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High-order Supper-twisting Based Terminal Sliding Mode Control Applied on Three Phases Permanent Synchronous Machine

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Abstract

Nowadays, research on electric drive control has become popular because hybrid methods to collect the advantages of individual controllers. Moreover, these methods aim to reach better performance and robust control even in the presence of uncertainties and disturbances which are typically evident in high-speed dynamics where the influence of external disturbances and modeling errors are more evident. Therefore, in this paper, a novel hybrid controller is proposed between the super-twisting algorithm based on high order design (HO-STA) and terminal sliding mode control (T-SMC) applied on a permanent magnet synchronous motor PMSM. Whereas, it accounts to deal with the weaknesses of both terminal sliding mode control and super twisting algorithm (STA) and at the same time combining their advantages; furthermore, it provides exceptional characteristics, including fast finite-time convergence, stabilization of the performance and its reaching law developer based on new design which contributes to reducing the chattering problems afflicted by C-SMC. This proposed hybrid technique contributes to gaining robust control under variation between slow, medium, and high speed levels, no matter what load torque is applied or whatever PMSM parameters change. Moreover, it also offers optimum performance characteristics such as smaller settling time and steady state error. Whereas, the control efficiency is demonstrated by Matlab/Simulink simulation to confirm our design parameters.

Keywords

robust control, nonlinear control, supper twisting algorithm, terminal sliding mode, high order sliding surface, permanent magnet synchronous motor, exponential reaching law

1 Introduction

Many various areas such as electric vehicles, aerospace, numerical control systems, and wind power generation are highly dependent on the permanent magnet synchronous motors (PMSM) due to small volume, light weight, high efficiency, high power factor, fast response, wide speed range, and good accuracy [1–4].

Despite its dominance over the other electrical machines like induction motor and its supremacy in actuation performance as mentioned above, it is a non-linear model, strongly coupled, and multivariable [5, 6].

Traditional controllers have been applied like FOC, which depends on the PI regulator, but they aren't effective for a high-performance control when external system disturbance, uncertainties, or variation of speed levels is required [7–10].

The researchers are focused on advanced controls, where each technique depends either on nonlinearity, optimization, robustness method like backstepping, adaptive, sliding mode, feedback linearization, passivity-based, optimal, and intelligent techniques to name few [11–14]. Furthermore, the conventional sliding mode technique is one of the most important techniques that have been successfully applied to the PMSM system because of its fast dynamic response, easy implementation, and its robustness in the high-performance control as mentioned above [15, 16].

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Despite these features of the sliding control, it suffers from the problem of chattering because of time delay and space lag of the switch, the error of the state detection, and other factors when applied to the actual system [17, 18].

Several researchers have tried reducing this problem by proposing several ways based on SMC methods, for example, in the articles [19–22], the researchers developed a sliding mode control to use exponential switching law and sigmoid function.

Although, it effectively contributed to the suppression of chattering in the slipping position, it is the convergence stability of the system, which is reduced to a certain extent, and there performance better against the sliding mode chattering and switching performance and robustness due to the sigmoid function and the exponential reaching law respectively.

The articles [23–26] contributed to reducing the steady-state error, the fast response time of the PMSM performance, and robustness to external disturbances like load torque variation and applied the integration of state variables into the conventional sliding mode surface to use integral sliding mode surface.

But the addition of the integral on the surface leads to a large overshoot, which affects the quality of the controller because it produces integral saturation of the integral sliding mode surface.

The articles [1, 27–29] used a terminal sliding mode control, which affords remarkable characteristics, including fast and finite-time convergence, however, since the convergence time is relatively long and the dynamic properties are worsen when the state of the system is far from the equilibrium point.

Some other researchers solved the problems mentioned above by proposing a hybrid technique between the sliding mode control and other advanced technique like adaptive, intelligent, or optimal control.

Article [30] proposed a new design control between the sliding mode control based on the exponential reaching law and the passivity-based control. In their design, SMC is applied on the speed loop, while the passivity-based control is applied on the *d*-*q* currents loop.

Although, this hybrid controller performs better than a classical SMC, it does not significantly improve the performance characteristics, as undershoot appeared on the speed performance during disturbance and uncertainties. Article [31] proposed a new design of high order based on a super twisting algorithm (NSTA) applied on the speed loop and leave classical control (FOC) applied on the currents loop, where a proportional term along with an adaptive term is used in addition to the original of NSTA.

This proposed controller contributed to solving low reaching speed, and poor anti-disturbance ability due to the square root calculation of proportional term in the original super twisting algorithm. However, the problem of overshoot and undershoot is a concern when applying at high speed or applying torque with increased steady-state error. In addition, the uncertainties like resistance will impede the performance and stability of the motor due to the application of classical control (FOC) on the current loop.

