IEICE
TRANSACTIONS

on Fundamentals of Electronics,
Communications
and Computer Sciences

DOI:10.1587/transfun.2024EAL2070

Publicized:2024/10/18

A PUBLICATION OF THE ENGINEERING SCIENCES SOCIETY
The Institute of Electronics, Information and Communication Engineers
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LETTER

Research on model reference adaptive sliding mode control strategy for permanent magnet synchronous wind generator

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SUMMARY This research proposes a sliding mode variable structure model reference adaptive system based on the modified super-twisting algorithm (MST-SM-MRAS) to estimate the position and speed of the generator in a permanent magnet synchronous wind power system. Firstly, the reference model and the adjustable model are designed according to the mathematical model of PMSG; secondly, the MST-SMC is constructed according to the output error between the two models, which makes the output error converge in finite time and improves the system's anti-disturbance capability. A smooth sigmoid function is used instead of the sign function to suppress the sliding mode chattering and improve the control accuracy of the system. The proposed strategy's effectiveness is verified through simulation.

key words: *PMSG; Chattering; Sensorless; Model Reference Adaptive System.*

1. Introduction

PMSG is a kind of motor in which the rotor excited by permanent magnets rotates synchronously with the stator space magnetic field. It has the advantages of wide speed range, high efficiency, high power density, etc., and is widely used in the field of wind power generation [1-3]. However, the harsh environment unique to wind power generation can easily cause damage to the photoelectric encoder, leading to a reduction in the reliability of the power generation system [4].

Sensorless control provides a solution to the above problem. it is divided into the following categories: high-frequency injection method [5-6], sliding mode observer method [7-8], model reference adaptive system (MRAS) method [9-10], etc. Among them, the model reference adaptive system estimates the speed and position information according to the adaptive mechanism, which is widely used because of its simple structure and small computation, but its estimation accuracy is too dependent on the motor parameters [11]. In order to improve the system's anti-disturbance performance, literature [12] used a fuzzy algorithm to adjust the parameters of the PI in the MRAS, which enabled the strategy to better estimate the velocity and position information. However, the fuzzy algorithm's simple processing of error information leads to a degradation of control accuracy and dynamic performance. Literature [13] combines the sliding mode variational structure control (SMC) theory with MRAS (SM-MRAS) to improve the robustness of the system. However, it also brings a large amount of sliding mode chattering, which needs to be filtered by a low-pass filter, which not only reduces the control accuracy of the system but also increases the complexity of the system.

For this reason, this paper introduces a modified super-twisting algorithm [14] (MSTA) based on the sliding mode model reference adaptive system, which ensures the finite time convergence of the system error and improve the system's anti-disturbance capability. Secondly, the smooth sigmoid function is designed and replaces the sign function to further weaken the chattering phenomenon and improve the observation accuracy of the system.

2. Design of MRAS

2.1 Adjustable model and reference model

Permanent magnet synchronous wind power generation systems typically employ surface mounted permanent magnet synchronous generators (SPMSGs), which are characterised by equal cross-axis and straight-axis inductances, i.e., $L_d = L_q = L_s$. For the purpose of modelling and analysis, the mathematics of the SPMSG in the synchronous rotating (d-q) coordinate system, ignoring the core saturation, the differences in the electrical parameters of the windings of the different phases, and the rotor operation damping, are [15]:

$$\begin{cases} L_s \dfrac{\mathrm{d}i_d}{dt} = -Ri_d + \omega_e L_s i_q + u_d \\ L_s \dfrac{\mathrm{d}i_q}{dt} = -Ri_q - \omega_e L_s i_d - \varphi_f L_s \omega_e + u_q \end{cases} \tag{1}$$

Where i_d, i_q, u_d, u_q are the stator current as well as stator voltage in the d-q axis, separately; ω_e represents the electrical angular speed; ψ_f is the magnetic flux; R is the stator resistance. The reference model is designed according to Eq. (1) as:

