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A Comparison Research on Sliding Mode Observation Methods for SPMSM in Sensorless Environment of Medium-to-High Speed

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Abstract: Aiming at sensorless control system of surface attached permanent magnet synchronous motor (SPMSP), three observation algorithms proposed in recent years to estimate rotor position and speed under medium-high speed operation were introduced in this paper. The working principles, advantages and disadvantages of these algorithms such as the Extended Kalman filter algorithm (EKF), Model Reference Adaptive System (MRAS) and Sliding Mode Observer (SMO) were compared, and the applicability of these three algorithms on SPMSP at present was compared and summarized. Furthermore, a sensorless control strategy based on improved SMO was designed to ensure sensorless control effect under medium-high speed operation of SPMSM.

1. Introduction

Permanent magnet synchronous motor (PMSM) has become a research focus in many fields due to its advantages of high control accuracy, fast dynamic response and large speed regulation range, and has unlimited development potential especially in the fields of UAV and electric vehicle [1]. Field Oriented Control (FOC) is generally adopted in electric vehicles to achieve highly standardized control of PMSM with the characteristics of torque ripple and noise. PMSM is a time-varying system with nonlinear coupling, which is mainly used to drive normal running motors and air conditioning compressors [2]. Traditional PMSM relies on mechanical sensors such as photoelectric encoders and rotary transformers to measure the position and speed of the motor, so as to achieve closed-loop control of speed and position with high precision and dynamic performance. Compared with mechanical rotor position sensor system, the sensorless control technology is a breakthrough. To obtain the rotor position and speed information, it processes and calculates the sampled current, voltage and other physical quantities through software programming [3-4], which not only effectively reduces the system cost, volume and complexity of hardware design, but also improves the reliability of the control strategy of the full set of drive systems. Therefore, the sensorless control technology has attracted much attention in the industry, and the algorithm driven by sensorless has also become a research hotspot of PMSM control strategy at present.

In medium-to-high speed operation mode, the effective signal-to-noise ratio (SNR) control of the motor for electric vehicle has a very high requirement. In order to achieve the optimal efficiency mode with the high SNR and high torque ripple under the vector control [5], the control algorithm and initial position estimation for detecting rotor angle under medium-to-high speed operation mode of PMSM have become the focus of current research. The sensorless control technology of PMSM is based on the mathematical model of KIPPO subjected to the back electromotive force for motor to detect the rotor position and speed information. The algorithm has advantages and disadvantages in different applications. In view of this, this paper takes the control strategy selection of the surface attached permanent magnet synchronous motor (SPMSM) as the object, and describes and designs several commonly used algorithms. And then, the measurement algorithm and estimation accuracy of rotor position are compared and analyzed.

2. Sensorless control method of motor in medium-to-high speed

In medium-to-high speed, the observer method suitable for the sensorless control is to observe the rotor position and speed by constructing an observer based on the certain algorithms and the information such as motor voltage, rotor flux and torque [6]. The observer method is the most effective sensorless control of SPMSM. However, the noise and measurement error exist in the operation process of SPMSM. Although the open-loop observer method has simple principle and fast dynamic response, it is easy to be affected by the change of motor parameters, leading to the low algorithm stability. Currently, the closed-loop algorithms applicable to observer method mainly include the methods such as the Extended Kalman Filter (EKF), Model Reference Adaptive System (MRAS), Sliding Mode Observer (SMO) and so on [7]. SMO is an indirect detection calculation method based on the mathematical model of the fundamental wave for motor. Its internal state is determined, which can effectively avoid the large deviation problem existing in the open-loop measurement method. The sensorless SPMSM based on the above-mentioned algorithms can greatly improve the observation accuracy of the rotor position and the stability of the system.

