Research on PMSM control without speed sensorless applied to industrial electric drive system based on ADSMC method

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ABSTRACT

The paper research, calculates, and designs an industrial electric drive system control such as: computer numerical control (CNC) machining machines, milling machines, and grinding machines, with sensorless permanent magnet synchronous motors (PMSM) based on measuring current components, axial position and applied voltage to obtain information about rotation angle and speed for PMSM based on adaptive sliding mode control (ADSMC) method. Here an optimal sliding surface will be designed to demonstrate faster convergence than conventional sliding mode control. Then, an adaptive law is researched and developed to make the control parameters, especially the switching gain, updated quickly online. Therefore, the motor noise can be effectively reduced and the system can be better eliminated from noise, Chattering, and nonlinear noise. Finally, a reference model was created, the exponential decay curve was applied to track the angular position error. The ADSMC system with model reference proposed by the authors in the paper has combined the advantages of sliding mode control method and adaptive control method according to the sample model. The simulation results show that the performance is achieved faster and the control process is more accurate, the error of speed and angular position (less than 0.01%) compared to other control methods.

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1. INTRODUCTION

Nowadays, the automation control of some intelligent electric drive systems of industrial machines is developing strongly, as shown in Figure 1. This electric drive system always needs to work with high precision and limited rotation angle: electric drive system for military weapons, electric drive system in ground radar antenna system and on aircraft, the mechanisms of electric drive system for cutting tools of computer numerical control (CNC) metal cutting machines, lathes, milling machines, and bed planers. Therefore, in this paper, the authors have used speed control and position control of the motor to increase the accuracy when not using speed sensors in the control process, but using adaptive sliding mode control (ADSMC) control algorithm to control, by measuring and estimating the current and voltage components of the rotation angle and speed of the motor to evaluate the output components to replace the speed sensor, [1]-[5]. From there, the authors researched the design, calculation, and simulation modeling of the drive system based on the sliding mode control method combined with adaptive law using permanent magnet synchronous motors (PMSM) motor, taking into account noise and nonlinear components in the control synthesis process, to improve the control accuracy for industrial electric drive systems [6]-[9].

Some common ways to obtain speed values and obtain accurate feedback positions are to use speed and position sensors, [3], [5], [8] which have not been very effective in control. Some authors have used classical (old) controllers for calculation and traditional controllers (not very effective) such as: using proportional integral derivatives (PID) to calculate estimates, proportional derivative (PD) controller, sliding fuzzy PD, and PD+I method combined with sliding control, proportional integral (PI) set combined with sliding control, sliding control combined with neural networks, using adaptive controllers without sliding mode in machining drives (not yet solved), quadratic and cubic linear regulators - linear quadratic regulator (LQR) and many other classical controllers, and recently authors have also used direct measurement methods [7], [9]-[13]. These methods have not yet improved the control quality for machine drive systems such as drilling machines, CNC grinding machines, leading to quality not being as good as current controllers, [3]-[5], [14], [15]. Therefore, it always causes many errors (interference, nonlinear factors) and the system operates inaccurately, causing the quality of the controller to be low and the product cost to be high, [16]-[19]. The system works non-optimally, is not synchronized, and is not economically efficient, [19]-[22]. Therefore, it is necessary to have a controller that brings economic efficiency and improves control quality, reducing costs for processing machines such as the ADSMC controller [23]-[26].