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$$\begin{bmatrix} \frac{\mathrm{d}i'_d}{dt} \\ \frac{\mathrm{d}i'_q}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{R}{L_s} & \omega_e \\ -\omega_e & -\frac{R}{L_s} \end{bmatrix} \begin{bmatrix} i'_d \\ i'_q \end{bmatrix} + \begin{bmatrix} \frac{1}{L_s} & 0 \\ 0 & \frac{1}{L_s} \end{bmatrix} \begin{bmatrix} u'_d \\ u'_q \end{bmatrix} \tag{2}$$

Where $i'_d = i_d + \frac{\varphi_f}{L_s}$、$i'_q = i_q$、$u'_d = u_d + \frac{R\varphi_f}{L_s}$、$u'_q = u_q$. Meanwhile, the adjustable model can be obtained according to Eq. (2) as:

$$\begin{bmatrix} \frac{\mathrm{d}\hat{i}'_d}{dt} \\ \frac{\mathrm{d}\hat{i}'_q}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{R}{L_s} & \hat{\omega}_e \\ -\hat{\omega}_e & -\frac{R}{L_s} \end{bmatrix} \begin{bmatrix} \hat{i}'_d \\ \hat{i}'_q \end{bmatrix} + \begin{bmatrix} \frac{1}{L_s} & 0 \\ 0 & \frac{1}{L_s} \end{bmatrix} \begin{bmatrix} u'_d \\ u'_q \end{bmatrix} \tag{3}$$

In the equation, the variable with "^" is the estimated value of the corresponding variable. This is obtained by subtracting Eq. (3) from Eq. (2):

$$\begin{bmatrix} \frac{\mathrm{d}}{dt}\tilde{i}'_d \\ \frac{\mathrm{d}}{dt}\tilde{i}'_q \end{bmatrix} = \begin{bmatrix} -\frac{R}{L_s} & \omega_e \\ -\omega_e & -\frac{R}{L_s} \end{bmatrix} \begin{bmatrix} \tilde{i}'_d \\ \tilde{i}'_q \end{bmatrix} + \begin{bmatrix} 0 & \tilde{\omega}_e \\ -\tilde{\omega}_e & 0 \end{bmatrix} \begin{bmatrix} \hat{i}'_d \\ \hat{i}'_q \end{bmatrix} \tag{4}$$

Where $\widetilde{\omega_e} = \omega_e - \widehat{\omega_e}$、 $\tilde{i}'_d = i'_d - \hat{i}'_d$、 $\tilde{i}'_q = i'_q - \hat{i}'_q$. According to Popov's superstability theory [10], $\widehat{\omega_e}$ and $\widehat{\theta_e}$ are shown below:

$$\begin{cases} \hat{\omega}_e = K_p e + \int K_i e dt \\ \hat{\theta}_e = \int \hat{\omega}_e dt \end{cases} \tag{5}$$

Where e for stator current error, $e = \left(i'_d \hat{i}'_q - \hat{i}'_d i'_q\right)$. From Eq. (5), it can be seen that conventional MRAS relies on PI to regulate the output error between the reference model and the adjustable model.

2.2 Design of MST-SM-MRAS

However, when the system suffers from disturbances, the PI often fails to provide satisfactory performance. To address this problem, sliding mode variable structure control (SMC) is introduced to replace PI and enhance the robust performance of the system. The design sliding mode surface for:

$$s = e \tag{6}$$

The super-twisting algorithm (STA) is chosen as the reaching law for SMC, i.e:

$$\dot{s} = -\upsilon_1 |s|^{0.5} sign(s) - \upsilon_2 \int \left(sign(s) + f(t)\right) dt \tag{7}$$

From the above equation, it can be seen that STA achieves the purpose of weakening the chattering by placing the discontinuous sign function in the integral operation, thus ensuring the continuity of the control law in time. However, the STA cannot effectively deal with the linear growth disturbance. Therefore, in this paper, MSTA is proposed by combining the smooth sigmoid function, and its expression is:

$$\dot{s} = -\upsilon_1 \Gamma_1(s) - \upsilon_2 \int \left(\Gamma_2(s)\right) dt \tag{8}$$