2.1. EKF algorithm

EKF is an optimal prediction estimation based on minimum variance, and is also a nonlinear estimation method based on iterative algorithm. Its outstanding feature is that it can effectively suppress the influence of random interference and measurement noise. The principle of SPMSM sensorless system design based on EKF is that the position and speed of the motor rotor are estimated online by using the previously mentioned observer [8], or to be more exact, the mathematical model of dynamic characteristics for SPMSM is described by measuring the voltage and current parameters in the motor rotor, and the rotor position information is estimated by using the algorithm realized by software programming. The designed control block is shown in Figure 1. As can be seen from Figure 1, in vector control strategy of SPMSM system, the value i_d is set as 0, the instruction value i_d^* of the direct axis current is 0, the estimation of direct axis current for EKF is input into PI regulator as feedback value [9], and the output is the given value of system for the direct axis voltage of motor. According to the SVPWM control technology, the two given values of the control voltages are used to generate PWM control signal, and the inverter bridge can be controlled to drive the operation of SPMSM.

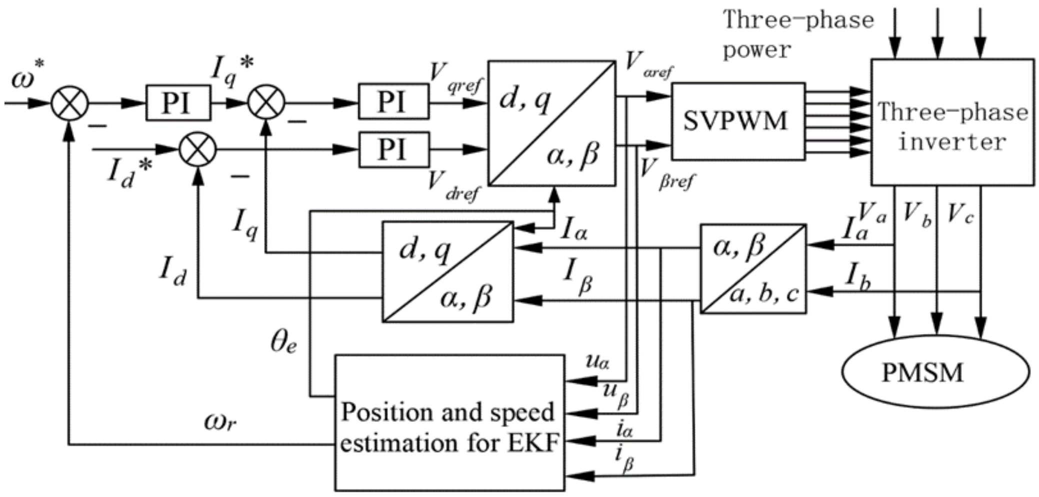

Figure 1: Design block of sensorless control system of three-phase SPMSM for EKF.

In Figure 1, the voltages μ_α and μ_β in the input EKF module is the command values of the input module SVPWM, which can truly reflect the voltage at the motor terminal, and avoid the measurement error during voltage measurement, improving the control accuracy of system. And the input currents i_α and i_β is obtained by the coordinate change of the phase currents i_A and i_B, so as to the EKF does not require accurate initial conditions to achieve stable convergence of the observer and better realize sensorless direct control [10]. The key of Kalman Filtering is to select coefficient values to obtain the best possible position estimation performance, and its calculation process includes prediction, correction and Kalman gain parts [11]. Its prediction part can be expressed as follows

$$\begin{cases} xe_\alpha = xe_\beta + [F(xe_\beta)xe_\beta] + B(u_{k-1})]T_c \\ P_\alpha = P_\beta + (F_{k-1}P_\beta + P_\beta F'_{k-1})T_c + Q_d \end{cases} \tag{1}$$

where α equals to $k \mid k$-1, and β equals to k-1 | k-1. The correction and Kalman gain parts can be calculated in the following form.

$$\begin{cases} xe_\gamma = xe_\alpha + K_k[y_k - h(xe_\alpha)] \\ P_\alpha = P_\beta + (F_{k-1}P_\beta + P_\beta F'_{k-1})T_c + Q_d \end{cases} \tag{2}$$

where $\gamma = k \mid k$. The calculation formula of Kalman gain in the process of position estimation can be expressed as below.

$$K_k = P_\alpha H'_k (HP_\alpha H'_k + R)^{-1} \tag{3}$$

As can be seen from equations (1) ~ (3), the EKF observer depends on the selection of state variables in the two-phase coordinate system of stator or the synchronous coordinate system of rotor, and its algorithm is complex, requiring matrix inversion operation and a considerable amount of computation. At the same time, EKF algorithm is established on the basis of the known statistical characteristics of error and measurement noise. Due to the complex model and many factors involved, it is difficult to analyze these parameters, and it is necessary to determine the appropriate characteristic parameters through the trial and errors in experiments.