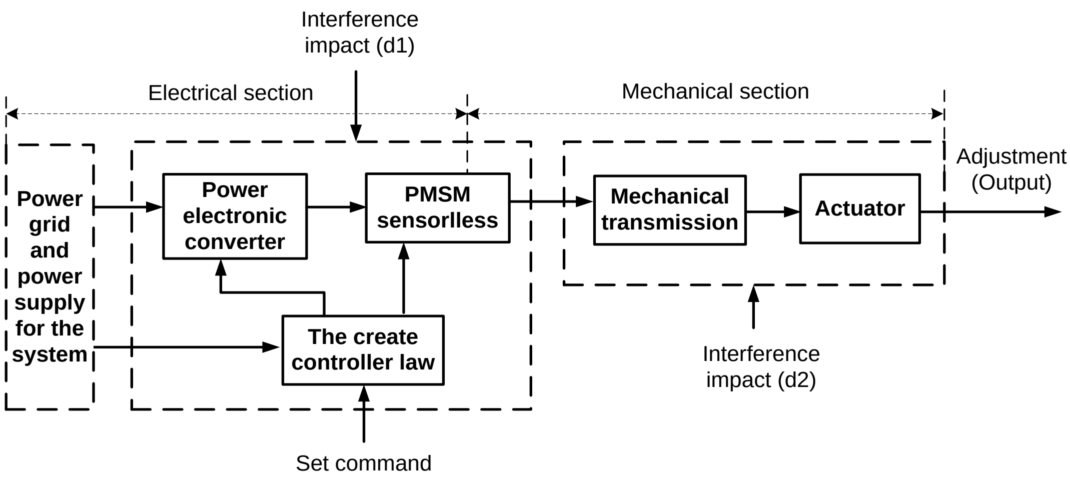

Figure 1. The structural diagram of an industrial electric drive system using PMSM sensorless

In this paper consists of the following main parts: section 1 introduces a general overview of the research methodology. Section 2 builds a mathematical model of the PMSM motor drive system. Section 3 authors research the calculation and design of an adaptive sliding controller using a sensorless PMSM motor for industrial electric machine drive systems. Section 4 presents the simulation results and discusses the issues. Section 5 is the general conclusion of the paper.

2. RESEARCH AND BUILD A PMSM MOTOR CONTROL MODEL FOR INDUSTRIAL ELECTRIC DRIVE SYSTEMS

From the model of the industrial electric drive system with the structure introduced in Figure 1. The author conducts research on the PMSM motor with its spatial vector coordinates as Figure 2. Then, the spatial vector coordinates are taken with the d-q system as the reference coordinate system, from which the mathematical model of the PMSM motor is expressed as (1) [5], [6], [11], [12], [18]:

$$\begin{cases} u_d(t) = L_s \dot{i}_d(t) - L_s \omega_r(t) i_q(t) + R_s i_d(t) \\ u_q(t) = L_s \dot{i}_q(t) - L_s i_d(t) \omega_r(t) + \psi_r \omega_r(t) + R_s i_q(t) \\ T_e(t) = K_t i_q(t) \\ \frac{J}{n_p} \dot{\omega}_r(t) = T_e(t) - \frac{B}{n_p} \omega_r(t) - T_L \end{cases} \tag{1}$$

Where, the components $u_d(t)$, $u_q(t)$ are the stator voltage values of the d axis and q axis, respectively; the current components $i_d(t)$, $i_q(t)$ are the stator currents of the d axis and q axis, respectively; L_s is the stator inductance; R_s is the stator resistance value; $\omega_r(t)$ is the motor rotor angular velocity; $T_e(t)$ is the electromagnetic torque; n_p is the number of pole pairs; K_t is the motor torque constant; J is the system moment of inertia; B is the standard value of the viscous friction coefficient; T_L is the load torque; ψ_r is the flux linkage of the motor rotor. The reference current value on the d-axis (i_d^*) is always set to 0. Suppose we do not consider external disturbance factors. Then, we take the angular position and velocity as state variables for the system, from which the model can be represented as (2):

$$\begin{cases} \dot{\theta}_r(t) = \omega_r(t) \\ \dot{\omega}_r(t) = \frac{n_p K_t}{J} i_q(t) - \frac{B}{J}\omega_r(t) = \frac{n_p K_t}{J} i_q^*(t) - \frac{B}{J}\omega_R(t) + \frac{n_p K_t}{J}\left(i_q(t) - i_q^*(t)\right) \\ \quad = a i_q^*(t) + b\omega_r(t) + c(t) \end{cases} \tag{2}$$