Where υ_1 and υ_2 are constant; $\Gamma_1(s)$ and $\Gamma_2(s)$ are shown below:

$$\begin{cases} \Gamma_1(s) = |s|^{0.5} sigmoid(s) + \lambda s \\ \Gamma_2(s) = \Gamma_1(s)\dot{\Gamma}_1(s) = \frac{1}{2} sigmoid(s) \\ + \frac{3}{2}\lambda |s|^{0.5} sigmoid(s) + \lambda^2 s \\ sigmoid(s) = \frac{2}{1 + \mathrm{e}^{-as}} - 1 \end{cases} \tag{9}$$

Where $a > 0$, the magnitude of a which influences the convergence of the system. Therefore, combining Eq. (6) and Eq. (8) gives:

$$\begin{cases} \hat{\omega}_e = \upsilon_1 \Gamma_1(s) + \upsilon_2 \int \left(\Gamma_2(s)\right) dt \\ \hat{\theta}_e = \int \hat{\omega}_e dt \end{cases} \tag{10}$$

2.3 System stability analysis

Design the Lyapunov function as:

$$V = \frac{1}{2} s^2 \tag{11}$$

Derivation of Eq. (11) is obtained:

$$\begin{aligned} \dot{V} &= s \cdot \dot{s} \\ &= s \cdot \left(-\upsilon_1 \Gamma_1(s) - \upsilon_2 \int \left(\Gamma_2(s)\right) dt\right) \\ &\le -\upsilon_1 |s|^{1.5} - \upsilon_1 \lambda s^2 - \upsilon_2 \frac{1}{2}|s| - \frac{3}{2}\lambda |s| - \lambda^2 s^2 \end{aligned} \tag{12}$$

To make the system approximately stable gradually, i.e., $\dot{V} \le 0$. υ_1, υ_2 and λ should be satisfied [9]:

$$\begin{cases} \upsilon_1 > 2 \\ \upsilon_2 > \dfrac{\upsilon_1^3 + \eta^2 (4\upsilon_1 - 8)}{\upsilon_1 (4\upsilon_1 - 8)} \\ \lambda > 0 \end{cases} \tag{13}$$

3. Simulation

The simulation model of the SPMSG sensorless control is built in the MATLAB2022a/Simulink environment, the system parameters are: stator resistance $R = 0.1763\,\Omega$, magnetic flux $\psi_f = 0.0109\,Wb$, stator inductance $L_s = 0.000195185$H, number of pole pairs $p = 5$, rotor inertia $J = 0.0028 kg \cdot m^2$, and viscous friction coefficient $B = 0.005\, N \cdot m \cdot s$. To verify the effectiveness of the proposed strategy, it is compared with MRAS based PI (PI-MRAS), SM-

MRAS based super twisting algorithm (ST-SM-MRAS), respectively, with each controller parameter: PI-MRAS: $k_p = 1$，$k_i = 1000$; ST-SM-MRAS: $\upsilon_1 = 50$, $\upsilon_1 = 80000$; MST-SM-MRAS: $\upsilon_1 = 8$, $\upsilon_1 = 30000$, $\lambda = 5$.

The system is started with no load, given a speed of 1000 r/min, the load becomes 0.5N·m at 0.2 and the speed drops to 800 r/min at 0.4s.

Fig. 1 shows the speed error plots of the three different control strategies, from which it can be seen that all three strategies are able to recover to the steady state phase when subjected to perturbations, with the PI-MRAS taking the longest time to regulate and generating an increased amount of overshooting in the speed error. After the introduction of ST-SMC, the overall disturbance resistance of the system, but its steady state performance deteriorates, i.e., the speed error is the largest, 1.3 r/min. compared with the first two control such as, MST-SM-MRAS not only maintains the strong anti-disturbance performance of the sliding mode control, but also effectively suppresses the sliding mode chattering, which results in the smallest speed error, 0.045 r/min.