Article [32–35] used a hybrid technique between the terminal sliding mode and backstepping control to achieve speed regulation despite uncertainties and disturbances, this latter contributed to giving a relatively robust control and stabilizing the steady state error. However, the phenomenon of chattering, overshoot and undershoot are present during the change of speed and during the application of the torque.

Other articles suggested some new super-twisting sliding mode based on intelligent proportional-integral control [36], adaptive control based on a super-twisting sliding mode [37], sliding mode control based on the fractional-order method [38, 39], sliding mode based on intelligent control [40, 41], and hybrid control composed of adaptive, sliding mode and intelligent control [42, 43]. However, optimizing more performance characteristics of PMSM and applying robust control to achieve high-performance, robust to uncertainties, and external disturbances remain the researchers' main challenge.

To overcome the above problems, this paper proposes a High-order super-twisting algorithm based terminal sliding mode control (HO-STA based T-SMC) applied on the speed loop and the exponential reaching law based sliding mode control applied on the current loop. This hybrid design is found to exhibit improved speed performance characteristics and gives a robust control for the hardest sceneries as discussed above. The remainder of the paper is organized as follows.

In Section 2, the modeling of the PMSM is shown. In Section 3, the design of hybrid control is proposed. In Section 4, simulation results and discussion are shown to demonstrate the effectiveness of the proposed control strategy. Some conclusions are drawn in Section 5.

2 PMSM model

The PMSMs is characterized by a nonlinearity feature to the electromagnetic torque, multi-state variable, external disturbances formed in *d-q* axis or what called back EMF to the *a-b* axis, in adding to eddy current and hysteresis loss, ignoring magnetic circuit saturation. Relying on these features, the model of the PMSM can be presented in the *d-q* axes as follows [44]:

$$\begin{cases} \frac{di_d}{dt} = \frac{1}{L_d}\left(-r \cdot i_d - p \cdot L_q \cdot \Omega \cdot i_q + V_d\right) \\ \frac{di_q}{dt} = \frac{1}{L_q}\left(-r \cdot i_q - p \cdot L_d \cdot \Omega \cdot i_d - p \cdot \psi_f \cdot \Omega + V_q\right) \\ \frac{d\Omega}{dt} = \frac{1}{J}\left(T_e - T_l - F \cdot \Omega\right) \\ \frac{d\theta_r}{dt} = \Omega \end{cases} . \quad (1)$$

The electromagnetic torque equation:

$$T_e = \frac{2}{3} p\left(\left(L_d - L_q\right) i_d \cdot i_q + \psi_f \cdot i_q\right), \quad (2)$$

where i_d, i_q are *d-q* axis equivalent stator currents, V_d, V_q are *d-q* axis equivalent stator voltages, Ω is mechanical speed, *p* is number of pole pairs, *r* is per phase stator resistance, L_d, L_q are *d-q* axis equivalent stator inductance, T_e, T_l are electromagnetic and load torques, *J* is moment of inertia of the rotor, *F* is friction constant of the rotor and ψ_f is rotor magnetic flux linking the stator.

3 Design of the hybrid control proposed

Classical SMC control has been widely used on PMSMs due to its relatively robust performance against the uncertainties, and the external disturbances, in addition to its ease of application and its fast response; however, it suffers from an chattering problem due to the time delay and space lag of the switch, the error of the state detection, and other factors during it applied on the actual model as these problems result in the deterioration of system performance [20].

On the other hand, it cannot deal with the finite-time convergence property of system state because it depends only on a linear sliding surface this indicates it is only guarantee to converge asymptotically the states of the system.

3.1 Formulation to a high order of sliding surface based PMSM speed

Sliding surface selection is the most important step before applying surface conditions for sliding mode control, as at present it has been greatly developed in order to solve the problem of chattering and convergence of system states. Wherefore, the general form of sliding surface and sliding condition can be designed as follows:

$$s(x,t) = \left(\frac{d}{dt} + \lambda\right)^{n-1} \varepsilon(t) \quad (3)$$

$$\frac{1}{2} \cdot \frac{d}{dt} \cdot s^2 \le -|s| \quad (4)$$

where $\lambda > 0$, *n* is system order, *ε* is tracking error and *s*(*x*, *t*) is sliding surface.