where, θ_r is the rotor angle, $a = n_p K_t / J$, $b = -\frac{B}{J}$, $c(t) = a(i_q(t) - i_q^*(t))$. In fact, the working process of the drive system has noise and nonlinear factors caused by the load torque T_L to the system. Then we can rewrite the system model as (3):

$$\begin{cases} \dot{\theta}_r(t) = \omega_r(t) \\ \dot{\omega}_r(t) = (a + \Delta a) i_q^*(t) + (b + \Delta b)\omega_r(t) + c(t) - T_L = a i_q^*(t) + b\omega_r(t) + d(t) \end{cases} \tag{3}$$

where, d(t) is called the disturbance and and is written as (4):

$$d(t) = \Delta\, a i_q^*(t) + \Delta b \omega_r(t) + c(t) - T_L \tag{4}$$

There disturbance is given as (5):

$$|d(t)| < \eta_0 \tag{5}$$

where, η_0 is a given positive constant. However, the η_0 component can be calculated in (4) for some applications in each specific drive system, depending on the control quality assessment.

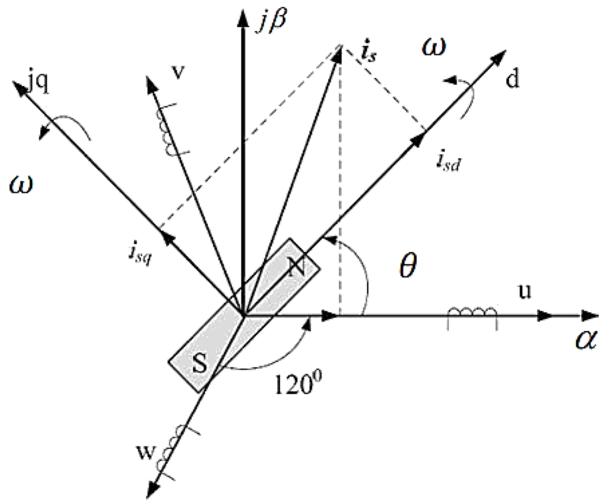

Figure 2. The space vector coordinate of PMSM

The currently, in industrial electric drive systems, the uncertain nonlinear components mainly arise from the load torque (resistance torque) and frequently change due to the inertia of the system, leading to disturbance factors. In order to optimize the motor performance and improve the rigidity of the mechanical characteristics when controlling sensorless PMSM motors, it is very important to ensure the operating conditions, which requires the application of intelligent control strategies, [5], [6], [9], [10].

3. RESEARCH AND DESIGN AN ADAPTIVE SLIDING MODE CONTROLLER USING SENSORLESS PMSM MOTORS FOR INDUSTRIAL ELECTRIC DRIVE SYSTEMS

The field-oriented vector control for systems with PMSM position controllers has been widely used, [15], [16], [21], [26]. It has a structure consisting of a position loop, a speed loop and a current loop. In this paper, the position loop and the speed loop will be unified (hereinafter referred to as the position-speed loop). Based on a reference model with a sliding mode controller. The authors research and develop an ADSMC controller for position control of sensorless PMSM drive systems, then calculate the stability of the system control algorithm and prove it by the Lyapunov method. Then the reference model expression is selected as:

$$\dot{e}_m + \lambda_m e_m = 0 \quad (6)$$

where, e_m is the output value of the reference model and λ_m is a positive constant, position error is $e = \theta_r - \theta_{ref}$, and θ_{ref} is position reference.

$$e_m = c(e^{-\lambda_m})^t \quad (7)$$

With $c > 0$, t is the time, λ_m is the adjustment factor. We determine the state of the system $x_1 = e - e_m$, then we have:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = \ddot{\theta}_r(\text{t}) + \ddot{\theta}_{ref}(\text{t}) + \ddot{e}_m = ai_q^*(t) + b\omega_r(t) + d(t) + \ddot{\theta}_{ref}(\text{t}) - \ddot{e}_m \end{cases} \quad (8)$$