Overall, EKF is not suitable for SPMSM-based on fundamental wave model in medium-to-high speed operation mode, but is more suitable for the PMSM with convex pole at zero low speed stage. The reason is that the parameters of the coefficient matrix of state equation for the convex pole

SPMSM are variable, and the matrix inversion requires a lot of operations. However, the coefficient matrix of the state equation for EKF in the synchronous coordinate system of rotor is a constant matrix, and the amount of inverse operation is small, so the control of convex pole SPMSM can be simplified by using this algorithm.

2.2. MRAS algorithm

The research object of MRAS is an uncertain system. It is a position estimation method based on the assumed rotor position, which does not require the exact mathematical model of the object or parameter estimation, but only needs to find a suitable reference model [12]. Figure 2 is a technical block based on MRAS estimation. It can be seen from Figure 2 that MRAS consists of reference model, adjustable model and parameter adaptive law. The corresponding key problem is to transfer the difference between the reference model and the adjustable model into the adaptive adjustment mechanism, and use the estimated rotor speed generated by the mechanism to adjust the adaptive model.

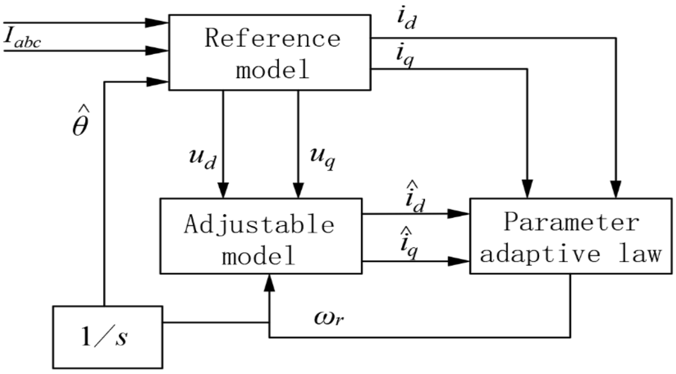

Figure 2: Schematic diagram of the system for MARS.

According to the time-varying characteristics of stator and rotor parameters of SPMSM, the stator current of PMSM's d-q axis is taken as the reference model, the equation of state of PMSM is taken as the adjustable model, and the measurable current deviation in the motor is used to adjust the adaptive model in real time. When the difference value is zero, it can be considered that the assumed position is the real position. Thus, the position and speed information of PMSM rotor can be accurately obtained.

However, whether MARS can be used to estimate the rotational speed of SPMSM, the key problem is to select the appropriate parameter adaptive law. According to different parameter adaptive law design methods, different model reference adaptive control systems are constructed [13]. Among them, there are three parameter adaptive law design methods, which are based on the designs of the optimization theory of local parameters, the Lyapunov functions, and the Popov hyper-stability and the positive qualitative dynamic system. For SPMSM, the current matrix equation of synchronous rotation of rotor in *d-q* coordinate system can be expressed as follows:

$$P\begin{bmatrix} i_d' \\ i_q' \end{bmatrix} = \begin{bmatrix} -R/L & w_e \\ -w_e & -R/L \end{bmatrix} \begin{bmatrix} i_d' \\ i_q' \end{bmatrix} + \frac{1}{L} \begin{bmatrix} u_d' \\ u_q' \end{bmatrix} \tag{4}$$