Choosing a high-order surface is the best choice during apply SMC. In order to achieve this and through the PMSM model represented in the Eqs. (1) and (2), the PMSM speed system is designed based on the high order state-model HOSM as follow:

$$\begin{cases} x_1 = \theta_r \\ x_2 = \dot{\theta}_r = \Omega \\ x_3 = \ddot{\theta}_r = \dot{\Omega} \end{cases} . \quad (5)$$

And the HOSM based on tracking error designed like following:

$$\begin{cases} \sigma_1 = \varepsilon_\theta = \theta_{r-ref} - \theta_r \\ \sigma_2 = \dot{\varepsilon}_\theta = \varepsilon_\Omega = \Omega_{ref} - \Omega \\ \sigma_3 = \ddot{\varepsilon}_\theta = \dot{\varepsilon}_\Omega \end{cases} . \quad (6)$$

It is common that the operation of classical SMC is structured according two phases main are a sliding phase and an approaching, in order to determination the control law [45, 46].

The first phase require to select an appropriate sliding manifold to ensure the system state remains on the sliding surface until to the desired control performance is achieve, during this phase can the equivalent component $u_{eq}(t)$ is supposed to hold the system stationary on the sliding surface, depending on the two conditions shown in Eq. (7):

$$\begin{cases} s(x,t) = 0 \\ \dot{s}(x,t) = 0 \end{cases} . \quad (7)$$

The second phase make the system state to the sliding surface an invariant manifold and forces it to achieve the sliding surface in a finite amount of time in order to designing an appropriate control law which so-called switching or reaching component $u_s(t)$.

Whereas the equivalent and switching component law of the system PMSM speed is described by Eq. (8):

$$\left[u_{eq}(t) \quad u_s(t)\right]^t = \left[i^*_{q-eq} \quad i^*_{q-s}\right]^t . \quad (8)$$

3.2 T-SMC designing

In order to solve the "asymptotic tracking" feature in conventional sliding mode control design (CSMC) and provide the finite-time convergence to the system states on the nonlinear sliding surface, a terminal sliding mode control is proposed by Zaky and many other researchers [47].

Moreover, this technique contributes infinitely to the stability of the closed loop system and the reason for this feature is to provide convergence of the system states with the desired control point in a limited time.

The main objective of the sliding controller is to ensure rapid and finite-time states convergence during the sliding phase by implementing fractional power in the terminal sliding surfaces used.

The proximity to the equilibrium point contributes significantly to raising the accuracy of the control performance, by accelerating the rate of convergence [47].

Through this, the terminal sliding surface is as follows:

$$s_1 = \dot{\sigma}_1 + \beta_1 \sigma_1^{\frac{q_1}{p_1}} = \sigma_2 + \beta_1 \sigma_1^{\frac{q_1}{p_1}} . \tag{9}$$

The derivative of the terminal sliding surface is as follows:

$$\dot{s}_1 = \sigma_3 + \beta_1 \frac{q_1}{p_1} \sigma_2 \sigma_1^{\left(\frac{q_1}{p_1}-1\right)} . \tag{10}$$

During the sliding phase, if $s_1(\sigma, t) = 0$ and $\dot{s}_1(\sigma, t) = 0$, the equivalent component $u_{eq}(t)$ is supposed to hold the system stationary on the sliding surface. In the approaching phase, the switching component $u_s(t)$ is made to meet the reaching condition (sliding condition), in adding, the switching component is developed to use exponential reaching law as following:

$$u_s = k_1 s_1 + k_2 \operatorname{sign}(s_1) . \tag{11}$$

Finally, the law of control based on T-SMC is given by Eq. (12):

$$u_{\text{T-SMC}} = u_{eq} + u_s , \tag{12}$$

where σ_1, σ_2, σ_3 are states variable based on tracking error, and β_1, q_1, p_1, k_1, k_2 are T-SMC gains.

3.3 HO-STA designing

Although, T-SMC contributed to solving the second problem that it suffers from C-SMC aforementioned but it remained the chattering problem, which will reduce the control accuracy and lead to exciting neglected resonant modes may causes system performance to deteriorate.

Another Professor named Levant suggested a high order sliding mode algorithm so-called super twisting algorithm (STA) to overcome the chattering problems, reaching speed, and antidisturbance ability [48].

The super twisting algorithm simultaneously stabilizes the sliding surface with its derivative at zero, where no noise input contributes to the design of the control law, and this one of the most feature to high-order sliding mode algorithms.

The super twisting algorithms (STA) are based in two important parts to construct the control law, the first part is related to time and is determinate from its derivative. As for the second, it is determinate through the function of the sliding variable.

Hence, the general form of the Super-twisting algorithm [49–51] is as follows:

$$\begin{cases} u_{\text{STA}} = -\lambda_1 \cdot |s_2|^{\rho_1} \operatorname{sign}(s_2) + w \\ \dot{w} = -b_1 \cdot \operatorname{sign}(s_2) \end{cases} \tag{13}$$

with $s_2 = \sigma_2$, where s_2 is sliding surface of T-SMC, and λ_1 and b_1 are the gains used to regulate the Super Twisting controller, ρ_1 is a coefficient used to regulate the degree of nonlinearity.

