Anti-disturbance GITSMC with quick reaching law for speed control of PMSM drive

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ABSTRACT

In this article, in order to minimize response time and enhance anti-disturbance performance of parmanent magnet synchronous motor, a global integral terminal sliding mode control based on improved quick reaching law (GITSMC-QRL) is developed. This novel reaching law has two terms which play a key role of bringing state trajectory to sliding surface as quick as possible whenever the system is close to or far from the manifold. The proposed controller cannot only speed up the convergence rate, but also has ability to suppress the chattering and ensure finite time stability. In order to avoid the chattering phenomenon caused by load disturbances and high switching gain of sliding mode control, an extended hyperbolic tangent state observer is designed as feedforward compensation compensator that is added to GITSMC. Finally, the novel scheme is validated on paremanent magnet synchronous motor (PMSM) drive through simulation, and the comparative results in various conditions show the robustness, the feasibility and the effectiveness of the proposed controller.

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1. INTRODUCTION

In recent decades, permanent magnet synchronous motor has been intensively utilized in many different industrial applications as electric vehicles [1], [2] and computer numerical control (CNC) machines [3] due to its small size, simple structure, high torque to inertia rating, and high efficiency [4]. Paremanent magnet synchronous motor (PMSM) is nonlinear, multivariate, and highly coupled system, they generally have critical issues in modeling error, operating condition complexities and sensitivity to uncertainties [5] these disadvantages make difficulties to the conventional controllers proportional integral (PI) to meet the desired dynamic performance control of PMSM drives, which are extremely sensitive to parameter variations and external perturbations. To address the above drawbacks, PMSM system needs advanced control paradigms to overcome the internal and external perturbations.

In control engineering, several control techniques are developed for speed regulation to make PMSM suitable for different and sophisticated applications. The main known control algorithms are used for this purpose; robust control, adaptive control, predictive control, and intelligent control. Intelligent control is inspired from human thinking, which does not need any mathematical modeling of the system as fuzzy logic control (FLC) [6] and neural network (NN) [7], where the researchers designed to improve the quality of speed performance and suppress electromagnetic torque ripples. For Adaptive control, a model reference adaptive control is one of the known adaptive control that is applied in speed control under high parameter variations and lumped disturbances [8]. Predictive control or model predictive control (MPC) is an advanced optimal control technique, it depends on historical information of the system to generate the future control action, in [9] a Laguerre function with MPC is applied to speed up the response and damp the load effect of PMSM. Moreover, robust control aims to achieve a robustness criteria in the presence of bounded matched and dis-matched disturbances, the famous robust controllers are synergetic control (SC) [10] and sliding mode control (SMC) [11]. However, SMC method became a hotspot topic in control engineering society because of its high robustness and successfulness use in various applications like robotic [12], power electronic [13], and renewable energy [14]. In spite of that, chattering problem could produce serious issue in several practical applications due to its high frequency and power consumption.

In literature, a numerous methods have been presented for reducing chattering phenomenon. A continuous function (saturation, sigmoid) was replaced within control law instead of discontinuous one, but this method gives rise to a high steady state error [15]. A nonsingular terminal sliding mode control was utilized to solve the problem of chattering, but it is noticed that the reaching rate is decreasing when state trajectory is near to the manifold [16]. A various reaching laws were presented to eliminate the chattering phenomenon such as constant, power, and exponential reaching laws [17]–[19]. Taking every things into account, the convergence speed is slow for both constant and power reaching laws whereas the exponential reaching law may not guarantee the elimination of chattering problem. A combination of them may overcome the pre-mentioned drawbacks as in [20].

Generally, the switching gains of SMCs should be tuned high enough to avoid the disturbances effect of system and to ensure robustness [21]. However, the bounded values of disturbances are difficult to know, meanwhile, the large gain induces the chattering phenomenon. Thus, to solve this issue above, anti-disturbance SMC is required, i.e integrating disturbance observers in control loop is necessary proposition. Recently, various disturbance observers have been developed for dismatched disturbances. These approaches have been practically tested on PMSM drive, which demonstrated that disturbance can be suppressed by developing feed-forward compensation loop, and the performance will not be influenced directly [18], [22]–[24].

In this article, intending to further enhancement of PMSM regulation speed, a quick reaching law is proposed rather than improved exponential reaching law in [5], [18]. Because it ensures a quick speed convergence rate whenever the state trajectory position and suppresses the chattering effects. A global integral terminal sliding mode control is used to reduce steady state error, improve transient response by minimizing overshoot. Moreover, extended state observer is developed to estimate the velocity of PMSM as well as the lumped load disturbances to help global integral terminal sliding mode control (GITSMC) schema to convene the desired performance under bounded disturbances.

The rest parts of this article are arranged as follows. Section 2 presents mathematical development of sliding mode reaching laws. Section 3 the mathematical model of PMSM drive, the proposed quick reaching law (GITSMC-QRL) speed controller design, the development of extended state observer and the laypunov's stability analysis of the compound controller extended state observer (GITSMC-QRL-ESO). In section 4, simulation verification of PMSM system is provided to demonstrate the advantages of GITSMC-QRL-ESO over different sliding mode controllers based on improved exponential reaching law. Finally, section 5 concludes the research work with a summary of main points.

