure 3 are chosen as: the $d$-axis current PI regulator ($K_p = 15, K_i = 2000$), the $q$-axis current PI regulator ($K_p = 15, K_i = 2000$), the sliding mode speed regulator ($\eta = 5, c = 200, \sigma = 0.01, k = 100$) and the sliding mode MRAS observer ($m = 1000, \epsilon = 0.01$). The parameters of PMSM used in this simulation model are as follows:

| Parameters                      | Value     |
|---------------------------------|-----------|
| Stator resistance $R_s$         | 2.875Ω    |
| Stator inductance $L$           | 8.5 mH    |
| Permanent magnet rotor flux linkage $\varphi_f$ | 0.175 Wb |
| Number of pole pairs $p$        | 4         |
| Rotor equivalent inertia $J$    | 0.001 kg · m² |
| Viscous friction coefficient $B$ | 0 N · m · s |
| Inverter switching frequency   | 20 kHz    |

Then, the effectiveness and practicability of the speed observer and controller for the motor control system are proved by two groups simulation experiments under the conditions of the reference speed variation and load torque variation. Figures 4–6 show the responses of the motor speed, current, and torque when $\omega^*$ changes from 1500 to 600 r/min at $t = 0.25$ s under the condition that $T_L$ is always 1 N · m. Figures 7–9 show the responses of the motor speed, current, and torque when $T_L$ changes from 1 to 5 N · m at $t = 0.25$ s under the condition that $\omega^*$ is always 1500 r/min.

As can be seen from Figures 4 and 7, the speed observer designed in this paper can accurately estimate the motor real speed and track the speed quickly when the reference speed changes. When the outside load torque changes, the motor speed can be fed into a stable state in a very short time. Figures 5, 6, 8 and 9 show the responses of three-phase current and torque of the motor also have a good
Figure 6. Torque response when $\omega^*$ varies from 1500 to 600 $r/min$ at $t = 0.25$ s.

Figure 7. Speed response when $T_L$ varies from 1 to 5 N·m at $t = 0.25$ s.

Figure 8. Current response when $T_L$ varies from 1 to 5 N·m at $t = 0.25$ s.

Figure 9. Torque response when $T_L$ varies from 1 to 5 N·m at $t = 0.25$ s.

dynamic performance when the reference speed and load torque change.

5. Conclusions

In this paper, a variable-structure MRAS speed observer is designed to avoid the installation of the mechanical sensor. To reduce system chattering, a sigmoid function with an adaptive gain is employed as a continuous control in variable-structure control instead of the traditional signum function. Secondly, the conventional speed PI actuator is replaced by a sliding mode controller. It makes up the shortcomings of speed PI regulator to a certain extent. Finally, the reasonability and validity of this method have been testified by the simulation results. The simulation results show that this speed observer can track the reference speed rapidly and precisely when the reference speed and load torque change, and the three-phase current and torque of the motor also have a good dynamic response. Obviously, simulation results indicate that the proposed control scheme eliminates the speed overshooting, and holds the advantages of fast response and strong robustness. In the future, the experimental study will be further proceeded to prove the designed method exactly and practicably.

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