Then we design the integral sliding surface with the following dynamic model:

$$s = \dot{x}_1 + \beta(t)x_1^\gamma + \alpha x_I \quad (9)$$

$$\dot{x}_I(t) = x_1^{q/p}(t) \quad (10)$$

where, γ calculation parameters, $\beta(t)$ is calculation and updated using an adaptive rule, α is a positive constant, *p>q>0*, $x_I(0) = (-1/\alpha)[\dot{x}_1(0) + \beta(t)x_1^\gamma(0)]$, and $\beta(0)$ initial value of $\beta(t)$. Then:

$$i_q^* = \frac{1}{a}\left(\ddot{\theta}_{ref} + \ddot{e}_m - b\omega_r - \beta(t)\gamma x_1^{\gamma-1}\dot{x}_1 - \alpha x_1^{\text{q/p}} - \eta(t)\,\text{sign}(s) - ks\right) \quad (11)$$

in (11), $\eta(t)$ updated online, $k > 0$, $\beta(t); \eta(t)$ parameters are tuned by adaptive law as (12) and (13):

$$\dot{\beta}(t) = -k_1 x_1^{2-\gamma} s \quad (12)$$

$$\dot{\eta}(t) = k_2|s| \quad (13)$$

where, $k_1 > 0, k_2 > 0$.
According to Utkin *et al.* [1] then we have (14) and (15):

$$s_I = \dot{x}_I + \beta_0 \text{x}_1 + \alpha_0 x_I \quad (14)$$

$$\dot{x}_I(t) = x_1^{q/p}(t) \quad (15)$$

where, $\beta_0 > 0, \alpha_0 > 0,\ \text{s} = s_I = 0$. From in (9) and (14) we have:

$$\dot{x}_1 = -\beta_0 x_1 - \alpha_0 x_I \quad (16)$$

$$\dot{x}_1 = -\beta(t)x_1^\gamma - \alpha x_I \quad (17)$$

with $\beta_0 = \beta(t), \alpha_0 = \alpha$, from (8), (9), (11)-(13), s=0 the parameter can be adjusted x_I, the errors x_1, x_2 are the average values that always approach 0. When taking into account the disturbance factor and error components $\tilde{\eta} = \eta(t) - \eta_0$, we choose the Lyapunov function as (18):

$$V = \frac{1}{2}s^2 + \frac{1}{2k_2}\tilde{\eta}^2 \quad (18)$$

Then, derivative of the Lyapunov function V have as (19):

$$\dot{V} = s\dot{s} + \frac{1}{k_2}(\eta(t) - \eta_0)\dot{\eta}(t) = s\left(\dot{x}_2 + \dot{\beta}(t)x_1^{\gamma} + \gamma\beta(t)x_1^{\gamma-1}x_2 + \alpha x_1^{\frac{q}{p}}\right) + \frac{1}{k_2}(\eta(t) - \eta_0)\dot{\eta}(t) = s\left(ai_q^*(t) + b\omega_r(t) + d(t) - \ddot{\theta}_{ref} - \ddot{e}_m + \dot{\beta}(t)x_1^{\gamma} + \gamma\beta(t)x_1^{\gamma-1}x_2 + \alpha x_1^{q/p}\right) + \frac{1}{k_2}(\eta(t) - \eta_0)\dot{\eta}(t) \quad (19)$$