in which, i_d' is the sum of i_d and ψ_f/L, i_q' equals to i_q, u_q' is the sum of u_q and $R\psi_f/L$, u_q' equals to u_q. u_d and u_q in turn are the components of the stator voltage in *dq* axis, and L and R are the stator inductance and stator resistance respectively, w_e and ψ_f in turn denote the rotor speed and rotor flux of the motor. As can be seen from Equation (4), w_e can be used as the adjustable model of MARS. Taking the motor as a reference model, the reference values i_d and i_q of the current in *dq* axis can be provided to the system. The four matrices in Equation (5) are respectively represented by i', u', A and B, and the form of estimated values, which is simplified into state space expressions, can be described as follows

$$\frac{d}{dt}\hat{i}' = \hat{A}\hat{i}' + B\hat{u}' \tag{5}$$

The above model only needs to estimate the value of w_e, and other parameters remain unchanged, so the difference of current can be calculated by Equation (6)

$$e = i' - \hat{i}' \tag{6}$$

Based on the principle of rotor speed estimation for the above-mentioned MRAS system, the sensorless vector control structure of SPMSM is designed, as shown in Figure 3. It can be seen that the system control mode based on MRAS algorithm is $i_d = 0$. It should be noted that the direction of the magnetic field for motor rotor under this control mode is orthogonal to that generated by the stator current. In vector control system of SPMSM, the rotation position of rotor is captured in real time, and then the angle of the synthesized magnetic field in the stator is determined.

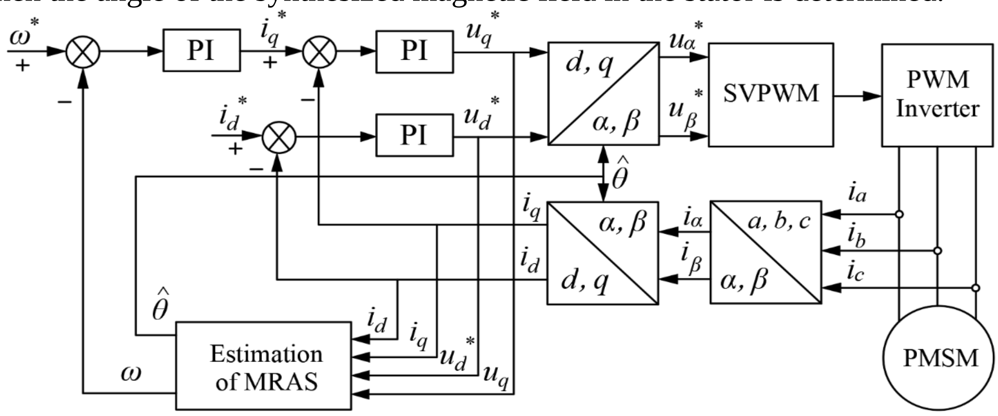

Figure 3: Design illustration of Sensorless vector control system of SPMAS based on MARS.

In the system mentioned above, the input of MRAS module is the voltage controlled by PI loop and the electrical flow in *dq* axis after transformation [9]. After processing by MRAS module, the estimated values of speed w and rotor position $\hat{\theta}$ can be obtained. However, the core of ensuring the estimation accuracy of MRAS method is to accurately estimate the position deviation. Although the mathematical model is accurate, the estimation accuracy is still affected by the variation of motor parameters and the accuracy of current detection. Although closed-loop control is adopted, it still does not completely get rid of the dependence on motor parameters.

2.3. Improved SMO algorithm

Conventional SMO method based on linear system cannot guarantee accurate observation results when nonlinear system operation changes. At the same time, the uncertainty of parameters and chattering caused by motor operation will affect the accuracy of the observer, not only affect the accuracy of the control system, but also destroy the dynamic performance of the system and make the system unstable. Therefore, how to weaken and suppress chattering phenomenon while maintaining the advantages of SMO control has become a hot issue in current research. Therefore, a sensorless control strategy of SPMSM based on improved SMO is designed. The voltage equation of motor stator of SPMSM in α-β coordinate system is shown in Equation (7) [14]

$$\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = \begin{bmatrix} R_s & 0 \\ 0 & R_s \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} + p \begin{bmatrix} L & 0 \\ 0 & L \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} + \begin{bmatrix} E_\alpha \\ E_\beta \end{bmatrix} \tag{7}$$