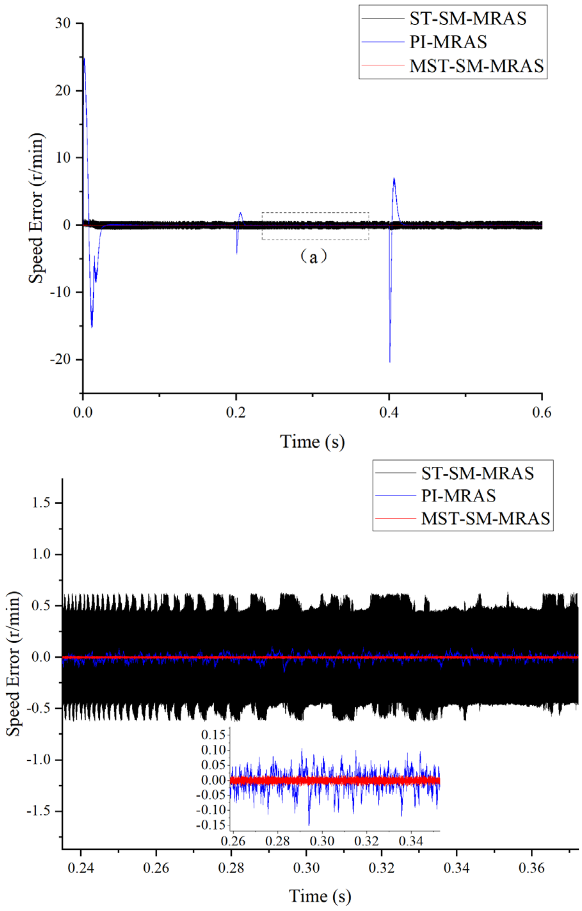

Fig. 1 Speed Error

Fig. 2 shows the position error plots for the three different control strategies. It can be seen from the figure that PI-MRAS has the worst performance index in the disturbance and steady state phases, not only has a large amount of position error overshooting, but also has the largest position error in the steady state, and low position estimation accuracy. Comparing the three control strategies, the MST-SM-MRAS has a stronger ability to anti-disturbances and has the smallest position error and the highest estimation accuracy.

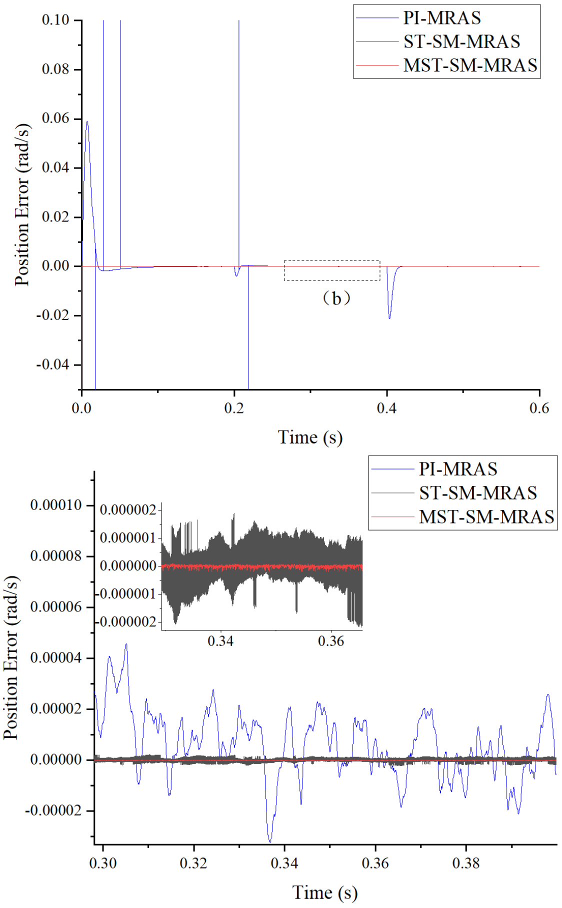

Fig. 2 Position Error

4. Conclusions

For the SPMSG wind turbine sensorless control system, this paper proposes an MST-SM-MRASO for estimating the velocity and position information. Hand firstly, based on the traditional MRAS, the SMC is introduced to replace the original PI to improve the system's anti-disturbance capability. Secondly, considering the inherent chattering problem in SMC, MSTA is adopted to suppress the chattering phenomenon, which in turn improves the estimation accuracy of the system under the premise of ensuring strong anti-disturbance capability. Comparison with PI-MRAS, ST-SM-MRAS is also made to prove the effectiveness of the proposed strategy.