Substitute (11) into (19) and we get:

$$\dot{V} = s\left[\begin{matrix}\left(\ddot{\theta}_{ref} + \ddot{e}_m - b\omega_r - \beta(t)\gamma x_1^{\gamma-1}x_2 - \alpha x_1^{\frac{q}{p}} - \eta(t)\,\mathrm{sign}(s) - ks\right) \\ b\omega_r(t) + d(t) - \ddot{\theta}_{ref} - \ddot{e}_m + \dot{\beta}(t)x_1^{\gamma} + \gamma\beta(t)x_1^{\gamma-1}x_2 + \alpha x_1^{\frac{q}{p}}\end{matrix}\right] + \frac{1}{k_2}(\eta(t) - \eta_0)\dot{\eta}(t) = s\left[d(t) + \dot{\beta}(t)x_1^{\gamma} - \eta(t)\,\mathrm{sign}(s) - ks\right] + \frac{1}{k_2}(\eta(t) - \eta_0)\dot{\eta}(t)$$
$$= sd(t) + s\dot{\beta}(t)x_1^{\gamma} - |s|\eta(t) - ks^2 + \frac{1}{k_2}(\eta(t) - \eta_0)\dot{\eta}(t) \quad (20)$$

From in (12) and (13), we have:

$$\dot{V} = sd(t) - k_1s^2x_1^2 - |s|\eta(t) - ks^2 + (\eta(t) - \eta_0)|s|$$
$$= -k_1s^2x_1^2 - ks^2 - \eta_0|s| + sd(t) \le -k_1s^2x_1^2 - ks^2 - \eta_0|s| + |s||d(t)|$$
$$= -k_1s^2x_1^2 - ks^2 - (\eta_0 + |d(t)|)|s| \quad (21)$$

From (5), (21) it is shown that $\dot{V} < 0$ values x_1 and x_2 have ensured the system to converge to 0 of the state variables according to Lyapunov theory. Moreover, the position error e shows that it always converges to the output of the reference model em in a finite time. The proposed system algorithm model in Figure 3 is completely suitable for the position control of PMSM for the electric drive system [23]-[25]. We have the controller structure diagram for the drive system as shown in Figure 3.

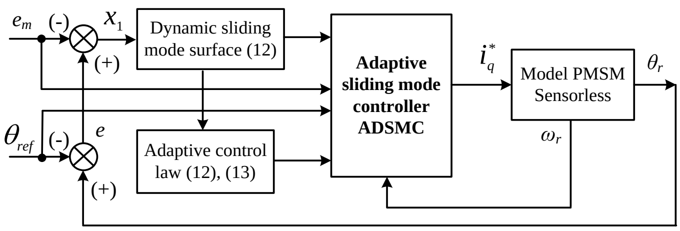

Figure 3. The block diagram of the control structure of the drive system using sensorless PMSM motor based on ADSMC

With the integral sliding surface that we have chosen, and the expressions from (11)-(21), representing the relationship between the output component y and the input u. Then we choose the control:

$$u = \frac{1}{a}(\ddot{\theta}_{ref} - bw_r - \beta_0\dot{e} - \alpha_0 e^{q/p} - k_3 sign_{(s_I)} - k_4 s_I) \quad (22)$$

in which, k_3 and k_4 are positive parameters.

$$u_{\mathrm{ADSMC}} = \hat{k}_{s1}|s_m|^{1/2}\,\mathrm{sign}(s_m) + \int \hat{k}_{s2}\,\mathrm{sign}(s_m)dt \quad (23)$$

where

$$\begin{aligned} s_m &= \theta_{ref} - \theta_r \\ \dot{x}_m &= a_m x_m + b_m \theta_{ref} \\ e_m &= \theta_r - x_m \\ \dot{\hat{k}}_{s1} &= -\left(\Gamma_{s1}|s_m|^{1/2}\text{sign }(s_m)e_m + \gamma_{s1}\hat{k}_{s1}\right) \\ \dot{\hat{k}}_{s2} &= -\left(\Gamma_{s2}(\textstyle\int \text{sign }(s_m)dt)e_m + \gamma_{s2}\hat{k}_{s2}\right) \end{aligned} \tag{24}$$

From that we can see that: the algorithm the authors studied above with the electric drive control system using PMSM motor does not use sensors but is based on measuring the current components, axial position and applied voltage to obtain information about the rotation angle position and speed. The estimated angular position value θ_r, θ_{ref} is then fed into the control structure to perform the calculation of the coordinate system conversion in the vector control structure, at the same time the estimated value of the speed parameter is fed back to participate in the speed controller. This shows that the problem of determining the rotor angle position with zero static error of the system is improved in control quality with the proposed algorithm.