2. STRUCTURE VARIABLE REACHING LAWS

SMC paradigm enables the state trajectories of the systems to reach the selected sliding hyperspace and force them to the equilibrium points. However, the trajectories can not always move along the desired path. Therefore, the reaching law algorithms are developed to suppress chattering phenomenon and to ensure the motion quality of trajectories. For this purpose, various methods have been used. Gao and Hung [25] applied exponential reaching law, which enhanced the arrival speed because of the additional velocity term, but the speed convergence and chattering problem are inversely proportional relationship. Moreover, in [26] the authors merge exponential reaching law with power reaching method, which improved the convergence rate and the process smoothness, but the chattering problem exists. At present, in [5], [18] an improved exponential reaching law are applied, the results show a small chattering due to the introduction power of state variable as illustrated in (1):

$$\begin{cases} \dfrac{ds}{dt} = -\delta|x|^a sgn(s) - K|s|^{bsgn(|s|-1)} s = E(s) \\ \lim\limits_{t\to\infty}|x| = 0, \delta > 0, K > 0, 0 < a < 1, 0 < b < 1 \end{cases} \tag{1}$$

Where: x is the controllable state and E(s) refers to IREL (2). According to (1), we can write:

$$\dot{s}s = -\delta|x|^a|s| - K|s|^{bsgn(|s|-1)}s^2 < 0 \tag{2}$$

According to the existence condition of sliding mode control, if $\dot{s}s < 0$ is verified, the equilibrium point $s = 0$, $\dot{s} = 0$ can be reached [18]. Hence, the state trajectory converges to zero under this reaching law. Although the improved exponential reaching law showed accepted results such as high speed convergence rate and small chattering, but they always require additional enhancement to eliminate chattering, minimize settling time and reduce overshot and undershot.

2.1. Proposed improved quick reaching law

Based on the above analysis, an improved QRL is proposed for optimizing the performance speed of PMSM drive [27]:

$$\dot{s} = -\alpha_1(b^{|s|} - 1)sgn(s) - \alpha_2|s|^a sgn(s) = M(s) \tag{3}$$

where: $0 < \alpha_1$ $0 < \alpha_2$, $0 < a < 1$, $1 < b < 1 + \frac{\alpha_1}{\alpha_2}$ and M(s) refers to QRL (3).

The first term $\alpha_1(b^{|s|} - 1)sgn(s)$ leads (3) to speed up the reaching rate when the state trajectory is far from manifold ($|s| > 1$). while the second term $\alpha_2|s|^a sgn(s)$ leads (3) to keep the rated speed high enough to reach sliding surface quickly when the system is near to manifold ($|s| < 1$).

Theorem 1. *For reaching law mentioned in (3), state trajectory converges to zero in finite time period, which means that after the convergence s will be* $s = 0$.

Proof. Let have Lyapunov candidate:

$$V(s) = \frac{1}{2}s^2 \tag{4}$$

the derivative of Lyapunov candidate function is expressed as:

$$\begin{aligned} \dot{V} &= s\dot{s} \\ &= -\alpha_1(b^{|s|} - 1)sgn(s)s - \alpha_2|s|^a sgn(s)s \\ &= -\alpha_1(b^{|s|} - 1)|s| - \alpha_2|s|^{a+1} \\ &\leq 0 \end{aligned} \tag{5}$$

Where: $sgn(s)s = |s|$, $\dot{V} \leq 0$ for all $b > 1$, $\alpha_1 > 0$ and $\alpha_2 > 0$.

The proposed reaching law guarantees finite time stability [28], and the reaching time can be expressed as:

$$T_f = t_{|s|>1} + t_{|s|<1} \tag{6}$$

when $|s| > 1$ the first term is used and the second is neglected and vice versa for $|s| < 1$ a) first stage: $t_{|s|>1}$ represents the time duration from $s > 1$ to $s = 1$ or from $s < -1$ to $s = -1$, and it can be calculated as:

$$\begin{aligned} ds &= -\alpha_1(b^{|s|} - 1)dt \\ dt &= -\frac{ds}{\alpha_1(b^{|s|} - 1)} \end{aligned} \tag{7}$$

integrating (7) in both side as:

$$\int_0^{t_{|s|>1}} dt = \int_{s(0)>1}^{1} \frac{ds}{\alpha_1(1 - b^s)} = \int_{s(0)<-1}^{-1} \frac{ds}{\alpha_1(1 - b^{-s})} \tag{8}$$

therefore,

$$t_{|s|>1} = \frac{ln(\frac{1-b^{-1}}{1-b^{s(0)}})}{\alpha_1 ln(b)} \tag{9}$$

b) Second stage: $t_{|s|<1}$ represents arrival time when the state travel from $|s| = 1$ to $s = 0$, in this case the first term of (3) is neglected:

$$ds = -\alpha_2 |s|^a dt \tag{10}$$

integrating both side as in (8), $t_{|s|<1}$ is shown in (11):

$$t_{|s|<1} = \frac{1}{\alpha_2(1-a)} \tag{11}$$

The worst case reaching time $T_f < t_{|s|>1} + t_{|s|<1}$. Hence (3) converges to zero in finite time period.