3.4 Determination of the control law by HO-STA based T-SMC

Although T-SMC solve the problem convergence and HO-STA solve the chattering problem of the CSMC. But, it is difficult to ensure system convergence because the identification of algorithm gain requires that the smooth and bounded condition for the disturbance term be satisfied, which is more difficult in scientific experiments.

Moreover, a dangerous phenomenon of system jamming and collapse if an excessively setting a profit value in order to ensure system convergence [20].

In order to solve problems of C-SMC. This article proposes a hybrid control between T-SMC and STA, where the proposed control aim is combine advantages and solve problems both of T-SMC and STA.

Moreover, HO-STA based T-SMC not only can to reduce the chattering phenomenon in original TSMC design but also can reach tracking performance in a finite amount of time [52].

Through this, the HO-STA based T-SMC schemes will be applied to the control of a PMSM speed model to demonstrate the applicability and effectiveness.

Firstly, based on the sliding surface of T-SMC and state-model HOSM, the sliding surface of HO-STA based T-SMC is designed like following:

$$s_2 = \dot{s}_1 = \dot{\sigma}_2 + \left(\beta_2 \sigma_1^{\frac{q_2}{p_2}}\right)' = \sigma_3 + \beta_2 \frac{q_2}{p_2} \sigma_2 \sigma_1^{\left(\frac{q_2}{p_2}-1\right)}. \tag{14}$$

During the sliding phase, if $s_1(\sigma, t) = 0$ and $s_2(\sigma, t) = 0$, the equivalent component $u_{eq}(t)$ is supposed to hold the system stationary on the sliding surface. Where, the input signal is the reference of quadratic current, and to depend on the vector control method, the equivalent law represent as follow:

$$T_e = J \cdot \dot{\Omega}_{ref} + T_l + F \cdot \Omega + J \beta_2 \frac{q_2}{p_2} \sigma_2 \sigma_1^{\left(\frac{q_2}{p_2}-1\right)} \tag{15}$$

$$I^*_{q\_eq} = \frac{2}{3 p \psi_f} T_e . \tag{16}$$

Secondly, by exploiting of the HO-STA based T-SMC approach and replacing the signum function with a continuous approximation, called hyperbolic tangent, the switching law of HO-STA based T-SMC is designed like following:

$$\begin{cases} I^*_{q\_s} = -\lambda_2 \cdot |s_1|^{\rho_2} \operatorname{tgh}(s_1) + w \\ \dot{w} = -b_2 \cdot \operatorname{tgh}(s_1) \end{cases} . \tag{17}$$

The general form for determining the value of ρ is as follows:

$$0 < \rho_2 \leq 0.5 .$$

But it often takes the value $\rho_2 = 0.5$, in order to provide maximum control, high-order sliding mode control [53].

Finally, the law of control based on HO-STA based T-SMC is given as follow:

$$I^*_q = I^*_{q\_eq} + I^*_{q\_s} \tag{18}$$

$$I^*_q = \frac{2}{3 p \psi_f} \left(J \cdot \dot{\Omega}_{ref} + T_l + F\Omega + J \beta_2 \frac{q_2}{p_2} \sigma_2 \sigma_1^{\left(\frac{q_2}{p_2}-1\right)} \right), \tag{19}$$
$$-\lambda_2 \cdot |s_1|^{\rho_2} \operatorname{tgh}(s_1) + w$$

where s_3 is a high order based terminal sliding surface and designed in Eq. (14), w is an integral switching term of supper-twisting algorithm and designed in Eq. (18).

3.5 Proof stability

In order to demonstrate stabilization of the system during applying the control law proposed in this paper must be using the Lyapunov function, where it is selected as follows:

$$V = \frac{1}{2} S_1^2 . \tag{20}$$

The system is stable if Lyapunov function is positive definite and its derivative is negative. Depending on this method, its derivative can be write as follow:

$$\dot{V} = S_1 \cdot \dot{S}_1 = S_1 \cdot S_2 . \tag{21}$$

The first surface derivative gives the second surface derivative, from Eqs. (14) and (21), we have:

$$S_1 \cdot S_2 = S_1 \cdot \left(\sigma_3 + \beta_2 \frac{q_2}{p_2} \sigma_2 \sigma_1^{\left(\frac{q_2}{p_2}-1\right)} \right). \tag{22}$$

Substituting the value of the σ_3 represented by Eq. (6), the Eq. (22) becomes as follows:

$$S_1 \cdot S_2 = S_1 \cdot \left(\dot{\Omega}_{ref} - \dot{\Omega} + \beta_2 \frac{q_2}{p_2} \sigma_2 \sigma_1^{\left(\frac{q_2}{p_2}-1\right)} \right). \tag{23}$$