4. RESEARCH RESULTS AND DISCUSSION PROBLEMS

In this paper, the authors study the industrial electric drive system for CNC machining machines with the main PMSM motor having: power 2.5 kW; rated torque 14.52 Nm; rated speed 1,500 rpm; stator resistance 1.79 Ohm; stator inductance 6.65×10^{-3} H; number of pole pairs 2p=4; torque constant 2.56 Nm/A; linking flux 0.4086 Wb; moment of inertia 1.8×10^{-3} kgNm^2; viscous friction constant 9.52×10^{-5} Nm s/rad; maximum allowable speed of the motor 3,000 rpm. The perform simulations with adaptive sliding mode controllers for: $\Gamma_{s1} = \Gamma_{s2} = 0.001$, $\gamma_{s1} = \gamma_{s2} = 0.5$, $a_m = -10, a_m = 10$, $\hat{k}_{s1}(0) = \hat{k}_{s2}(0) = 2$, $\alpha_0 = 100$, $\beta_0 = 250$, $p = 7$, $q = 1$, $k_3 = 210$, $k_4 = 52$, $\lambda_m = \alpha = 50$, $\beta(0) = 150$, $\eta(0) = 50$, $k_1 = 0.002$, $k_2 = 0.01$, $\gamma = 1.9$, $L_d = L_q = 0.124\,H$, and $T_L = (2.5 \div 5)\,Nm$. The authors then built a simulation program on MATLAB R2024a software, using a computer configuration with a Ryzen 9 5900X or Core i7 14700K CPU, 16 GB DDR4 RAM, and an Nvidia GeForce RTX 3090 Ti graphics card. The goal is to ensure that the simulation image quality meets the requirements and evaluate the results to prove the correctness of the control algorithm that the authors researched. From there, we have some simulation results.

Simulation results with rotor speed response and speed error as shown in Figures 4(a) and (b). Increasing speed change process (at time from 0 to 1 second, from 2 to 3 seconds), decreasing speed change (at time from 4 to 5 seconds), change process with total response time of 6 seconds (fast system response) with desired speed value and actual speed always closely following each other.

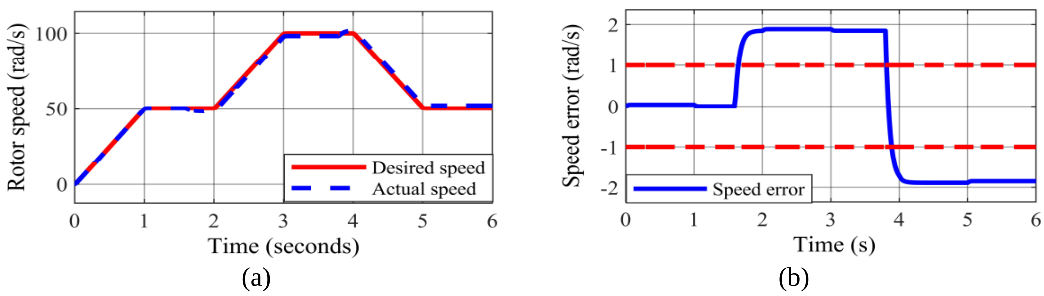

Figure 4. Simulation results of speed response: (a) rotor speed and (b) speed error

Simulation results with load torque response when changing at time t=1.65 s and t=3.86 s as shown in Figure 5(a), the rotor control position response value has actual value and estimated value always closely follows the set value, as shown in Figure 5(b) (the error is very small less than 0.01%). With the results that the authors studied the simulation of the ADSMC algorithm in this case, it shows that: the working angle position value of the system has to respond accurately when changing the torque at different increasing and decreasing points, the system still achieves good quality. The estimated value of the recognition unit when changing the position and torque of the output response motor has followed the input response very closely. This problem shows that the working quality of the system when controlling the rotor angle position always ensures that the electric drive system works well.