3. ANTI-DISTURBANCE SMC DESIGN FOR PMSM DRIVE

3.1. PMSM modeling

PMSM drives are nonlinear, multivariate, and highly coupled system. intending to simplify analysis, we assume that the magnetic field has a sinusoidal distribution, eddy current, and hysteresis effects are negligible.these issues force q-axis to track the rotation direction of the rotor and take d-axis in-line with excitation axis of PMSM drive. PMSM model is divided into electrical model and mechanical model. For electrical model represents stator current $i_q(t)$, $i_d(t)$ in dq coordinate system sense. Whereas, mechanical model stands up for mechanical motion equation that describes the change of motor speed $w(t)$ [29].

– Electrical model

$$\begin{cases} \dot{i}_d = \frac{1}{L}(u_d - Ri_d - w_e L_q i_q) \\ \dot{i}_q = \frac{1}{L}(u_q - Ri_q - w_e(L_d i_d + \psi_f)) \\ w_e = Pw \end{cases} \tag{12}$$

Where L, L_q, L_d, R, P, w_e refer to stator inductance, dq axis inductances, resistance of stator motor, pair pole of motor, and electrical angular speed respectively.

– Mechanical model

$$\begin{cases} \dot{w} = \frac{1}{J}(T_e - Bw - T_L) \\ T_e = \frac{3}{2}P[\psi_f iq + (Ld - Lq)i_q i_d] \end{cases} \tag{13}$$

Where J, B, T_e, T_L and ψ_f stand up for moment of inertia, viscosity damper, electromagnetic torque, load torque and flux linkage respectively. Substituting (12) into (13), the motion function of PMSM can be rewritten as:

$$\dot{w} = \frac{3P}{2J}(\psi_f iq) - \frac{B}{J}w - \frac{1}{J}T_L \tag{14}$$

in disturbance point of view, it can be modeled both parameter variation and external disturbances within the motion equation as described in (15):

$$\dot{w} = (\frac{3P}{2J} + \Delta\nu_1)(\psi_f i_q) - (\frac{B}{J} + \Delta\nu_2)w - (\frac{1}{J} + \Delta\nu_3)T_L + \Delta\nu_4 \tag{15}$$

where $\Delta\nu_{1,2,3}$ describe the internal disturbances and $\Delta\nu_4$ referes to external disturbance. To separate these disturbances from (15) and collect them into one separate equation q(t) which is formulated as:

$$q(t) = \frac{3P\psi_f}{2J}\Delta\nu_1 i_q - \Delta\nu_2 w - \Delta\nu_3(T_L + \Delta\nu_4) \tag{16}$$

plugging (16) into (15), the motion equation can be again rewritten as:

$$\dot{w} = -\frac{B}{J}w + \frac{3P\psi_f}{2J}iq - \frac{1}{J}q(t) \tag{17}$$

now, let define e_1 as error speed and e_2 error speed change of PMSM drive:

$$\begin{cases} e_1 = w_{ref} - w \\ e_2 = \dot{w}_{ref} - \dot{w} \end{cases} \tag{18}$$

substituting (17) into (18), the change of error speed is expressed as:

$$e_2 = \dot{w}_{ref} + \frac{B}{J}w - \frac{3P\psi_f}{2J}iq + \frac{1}{J}q(t) \tag{19}$$

3.2. GITSMC speed controller

In order to ensure the system convergence through the equilibrium point with high speed along the manifold and solving the problem of singularity of terminal SMC, the global integral terminal sliding mode control is used to construct the control law [14]. That is, the novel global integral terminal SMC is designed to improve the control performance of PMSM drive [30]. Now let define sliding surface as:

$$s = e_1 + K_1(\int_0^t e_1 d\tau) + K_2(\int_0^t e_1 d\tau)^{q/p} \tag{20}$$

where q and p are odd number and should satisfy $1 < q/p < 2$ and $K_{1,2} > 0$. The derivative of s leads to (21) and with subsequent replacement of (19) , $\dot{s}$ can be rewritten as (22):

$$\dot{s} = e_2 + K_1 e_1 + K_2 \frac{q}{p} e_1 (\int_0^t e_1 d\tau)^{(\frac{q-p}{p})} \tag{21}$$

$$\dot{s} = \dot{w}_{ref} + \frac{B}{J}w - \frac{3P\psi_f}{2J}iq + \frac{1}{J}q(t) + K_1 e_1 + K_2 \frac{q}{p} e_1 (\int_0^t e_1 d\tau)^{\frac{q-p}{p}} \tag{22}$$

to obtain the control law $\bar{i}_q$, $\dot{s}$ should be satisfied the following condition $\dot{s} = M(s)$:

$$\bar{i}_q = \frac{2J}{3P\psi_f}[\dot{w}_{ref} - M(s) + \frac{B}{J}w + \frac{1}{J}q(t) + K_1 e_1 + K_2 \frac{q}{p} e_1 (\int_0^t e1 d\tau)^{\frac{q-p}{p}}] \tag{23}$$

3.3. ESO based GITSMC-QRL design

Due to the unmeasurable states in GITSMC-QRL control law (23) like q(t) and w(t). the proposed controller will be become sensitive to these state variation. Therefore an observer is needed like nonlinear disturbance estimator and extended state estimator [31], [32]. In this paper, an extended hyperbolic tangent state is selected to compensate GITSMC-QRL control law as follows:

$$\bar{i}_q = \frac{2J}{3P\psi_f}[\dot{w}_{ref} - M(s) + \frac{B}{J}\hat{w}(t) + \frac{1}{J}\hat{q}(t) + K_1 e_1 + K_2 \frac{q}{p} e_1 (\int_0^t e1 d\tau)^{\frac{q-p}{p}}] \tag{24}$$

where: $\hat{q}(t)$ is estimated disturbance, $\hat{w}(t)$ estimated speed.