Depending on the expresion of the dynamic equation to the PMSM represented in Eq. (1):

$$S_1 \cdot S_2 = S_1 \cdot \left(\dot{\Omega}_{ref} - \frac{1}{J}\left(T_e - T_l - F \cdot \Omega\right) + \beta_2 \frac{q_2}{p_2} \sigma_2 \sigma_1^{\left(\frac{q_2}{p_2}-1\right)} \right). \tag{24}$$

Using the Eqs. (15), (16), (18) and (19), can be write the Eq. (24) as below:

$$S_1 \cdot S_2 = S_1 \cdot \left(-\frac{1}{J} \cdot \left(\frac{2}{3} p \cdot \psi_f \right) \cdot I^*_{q\_s} \right). \tag{25}$$

Finally must be the value of $I^*_{q\_s}$ is positive definite.

In order to achieve that, the gains of the HO-STA represented in the Eq. (17) must be take the negative value.

$$\begin{cases} \overline{\lambda_2} = |-\lambda_2| \\ \overline{b_2} = |-b_2| \end{cases} \tag{26}$$

4 Result simulatn and discussion

To demonstrate the effectiveness the technique proposed on the PMSM under the external disturbance, and its robustness against the uncertainties, as well as its durability during the high performance speed, a simulation model was created in Matlab/Simulink as illustrated in Fig. 1. The PMSM parameters adopted for the simulation are given in Table 1.

To achieve the above-mentioned objective, the most difficult scenarios in which the performance of the PMSM speed is going through are presented:

- Speed level varied to demonstrate the durability during the high performance;

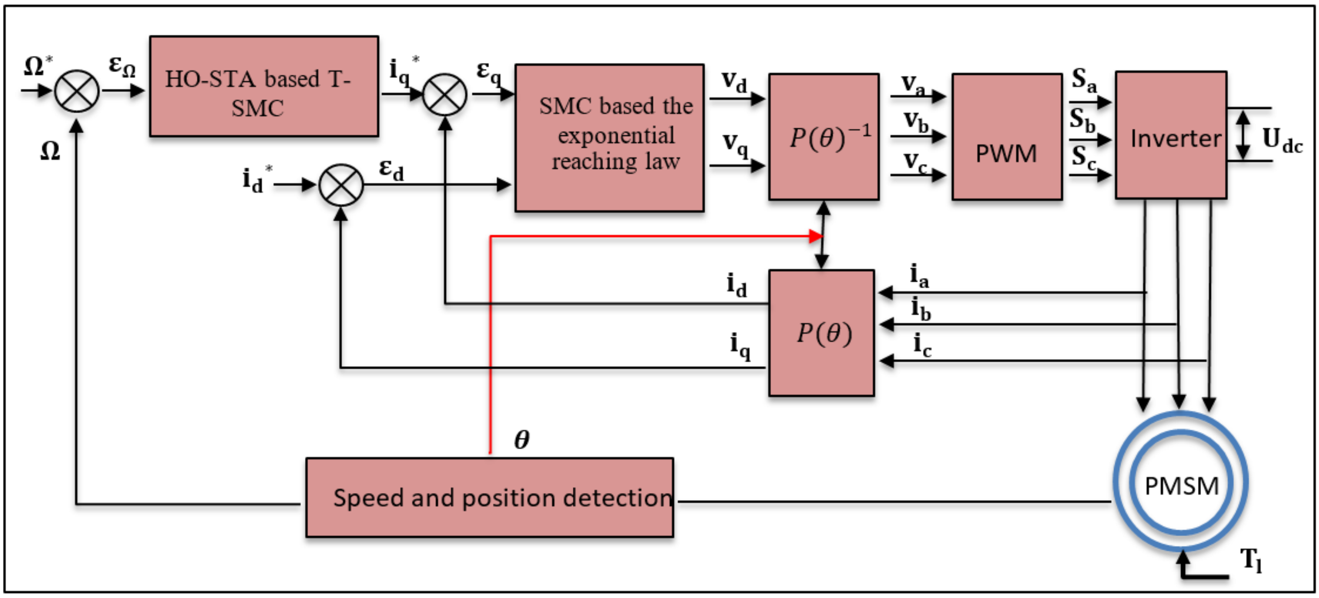

Fig. 1 Global scheme of PMSM control based on HO-STA based T-SMC

Table 1 Parameters of PMSM model

PMSM parameters	Value
Stator resistance r	0.6 Ω
D-axis induction L_d	1.4e – 3H
Q-axis induction L_q	2.8e – 3H
Friction constant F	0.0014
Rotational inertia J	0.0011 kg·m^2
Magnetic flux ψ_f	0.12 Wb
Number of pole pairs p	4
DC bus voltage V	100 V

- Load torque applied to demonstrate the effectiveness under external disturbance;
- Parameters varied to demonstrate the robustness control.