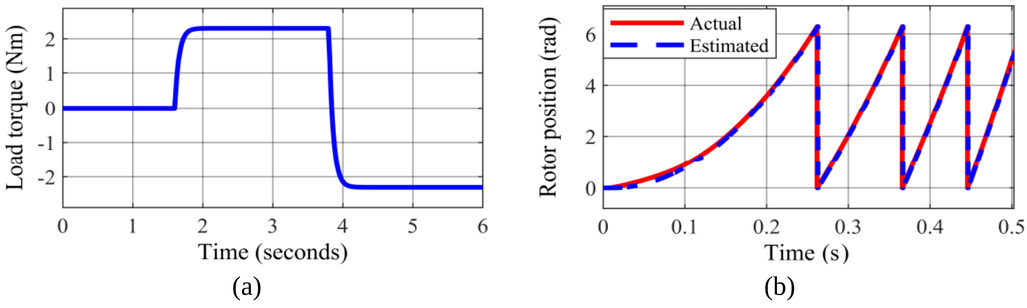

Figure 5. Simulation of rotor torque and angular position response: (a) load torque and (b) rotor posittion

The simulation results in Figure 6 are as follows: for industrial electric drive systems, high-speed control is always normal with the motor. What needs to be noted here is when running at low and very low speeds (near-stop speed). At that time, it is necessary to adjust the speed and angular position smoothly and ensure the control torque so that even when changing the speed, the output response still adheres to the equilibrium process. At the time of speed 50 rad/s (corresponding to 477 rpm) to 100 rad/s (corresponding to 955 rpm), the process changes from response time from 0 to 2 seconds then increases to 100 rad/s at time 3 s and at time 4 s the speed changes back to 50 rad/s and at time 5 s the motor then operates stably; with a total response time of less than 10 s (here 6 s) as shown in Figure 6(a). The error response in Figure 6(b) correctly represents the working process when changing speed. The estimated value as well as the desired speed value accurately represents the working process of the system Figure 6(c).

The working response of the system according to the proposed ADSMC controller in Figure 6(d) shows: with a small setting angle of 70 degrees, it corresponds to a setting angle of 1.22 rad/s with the preset value being the purple line, the preset response with the sliding controller is the red line, the response of the ADSMC-1 controller has the blue line, which is the response of the ADSMC controller working with high quality when there is no change in the system's load torque, then the system with the estimated speed of the parameters is always accurate, the output closely follows the input in the process of balancing the system, working stably without error, without static deviation. With the ADSMC-2 controller response, the black line is the ADSMC controller response when there is a change in the system's load torque, then the system works at a speed where the parameter estimate is always accurate there is a change in error compared to ADSMC-1, however the output still follows the input in the balancing process, the system works relatively stable with a small error.