3.3.1. Extended state observer design

The proposed extended state observer can be written as follows [22]:

$$\begin{aligned} \dot{\phi}_1 &= \phi_2 - \gamma_1(\phi_1 - x_1) + x_2 \\ \dot{\phi}_2 &= -\gamma_2 tanh(\gamma_3(\phi_1 - x_1)) \end{aligned} \tag{25}$$

where: $\gamma_i > 0$ are observer parameters for all $i = 1, 2, 3$. Assume $x_1(t) = w(t)$, $x_2(t) = \dot{w}$ and $\epsilon = \phi_1 - x_1$, substituting (17) into (25), we get (26):

$$\begin{aligned} \dot{\phi}_1 &= \phi_2 - \gamma_1 \epsilon + \frac{3P\psi_f}{2J}\bar{i}_q + \frac{1}{J}q(t) \\ \dot{\phi}_2 &= -\gamma_2 tanh(\epsilon) \end{aligned} \tag{26}$$

where: $\phi_1 = \hat{q}(t)$ observes q(t) and $\phi_2 = \hat{w}(t)$ estimates the actual motor speed. Based on [33], the parameter selection of ESO coefficient should satisfy this condition : $\gamma_1 > \gamma_2\gamma_3$.

3.3.2. Stability analysis of ESO based GITSMC-QRL

Let define estimated error of disturbance as follow $e_q = \hat{q}(t) - q(t)$ and its derivative as:

$$\dot{e}_q(t) = -Bs \tag{27}$$

to verify stability of PMSM drive with GITSMC-QRL-ESO controller, Lyapunov's stability approach is proposed. A selected lyapunov's candidate is defined in (28):

$$V = \frac{1}{2}(s^2 + \frac{1}{J}\frac{1}{B}{e_q}^2) \tag{28}$$

substituting (3), (21), (27) into (28) the derivative of (28) can be (29) as:

$$\begin{aligned} \dot{V} &= s\dot{s} + \frac{1}{JB}e_q\dot{e}_q \\ &= s[e_2 + K_1e_1 + K_2\frac{q}{p}e_1(\int_0^t e_1 d\tau)^{(\frac{q-p}{p})}] + \frac{1}{JB}e_q\dot{e}_q \end{aligned} \tag{29}$$

substituting (19) and (23) into (29), we obtain the following (30):

$$\begin{aligned} \dot{V} &= -s[M(s)] + s[\dot{w}_{ref} + \frac{B}{J}w - \frac{3P\psi_f}{2J}iq \\ &+ \frac{1}{J}q(t) + K_1e_1 + K_2\frac{q}{p}e_1(\int_0^t e_1 d\tau)^{\frac{q-p}{p}} + M(s)] \\ &+ \frac{1}{J}e_qs + \frac{1}{JB}e_q\dot{e}_q \\ &= -s[M(s)] \end{aligned} \tag{30}$$

(30) is satisfied, if and only if $\dot{e}_q(t) = -\dot{\hat{q}}(t)$.

As we can see, (30) is the same as (5), hence $\dot{V} \leq 0$ is confirmed. From direct Lyapunov's stability approach, the proposed system is finite time stable.

4. RESULT AND DISCUSSION

In this research work, anti-disturbance SMC is designed in MATLAB/Simulink environment. The block diagram of PMSM speed control is depicted in Figure 1. To prove the superiority of GITSMC-QRL-ESO, a three different speed reference signals (constant, step change and sinusoidal) will be applied. Furthermore, It will be compared with SMCs-IERL-ESO as described in (31). The essential parameters of PMSM are illustrated in Table 1. As it can be seen, the speed performance of PMSM under step reference has been improved when GITSMC-QRL-ESO is applied compared with other control schemes as depicted in Figure 2. The state variable and the proposed control law have perfect convergence speed and smoothness which implies that the chattering problem is suppressed whatever the type of speed reference signal as shown in Figures 3 and 4. When a step change is applied, the proposed control also optimizes the tracking response, minimizes the overshoot and undershoot and suppresses chattering phenomenon as presented in Figures 5 and 6. All summarized comparisons between the proposed controllers are informed in Tables 2 and 3.

4.1. GITSMC-IERL design

GITSMC control law:

$$\bar{i}_q = \frac{2J}{3P\psi_f}[\dot{w}_{ref} + \frac{B}{J}w + \frac{1}{J}q(t) + K_1e_1 + K_2\frac{q}{p}e_1(\int_0^t e_1(\tau)d\tau)^{\frac{q}{p}-1} - E(s)] \tag{31}$$

Where E(s) refers to (1). the control coefficients are:

$\delta = 5, a = 0.6, b = 0.3, K = 24, K_1 = 21, K_2 = 20$

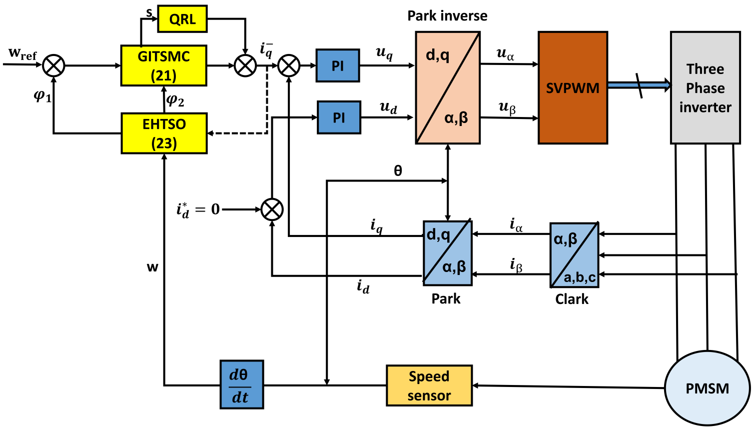

Figure 1. Block diagram of the proposed PMSM speed regulator

Table 1. PMSM parameter's specifications

Symbol	Parameter	Value and unit
P_r	rated power	0.4 KW
R	stator resistance	1.54 Ω
$L_{q,d}$, L	inductance	6.71 mH
ψ_f	flux linkage	0.174 wb
B	viscous friction	0.0007 N.m.s
J	Rotational inertia	0.005 $Kg.m^2$
P	motor's pole	6