Furthermore, the proposed technique (HO-STA based T-SMC), STA-SMC, and T-SMC are compared and simulated to verify the efficiency accuracy of the proposed control, where all the mentioned control above is applied on the speed loop, and the exponential reaching law based on the sliding mode control is applied on the current loop.

The control parameters designed in the simulation results are as follows, HO-STA based T-SMC parameters are β_1 = 0.01, q_1 = 0.6, p_1 = 0.5, k_1 = 0.05, k_2 = 0.0001, STA-SMC parameters are λ_1 = 2, b_1 = 0.001, ρ_1 = 0.38, T-SMC parameters are β_2 = 0.001, q_2 = 0.6, p_2 = 0.5, $\overline{\lambda_2} = 1.9$, $\overline{b_2} = 0.1$, $\rho_2 = 0.5$.

Fig. 2 shows the PMSM adopts its high-performance, where the speed level is varied between low, medium, and high speed.

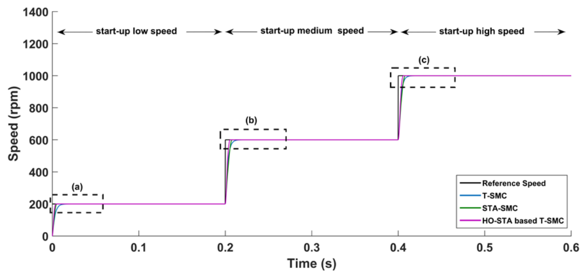

Fig. 2 High-performance of PMSM speed levels

To study the performance changes that occur at the level of each speed. Fig. 3 and Table 2 show the region (a) presented in Fig. 2, where it presents speed performance of the PMSM during the start-up low speed (200 rpm) with a comparative study among the techniques mentioned above, where the HO-STA based T-SMC has the least settling time approx. to 4 ms, and smallest steady-state error.

Fig. 4 and Table 2 show the region (b) presented in Fig. 2, it gives the second level of the speed performance, which is characterized by the medium speed of the PMSM to 600 rpm. Despite this, the HO-STA based T-SMC

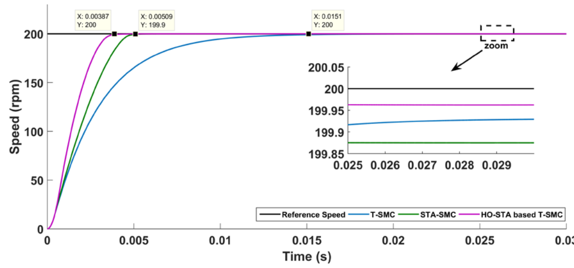

Fig. 3 Enlargement to the performance characteristics of low speed (region (a) of Fig. 2)

Table 2 Performance characteristics of speed PMSM model under variation of speed level

Performance characteristics		HO-STA based T-SMC	STA-SMC	T-SMC
Settling Time (ms)	Low speed	4	5	15
	Medium speed	5.6	8	18
	High speed	6	10	20
Steady-state error (%)	Low speed	0.02	0.08	0.03
	Medium speed	0.008	0.03	0.02
	High speed	0.1	0.4	0.3

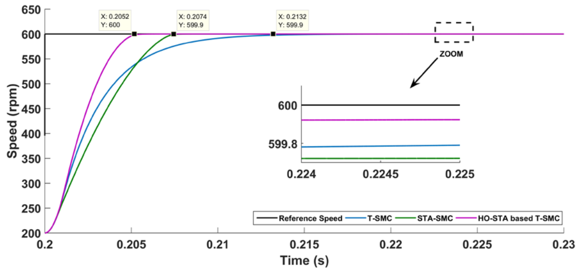

Fig. 4 Enlargement to the performance characteristics of medium speed (region (b) of Fig. 2)

maintains its durability under the change of speed from low to medium in terms of the lowest percentage change for each lower settling time and the steady-state error.

Fig. 5 and Table 2 show the region (c) presented in Fig. 2, where it shows a changing the speed to the third level, which represents the highest speed of the performance to 1000 rpm, even with this variation suddenly in PMSM speed from medium speed to high speed, the proposed control maintains superior durability to the characteristics of the PMSM compared to STA-SMC and T-SMC.

In order to achieve the robustness of the proposed control under the influence of uncertainties, the change of PMSM parameters which are resistance and inertia to increasing rates was studied.

Fig. 6 shows this scenario, where the PMSM parameters are changed to 0%, 50%, 100%, 150% and 200% with apply a medium speed; moreover, the proposed control and STA-SMC and T-SMC are compared.