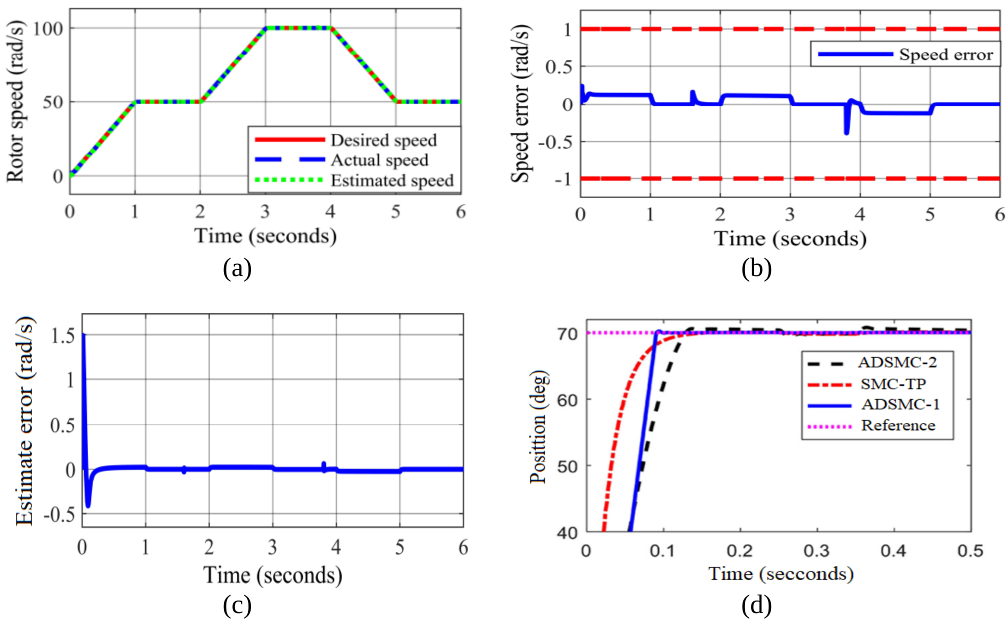

Figure 6. The sensorless rotor speed response using ADSCM controller: (a) rotor speed, (b) speed error, (c) estimate error, and (d) posittion response

Observing the research results of the proposed ADSMC controller, we see that the electric drive system when having this controller (industrial processing machines) used with PMSM motors works with high control quality, the output always follows the set amount in the control process. The speed of estimating parameters and taking into account the disturbance factor, the system always meets, this electric drive system will work with high quality [23]-[27]. Through this, we also see that the accuracy of the ADSMC controller is always superior to other methods such as: PID controller, PD controller with noise compensation, pure adaptive control, fuzzy control, neural network control, and sustainable control. Especially the algorithm when used with processing machines such as CNC machines, drilling machines, planers, grinders, and lathes the ADSMC controller using PMSM motors without sensors is always considered optimal.

5. CONCLUSION

The paper has conducted a study to design an electric drive system using a sensorless PMSM motor, based on the implementation of the ADSMC controller, with the estimation of information about the rotation speed and rotor angle position of the motor to accurately replace the speed measuring device on the motor during operation and provide the controller with estimated and measured information. The controller has performed calculations and estimates of rotation angle parameters to calculate the conversion of coordinate systems in the vector control structure of the motor, at the same time the estimated speed value is also accurately feedbacked to the controller to participate in the speed control process. The simulation results show the ability to calculate estimates and control well in the entire speed range from low speed to medium speed and high speed of the system. In addition, always improve and calibrate the parameter output, to increase the accuracy of the phase angle of the rotor angle as well as reduce the static error of the control process for the electromechanical drive system in industry. This is also the basis for studying the design of sensorless controllers in the design and manufacturing process of electric drive systems for processing machines: lathes, milling machines, planers, drills, and grinders. The angular position control response of the proposed ADSMC control system has stable dynamic characteristics even during transients and when increasing/decreasing speed with static errors almost eliminated in this industrial electric drive system. In addition, from these research results, we can see that the system has somewhat reduced the Chattering phenomenon in sliding mode control. Because looking at the simulation images, we can see: the control error is very small, the tracking quality of this controller is very high, the disturbance factors have been reduced to the maximum limit in control. The authors in the future will have clear experimental studies on the Onchip hardware system embedding (this control algorithm) into DSP (TMS 320F280XXs type) or field programmable gate array (FPGA), dSPACE, this issue is also a limitation of the paper. This issue will be the basis for research, design, and calculation of high-quality controllers for subsequent studies.

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AUTHOR CONTRIBUTIONS STATEMENT

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Nguyen Hoai Nam	✓		✓	✓	✓		✓		✓	✓	✓		✓	✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

If there are no conflicts of interest, please include the following author's statement: Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

ETHICAL APPROVAL

The research related to human use has been complied with all the relevant national regulations and institutional policies in accordance with the tenets of the Helsinki Declaration and has been approved by the authors' institutional review board or equivalent committee.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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