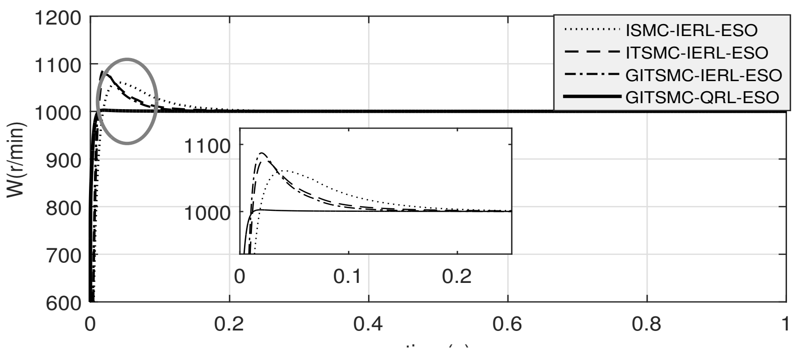

Figure 2. PMSM speed response under constant reference

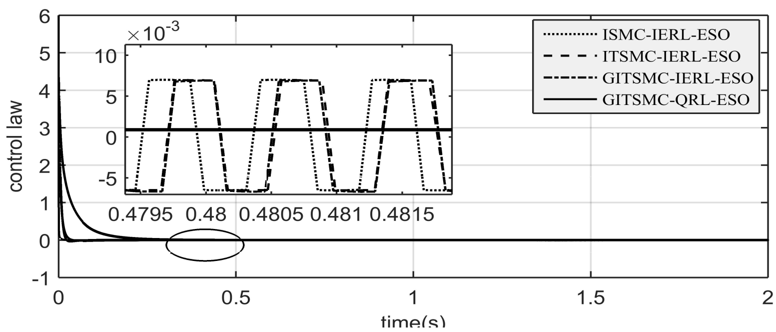

Figure 3. Control law under constant reference

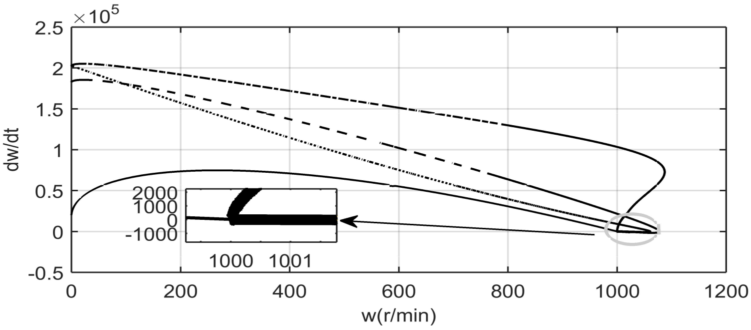

Figure 4. State trajectory of PMSM speed under constant reference

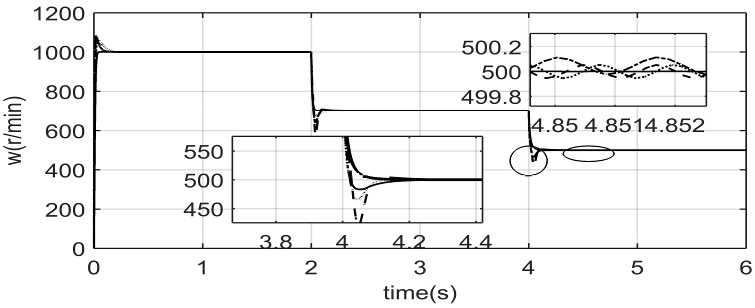

Figure 5. Speed performance under step change reference

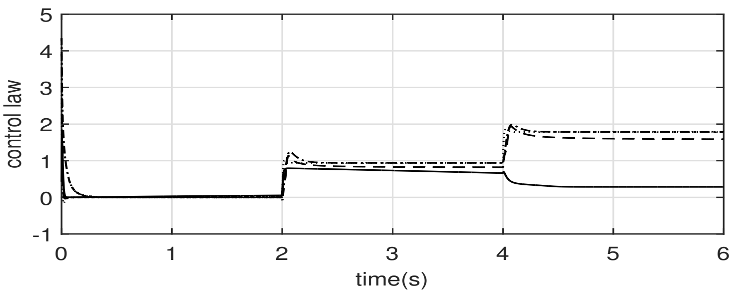

Figure 6. Control law

Table 2. Comparison of SMCs performance at $w = 1000r/min$

control method	settling time (s)	rising time (s)	overshoot(%)	steady state error
ISMC-IERL-ESO	0.016	0.01	6.1	0.043
ITSMC-IERL-ESO	0.010	0.0076	7.7	0.083
GITSMC-IERL-ESO	0.0094	0.00652	8.7	0.059
GITSMC-QRL-ESO	0.0069	0.0023	0.2	0.062

Table 3. Comparison of SMCs performance under step change reference

control method	undershoot (s)	peak to peak ripple at 500 r/min
ISMC-IERL-ESO	2.91%	0.1
ITSMC-IERL-ESO	17.84%	0.86
GITSMC-IERL-ESO	8.5%	0.1
GITSMC-QRL-ESO	0.0 %	10^{-4}

To validate more tracking performance, a sinusoidal speed reference $w(t) = 500sin(\frac{\pi}{3}t) + 500$ is applied. It can be seen from Figure 7 has a 0.02(s) as settling time. Conversely, the PMSM speed control under other SMCs-ERL-ESO have considerable overshoots and chattering. The transient response of speed has starting value of 565 r/min, 585 r/min, and 555 r/min under ISMC-ERL-ESO, GITSMC-ERL-ESO and ITSMC-ERL-ESO controllers respectively whereas the proposed control simultaneously starts with the reference signal. for Figure 8 shows again the chattering elimination in GITSMC-QRL-ESO controller.

In order to evaluate the robustness of the proposed controller under load disturbance, a load torque has been increased into 20 Nm at 0.2 s. According to Figure 9, the performance speed of PMSM drops to 691.5 r/min when GITSMC-QRL-ESO is used whereas it drops into 677 r/min using ISMC-IERL-ESO. Moreover, GITSMC-QRL-ESO takes short time less than 0.02s to reach again to the reference speed 700 r/min,which is faster than ISMC-IERL-ESO. Hence, it can be concluded that the proposed controller more robust than other ISMC-IERL-ESO under load disturbance conditions. Finally, from the analysis above we conclude that the PMSM drive with GITSMC+ESO controller based on improved quick reaching law has the advantages of perfect dynamic performance and high robustness.