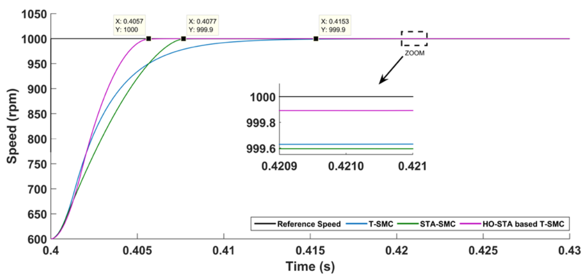

Fig. 5 Enlargement to the performance characteristics of high speed (region (c) of Fig. 2)

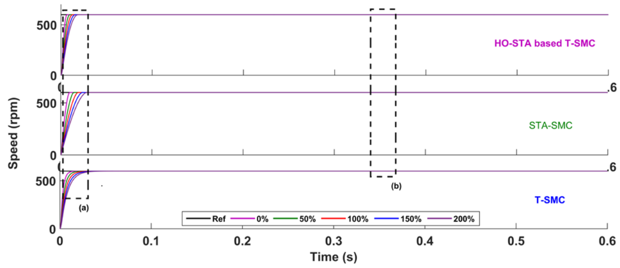

Fig. 6 Robustness scenario under the influence uncertainties

To clarify the change in the performance of the PMSM characteristics in light of the change of parameters in the above-mentioned ratios, the regions (a) and (b) of Fig. 6 are detailed in Fig. 7 and Fig. 8 respectively. Fig. 7 and Table 3 are presented the rate uncertainty change in the settling time to each control, as the proposed control takes the lowest rate of uncertainty change, which is estimated to 0.03 step among each the percentage of parameters variation mentioned above.

Fig. 8 and Table 3 are presented the rate of steady-state error change to each control during the parameters variation of the aforementioned ratios; however, the proposed control keep also characterized by the lowest rate of steady-state error change. With the rates of change presented by this scenario; therefore, the proposed control takes preference over the robustness of the control.

The most important problems that affect performance are external disturbances which were addressed by both controls T-SMC then STA-SMC, which were applied by a lot of research; however, there appear on the level of the speed performance some overshoot or undershoot peaks with there remains a steady state error; to reduce

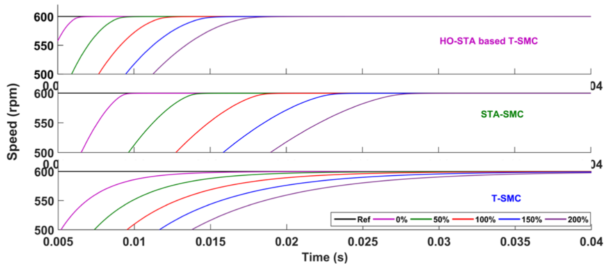

Fig. 7 Enlargement of the local speed response on region (a) of Fig. 6

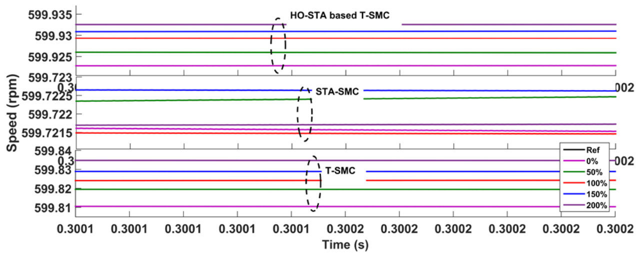

Fig. 8 Enlargement of the local speed response on region (b) of Fig. 6

Table 3 Performance characteristics of speed model under PMSM's uncertainties

Performance characteristics		HO-STA based T-SMC	STA-SMC	T-SMC
Steady-state error (%)	Uncertainties to 0%	0.0128	0.0464	0.0317
	Uncertainties to 50%	0.0123	0.04627	0.0300
	Uncertainties to 100%	0.0117	0.04642	0.0293
	Uncertainties to 150%	0.0115	0.04623	0.0255
	Uncertainties to 200%	0.0113	0.0463	0.0275
Settling time (ms)	Uncertainties to 0%	6	15	20
	Uncertainties to 50%	9	20	30
	Uncertainties to 100%	12	25	40
	Uncertainties to 150%	15	3	50
	Uncertainties to 200%	18	35	60

these peaks and the steady state error, this technique was proposed HO-STA based T-SMC, which contributes to improving the speed performance significantly compared to the aforementioned controls.

Wherefore, Fig. 9 shows the effectiveness of the proposed technique under the effect of the external disturbance, where the latter was represented by an applied load torque at different times with its value is 1 Nm with keeping the medium speed. The regions (a), (b) and (c) of Fig. 9 are detailed in Figs. 10, 11 and 12 respectively.