where u_α and u_β are the voltages of stator, i_α and i_β are the currents of stator, R_S and L are the phase resistance and phase inductance of stator respectively, p is the abbreviation for differential operator, i_α and i_β in turn are the back electromotive forces. If the back electromotive forces are calculated through SMO, Equation (7) can be written as an equation of the current state, as follows

$$P \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} -R_S K & w_e \\ -w_e & -R_S K \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} + \begin{bmatrix} K & 0 \\ 0 & K \end{bmatrix} \begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} - \begin{bmatrix} K & 0 \\ 0 & K \end{bmatrix} \begin{bmatrix} E_\alpha \\ E_\beta \end{bmatrix} \tag{8}$$

in which, K equals to $1/L$, By designing an improved SMO, the estimated value of back electromotive force for SPMSM can be effectively calculated as follows

$$P \begin{bmatrix} \hat{i}_\alpha \\ \hat{i}_\beta \end{bmatrix} = \begin{bmatrix} -R_S K & w_e \\ -w_e & -R_S K \end{bmatrix} \begin{bmatrix} \hat{i}_\alpha \\ \hat{i}_\beta \end{bmatrix} + \begin{bmatrix} K & 0 \\ 0 & K \end{bmatrix} \begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} - \begin{bmatrix} K & 0 \\ 0 & K \end{bmatrix} \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} \tag{9}$$

where $\hat{i}_\alpha$ and $\hat{i}_\beta$ are the stator current obtained by the estimation of motor in α-β coordinates, and u_α and u_β are the input of estimator. Subtract Equation (8) from Equation (9), and the calculation equation of current error can be expressed as

$$P \begin{bmatrix} \tilde{i}_\alpha \\ \tilde{i}_\beta \end{bmatrix} = \begin{bmatrix} -R_S K & w_e \\ -w_e & -R_S K \end{bmatrix} \begin{bmatrix} \tilde{i}_\alpha \\ \tilde{i}_\beta \end{bmatrix} + \begin{bmatrix} K & 0 \\ 0 & K \end{bmatrix} \begin{bmatrix} E_\alpha - v_\alpha \\ E_\beta - v_\beta \end{bmatrix} \tag{10}$$

where $\tilde{i}_\alpha = \hat{i}_\alpha - i_\alpha$, $\tilde{i}_\beta = \hat{i}_\beta - i_\beta$, $\tilde{i}_\alpha$ and $\tilde{i}_\beta$ are the estimated errors of the motor current. According to equations (8) and (10), the information of the back electromotive force is estimated, then the position angle θ of motor rotor can be written as below

$$\dot{\theta}_{eq} = -\arctan(\hat{E}_\alpha / \hat{E}_\beta) \tag{11}$$

Since the delay effect of the low-pass filter will cause the angle estimation error of motor position, by angle compensation for the rotor position calculated by Equation (11), the estimation error of position angle for SPMSM can be given as follows

$$\hat{\theta}_e = \hat{\theta}_{eq} + \arctan(\hat{w}_e / w_e) \tag{12}$$

where w_e is the cut-off frequency of the compensated low-pass filter. The Equation (12), corresponding to the rotor position, is differentially calculated, then the motor speed can be represented by the following equations

$$\begin{cases} \hat{w}_e = \sqrt{\hat{E}_\alpha^2 + \hat{E}_\beta^2} / \psi_f \\ e_{i\alpha} = i_\alpha - \hat{i}_\alpha \\ e_{i\beta} = i_\beta - \hat{i}_\beta \end{cases} \tag{13}$$