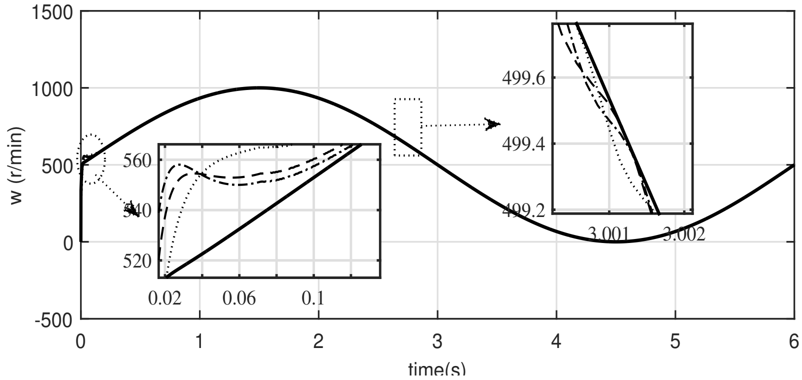

Figure 7. Speed performance under sinusoidal reference

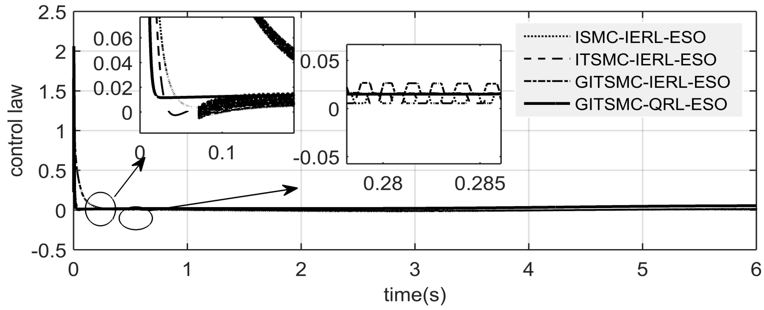

Figure 8. Dynamic performance of control effort under sinusoidal reference

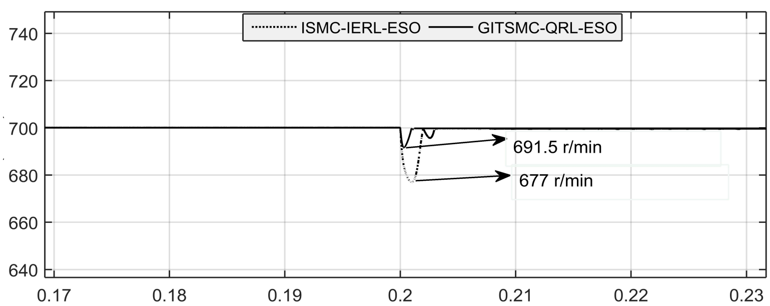

Figure 9. Speed performance under load torque $T_L = 20Nm$

5. CONCLUSION

In this research work, an anti-disturbance robust control schema of PMSM speed control system has been designed. A GITSMC based QRL is applied as to force the rotor to track the desired speed as fast as possible. QRL played an important role of suppressing the overshoot, undershoot and chattering. The proposed GITSMC have been designed to improve both transient response and steady state error exploited both the advantages of integral and terminal part. Moreover, in order to improve anti-disturbance performance, the extended hyperbolic tangent state observer have been applied. The preference of the compound controller GITSMC-QRL-ESO has been proved through simulation results a strong preferable dynamic speed performance of PMSM drive when it compared with the controllers SMCs-IERL-ESO. The proposed controller has been dramatically optimized the robustness under disturbances, steady state error, transient response and suppress the chattering phenomenon.

REFERENCES

[1] Y. Wang, Y. Xu, and J. Zou, "Sliding-mode sensorless control of PMSM with inverter nonlinearity compensation," *IEEE Transactions on Power Electronics*, vol. 34, no. 10, pp. 10206-10220, Oct. 2019, doi: 10.1109/TPEL.2018.2890564.

[2] G. Liao, W. Zhang, and C. Cai, "Research on a PMSM control strategy for electric vehicles," *Advances in Mechanical Engineering* , vol. 13 no. 12, p. 16878140211051462, 2021, doi: 10.1177/16878140211051462.

[3] L. Sheng, W. Li, Y. Wang, M. Fan, and X. Yang, "Sensorless control of a shearer short-range cutting interior permanent magnet synchronous motor based on a new sliding mode observer," *IEEE Access*, vol. 5, pp. 18439-18450, 2017, doi: 10.1109/ACCESS.2017.2734699.

[4] S. Fan and C. Tong, "Model predictive current control method for PMSM drives based on an improved prediction model," *Journal of Power Electronics*, vol. 20, no. 6. pp. 1456-1466, 2020, doi: 10.1007/s43236-020-00125-4.

[5] C. Jiang, Q. Wang, Z. Li, N. Zhang, and H. Ding, "Nonsingular terminal sliding mode control of PMSM based on improved exponential reaching law," *Electronics*, vol. 10, no. 15, p. 1776, Jul. 2021, doi: 10.3390/electronics10151776.

[6] C. Wang and Z. Q. Zhu, "Fuzzy logic speed control of permanent magnet synchronous machine and feedback voltage ripple reduction in flux-weakening operation region," *IEEE Transactions on Industry Applications*, vol. 56, no. 2, pp. 1505-1517, March-April 2020, doi: 10.1109/TIA.2020.2967673.

[7] F. -J. Lin, K. -J. Yang, I. -F. Sun, and J. -K. Chang, "Intelligent position control of permanent magnet synchronous motor using recurrent fuzzy neural cerebellar model articulation network," *IET Electric Power Applications*, vol. 9, no. 3, pp. 248-264, Mar. 2015, doi: 10.1049/iet-epa.2014.0088.

[8] A. T. Nguyen, M. S. Rafaq, H. H. Choi, and J. -W. Jung, "A model reference adaptive control based speed controller for a surface-mounted permanent magnet synchronous motor drive," in *IEEE Transactions on Industrial Electronics*,vol. 65, no. 12, pp. 9399-9409, Dec. 2018, doi: 10.1109/TIE.2018.2826480.

[9] G. Zhanga, L. Gao, H. Yang, and L. Mei, "A novel method of model predictive control on permanent magnet synchronous machine with Laguerre functions," *Alexandria Engineering Journal*, vol. 60, mo. 6, pp. 6473–6492, Dec. 2021, doi: 10.1016/j.aej.2021.03.035.

[10] T. Wang, J. Li, and Y. Liu, "Synergetic control of permanent magnet synchronous motor based on load torque observer," *Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering*, vol. 233, no. 8, pp. 980-993, Nov. 2018, doi: 10.1177/0959651818811253.

[11] C. Mu, W. Xu, and C. Sun, "On switching manifold design for terminal sliding mode control," *Journal of the Franklin Institute* , vol. 353, no. 7, 2019-, pp. 1553–1572, May 2016, doi: 10.1016/j.jfranklin.2016.02.014.

[12] D. Nojavanzadeh and M. Badamchizadeh, "Adaptive fractional-order non-singular fast terminal sliding mode control for robot manipulators," *IET Control Theory and Applications*, vol. 10, no. 13, pp. 1565–1572, Aug. 2016, doi: 10.1049/iet-cta.2015.1218.

[13] B. Babes, S. Mekhilef, A. Boutaghane, and L. Rahmani, "Fuzzy approximation-based fractional-order nonsingular terminal sliding mode controller for DC–DC buck converters," *IEEE Transactions on Power Electronics*, vol. 37, no. 3, pp. 2749-2760, March 2022, doi: 10.1109/TPEL.2021.3114277.

[14] C. Napole, M. Derbeli, and O. Barambones, "A global integral terminal sliding mode control based on a novel reaching law for a proton exchange membrane fuel cell system," *Applied Energy*, vol. 301, p. 117473, Nov. 2021, doi: 10.1016/j.apenergy.2021.117473.