Fig. 10 and Table 4 are presented a comparative study with regard to the settling time among the proposed technique and the aforementioned controls; through these results, the proposed technique remains better compared to other controls in terms of settling time, which is estimated at 6.1 ms.

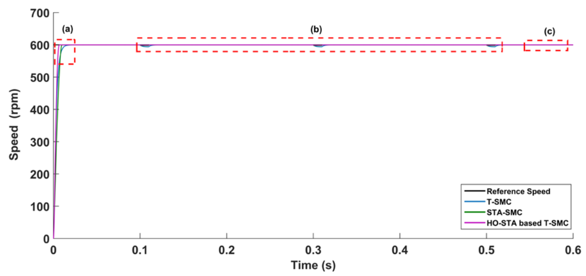

Fig. 9 Control effectiveness under external disturbance

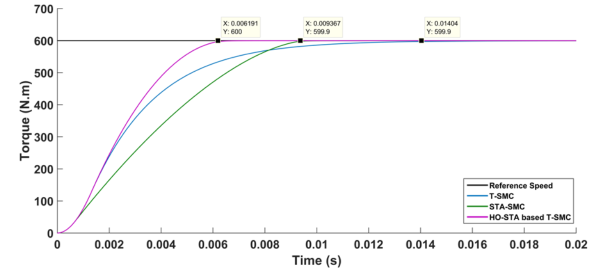

Fig. 10 Enlargement of region (a) of Fig. 9 to the external disturbance applied

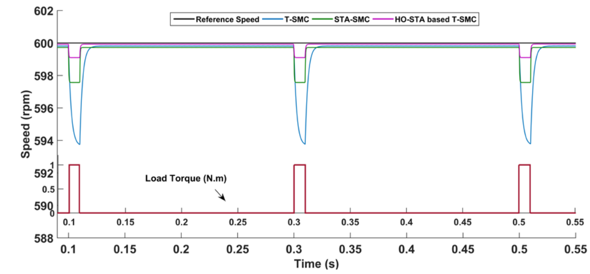

Fig. 11 Enlargement of region (b) of Fig. 9 to the external disturbance applied

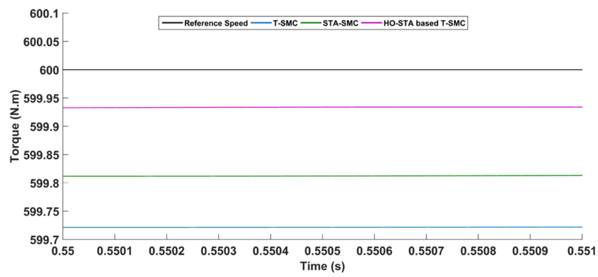

Fig. 12 Enlargement of region (c) of Fig. 9 to the external disturbance applied

Table 4 Performance characteristics of speed model under PMSM's external disturbance

Performance characteristics	HO-STA based T-SMC	STA-SMC	T-SMC
Settling time (ms)	6.1	9.3	14
Steady-state error (%)	0.01	0.03	0.045
Undershoot (%)	0.15	0.4	1
Undershoot period (ms)	1	1.2	1.8

Fig. 11 and Table 4 show the efficiency advantage of the proposed control compared to other controls, where during load torque applied on the PMSM, where the undershoot for the proposed control is almost three times less compared to HO-STA and six times less compared to T-SMC; moreover, its undershoot takes a period of 1 ms and represented the least estimated compared the other controls the above-mentioned.

Fig. 12 and Table 4 give a comparison of the steady state error among each studied control; also, the proposed control contributed to reducing the steady-state error by three times compared to the STA-SMC, and by four and half times compared to the T-SMC, where its steady state error is estimated to be 0.01%.

5 Conclusion

In this paper, a novel high order supper twisting algorithm based on a terminal sliding mode control (HO-STA based T-SMC) is proposed, aiming at improving the speed performance of permanent magnet synchronous motor.

Based on this goal, a new hybrid control has been designed, where it combines the advantage of the supper twisting, which is represented in the perfect performance characteristics such as small settling time and small steady-state error, and the advantage of the terminal which is represented by a high order of sliding surface the convergence feature, in addition, this design helped to obtain the stability of the system, increase the durability of the control under uncertainties and external disturbance of the system. Moreover, the simulation results obtained confirmed the efficiency of the proposed control.

In the future, we look forward to improving the speed reference to an estimated speed depending on the observation techniques; from it, the control performance will be better improved, and on the other hand, it is provided the sensorless speed of the PMSM.

In addition, will develop the inverter control by changing its classical control (PWM) by SVM based on predictive technique; where all control gains are improved using a reinforcement learning algorithm. Furthermore, all these contributions will be solidly prepared and with excellent performance characteristics for embodying this study in electric car systems.

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