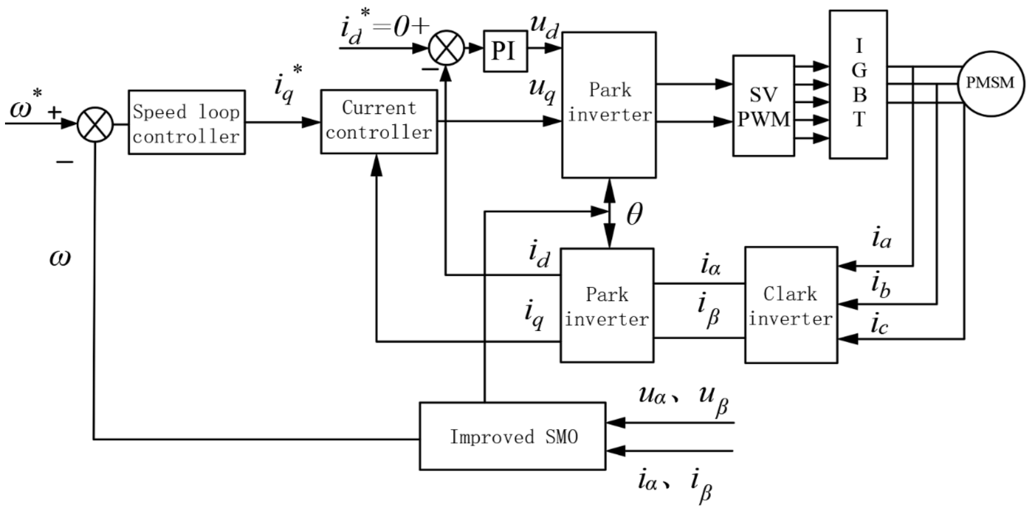

Figure 4: Design diagram of SPMAS control system based on improved SMO.

Figure 4 is the design diagram of the control system for the improved SMO, which is designed based on the above-mentioned SMO control strategy. On the basis of the principle diagram of the traditional SMO suitable for the detected rotor position, the phase-locked loop (PLL) technology is introduced to extract the rotor position and speed information, and the jitter problem of the traditional sliding mode controller is improved by the Sigmoid function. In addition, fuzzy PI algorithm is adopted in the vector control system of SPMSM to improve the control precision of speed loop and the dynamic response speed [9].

3. Comparison of methods applicable to medium-to-high speed

Observer method is one of the most used methods for sensorless motor control in medium-to-high speed operation. Through the detailed overview and algorithm designs of EKF, MRAS and SMO, it is clear that the SMO algorithm is a closed-loop control method based on the fundamental wave model of motor. Compared with EKF and MRAS algorithms, the improved SMO can better enable the system to achieve the optimal efficiency mode of high signal-to-noise ratio and high torque ripple under vector control, maximize the buffeting problem caused by the discontinuous switching function, and thus make the stability and robustness of the senseless control system more significant. At the same time, the improved SPMSM sensorless control also uses fuzzy PI algorithm to control the speed loop, and uses phase-locked loop technology to accurately estimate the position information of motor rotor.

Therefore, in medium-to-high speed operation, to ensure the signal-to-noise ratio and accuracy of the control system for sensorless rotor position, and effectively resist sliding mode jitter, the improved SMO needs to select appropriate gain parameters of sliding mode to achieve accurate estimation of rotor position.

4. Conclusions

(1) The applicability of EKF algorithm is based on the known statistical characteristics of error and measurement noise. The EKF method regarding the fundamental wave model is complicated and involves many factors, which is suitable for PMSM with the convex pole at zero low speed stage, but not suitable for SPMSM under medium-to-high speed operation mode.

(2) In sensorless control of SPMAM, the core of accuracy estimation based on MRAS method is to accurately estimate the position deviation. Although the mathematical model of MRAS method is

accurate, it is sensitive to load changes, and the estimation accuracy is easily affected by both motor parameter changes and current detection accuracy. In addition, this algorithm is not easy for engineering application due to its complex design and many parameters. Therefore, this algorithm is not suitable for SPMSM under medium-to-high speed operation mode.

(3) The traditional SMO method has the phenomena of low observation accuracy, high chattering and poor system stability when the nonlinear system is working. In order to realize sensorless control under medium-to-high speed operation of SPMSM, a SMO algorithm suitable for motor sensorless is proposed. On this basis, the Sigmoid function and phase-locked loop (PLL) technology are used. A novel sensorless control strategy based on improved SMO is designed to improve the system jitter and ensure the control accuracy and dynamic response performance of the sensorless control system.

Compared with EKF and MRAS, the improved SMO is more effective in SPMSM applications.

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