[15] M. Benosman and K.-Y. Lum, "Passive actuators' fault-tolerant control for affine nonlinear systems," in *IEEE Transactions on Control Systems Technology*, vol. 18, no. 1, pp. 152-163, Jan. 2010, doi: 10.1109/TCST.2008.2009641.

[16] Y. Yang and Y. Yan, "Neural network approximation-based nonsingular terminal sliding mode control for trajectory tracking of robotic airships," textslAerospace Science and Technology, vol. 54, , pp. 192–197, Jul. 2016, doi: 10.1016/j.ast.2016.04.021.

[17] A. Bartoszewicz and P. Leśniewski, "New switching and nonswitching type reaching laws for SMC of discrete time systems," in *IEEE Transactions on Control Systems Technology*, vol. 24, no. 2, pp. 670-677, March 2016, doi: 10.1109/TCST.2015.2440175.

[18] Y. Wang, Y. Feng, X. Zhang, and J. Liang, "A new reaching law for antidisturbance sliding-mode control of PMSM speed regulation system," in *IEEE Transactions on Power Electronics*, vol. 35, no. 4, pp. 4117-4126, Apr. 2020, doi: 10.1109/TPEL.2019.2933613.

[19] H. Ma and Y. Li, "Multi-power reaching law based discrete-time sliding-mode control," in *IEEE Access*, vol. 7, pp. 49822-49829, 2019, doi: 10.1109/ACCESS.2019.2904103.

[20] P. Dai, N. Xu, H. Q. Xie, and L. Yan, "PMSM sliding mode control based on fast power reaching law," *Electric Machines and Control*, vol. 21, no. 11, pp. 32-38, 2017.

[21] C. -C. Hua and X. -P. Guan, "Smooth dynamic output feedback control for multiple time-delay systems with nonlinear uncertainties," *Automatica*, vol. 68, pp. 1–8, Jun. 2016, doi: 10.1016/j.automatica.2016.01.007.

[22] S. -L. Shi, J. -X. Li and Y. -M. Fang, "Extended-state-observer-based chattering free sliding mode control for nonlinear systems with mismatched disturbance," in *IEEE Access*, vol. 6, pp. 22952-22957, 2018, doi: 10.1109/ACCESS.2018.2828868.

[23] E. Lu, W. Li, S. Wang, W. Zhang, and C. Luo, "Disturbance rejection control for PMSM using integral sliding mode based composite nonlinear feedback control with load observer," in *ISA Transactions*, vol. 116, pp. 203-217, Oct. 2021, doi: 10.1016/j.isatra.2021.01.008.

[24] Y. Ge, L. Yang, X. Ma, "Adaptive sliding mode control based on a combined state/disturbance observer for the disturbance rejection control of PMSM," in *Electrical Engineering*, vol. 102, pp. 1863–1879, 2020, doi: 10.1007/s00202-020-00999-4.

[25] W. Gao and J. C. Hung, "Variable structure control of nonlinear systems: a new approach," in *IEEE Transactions on Industrial Electronics*, vol. 40, no. 1, pp. 45-55, Feb. 1993, doi: 10.1109/41.184820.

[26] H. Li and Y. Cai, "Sliding mode control with double power reaching law," *Control and Decision*, vol. 31, no. 3, pp. 498-502, 2016.

[27] C. Xiu and P. Guo, "Global terminal sliding mode control with the quick reaching law and its application," in *IEEE Access*, vol. 6, pp. 49793-49800, 2018, doi: 10.1109/ACCESS.2018.2868785.

[28] S. P. Bhat and D. S. Bernstein, "Finite-time stability of continuous autonomous systems," in *SIAM Journal on Control and optimization*, vol. 38, no. 3, pp. 751-766, 2020, doi: 10.1137/S0363012997321358.

[29] N. Mohamed, F. Aymen, B. H. Mouna, and S. Lassaad, "Modeling and simulation of vector control for a permanent magnet synchronous motor in electric vehicle," in *2021 4th International Symposium on Advanced Electrical and Communication Technologies (ISAECT)*, 2021, pp. 1-5, doi: 10.1109/ISAECT53699.2021.9668411.

[30] S. Li, M. Zhou, and X. Yu, "Design and implementation of terminal sliding mode control method for PMSM speed regulation system," in *IEEE Transactions on Industrial Informatics*, vol. 9, no. 4, pp. 1879-1891, Nov. 2013, doi: 10.1109/TII.2012.2226896.

[31] H. Pan, W. Sun, H. Gao, and X. Jing, "Disturbance observer-based adaptive tracking control with actuator saturation and its application," in *IEEE Transactions on Automation Science and Engineering*, vol. 13, no. 2, pp. 868-875, April 2016, doi: 10.1109/TASE.2015.2414652.

[32] K. Ullah, J. Guzinski, and A. F. Mirza, "Critical review on robust speed control techniques for permanent magnet synchronous motor (PMSM) speed regulation," in *Energies*, vol. 15, no. 3, p. 1235, Feb 2022, doi: 10.3390/en15031235.

[33] R. Miklosovic and Z. Gao, "A robust two-degree-of-freedom control design technique and its practical application," in *Conference Record of the 2004 IEEE Industry Applications Conference, 2004. 39th IAS Annual Meeting*, 2004, pp. 1495-1502 vol.3, doi: 10.1109/IAS.2004.1348669.

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