Acknowledgment

This study was supported by Beijing Natural Science Foundation (3222060 and L211011)

References

[1] Anbalagan, Pratap, and Young Hoon Joo. "Fuzzy membership-function-dependent design of aperiodic sample-data control scheme for nonlinear PMSG-based WECS with quantization measurements via refined looped Lyapunov functional." Information Sciences 661 (2024): 120149.

[2] Yaramasu, Venkata, et al. "PMSG ‐ based wind energy conversion systems: survey on power converters and controls." IET Electric Power Applications 11.6 (2017): 956-968.

[3] Yang, Hao, Jing-Wei Tang, and Ying-Ren Chien. "Application of new sliding mode control in vector control of PMSM." IEICE Electronics Express 19.13 (2022): 20220156-20220156.

[4] Wang, Q. L., Xing Zhang, and C. W. Zhang. "Double sliding-mode model reference adaptive system speed identification for vector control of permanent magnet synchronous motors." Proceedings of the CSEE 34.6 (2014): 897-902. (In Chinese)

[5] Medjmadj, Slimane, et al. "PMSM drive position estimation: Contribution to the high-frequency injection voltage selection issue." IEEE Transactions on energy conversion 30.1 (2014): 349-358.

[6] Wang, Gaolin, et al. "Comparative investigation of pseudorandom high-frequency signal injection schemes for sensorless IPMSM drives." IEEE Transactions on Power Electronics 32.3 (2016): 2123-2132.

[7] Zhang, Lei, Jing Bai, and Jing Wu. "Speed sensor-less control system of surface-mounted permanent magnet synchronous motor based on adaptive feedback gain supertwisting sliding mode observer." Journal of Sensors 2021 (2021): 1-16.

[8] Kang, Weixin, and Hong Li. "Improved sliding mode observer based sensorless control for PMSM." IEICE Electronics Express 14.24 (2017): 20170934-20170934.

[9] Zhang, Lei, et al. "An improved sliding mode model reference adaptive system observer for PMSM applications." Expert Systems with Applications (2024): 123907.

[10] Liu, Jun-Feng, et al. "Fractional order second-order sliding mode MRASO for SPMSM." Measurement and Control (2024): 00202940241227126.

[11] Said, Mohamed Abdallah Anwar, Mini Sreejeth, and A. B. K. Bhattacharya. "Sensorless control of PMSM using Direct and Model References Adaptive system estimation techniques and observing the effect of using PI Fuzzy logic controller in MRAS Model." 2020 IEEE International Conference for Innovation in Technology (INOCON). IEEE, 2020.

[12] Comanescu, Mihai, and Longya Xu. "Sliding-mode MRAS speed estimators for sensorless vector control of induction machine." IEEE Transactions on Industrial Electronics 53.1 (2006): 146-153.

[13] Zhang, Lei, Sibo Wang, and Jing Bai, "Fast-super-twisting sliding mode speed loop control of permanent magnet synchronous motor based on SVM-DTC," IEICE Electronics Express, vol.18, no.1, pp.20200375-20200375, 2021.

[14] Kang, Jinsong, et al. "Study of position sensorless control of PMSM based on MRAS." 2009 IEEE International Conference on Industrial Technology. IEEE, 2009.

[15] Wang, Bu-Lai, et al. "Research on sensorless control of PMSM based on novel double-sliding mode MRAS." IEICE Electronics Express (2023): 20-20230483.