SSRG International Journal of Electrical and Electronics Engineering
ISSN: 2348 – 8379 / https://doi.org/10.14445/23488379/IJEEE-V8I3P101
Volume 8 Issue 3, 1-8, March 2021

Research the Electromechanical Tracking Control System Working in Slow Mode, Taking into Account the Nonlinear Uncertainty Factor and the State Observer

Tran Duc Chuyen[1], Vu Thi To Linh[2]

[1]*Faculty of Electrical Engineering, University of Economics - Technology for Industries, Viet Nam*

Received Date: 19 February 2021
Revised Date: 22 March 2021
Accepted Date: 03 April 2021

Abstract - *In this paper, presenting a study of electromechanical tracking drive system working in slow mode, taking into account the uncertainty of nonlinearity, the parameter change of the model, and the state observer using PMSM motors used in industry and military. The system consists of a position controller loop and loop speed controller. In which loop speed controller using adaptive law to compensate the uncertainty function and built the sliding mode state observers to estimate load torque, friction, and interferences. The controller is proposed to improve the quality system, taking into account the uncertain nonlinear components for drive systems such as the moment of inertia, friction torque, etc. Research results will be the basis for the establishment of control algorithms, system design electric drives in the industry, military, defense, and security.*

Keywords — *PMSM motor control, Drive system tracking, Adaptive sliding mode control, State observer, Variable structural control, Very low speed, Slow mode taking.*

I. INTRODUCTION

The electromechanical tracking drive systems working in slow mode include industrial robot joint control system, CNC metal cutting machine, military sight drive system, camera systems observer, military radar station, artillery system naval ships, etc. These systems require high kinetic accuracy and quality. In the past, tracking drive systems used to use direct-acting electric motors [1]-[7]. The DC motors have good control properties but have the disadvantage of always existing commutator and brush with low electrical and mechanical strength or maintenance, so in recent years it has been gradually replaced by AC motors, especially the PMSM motor (Permanent Magnet Synchronous Motors (the types with Ld ≠ Lq), [7, 17]. As in a number of previous studies, [8, 23, 24] just stopped at the speed controller with the tracking system but has not studied the position controller with the nonlinear uncertainty factors.

In addition, a number of documents [26, 28, 31] have not studied the tracking system that works in slow mode. These documents are only about controlling small power PMSM motors at near zero speeds and at very low speeds through intermittent. In the document [29], control research estimates the position of the rotor of the PMSM motor working at a very low speed while still ensuring the precise control of the engine speed and position, using a rotor speed observer to evaluate (non-measurable parameter estimate θ) of nonlinear components. Therefore, there are not many authors interested in studying the electromechanical tracking control system in slow mode, taking into account nonlinear uncertainty factors such as friction torque and taking into account the state observer.

When the tracking drive system uses a PMSM motor, the model of the control object is a clear nonlinear model with variable parameters. The controller synthesis problem requires a new approach different from the linear model; the control synthesis will be simpler. Here we go to consider the following system, [2, 3, 5]:

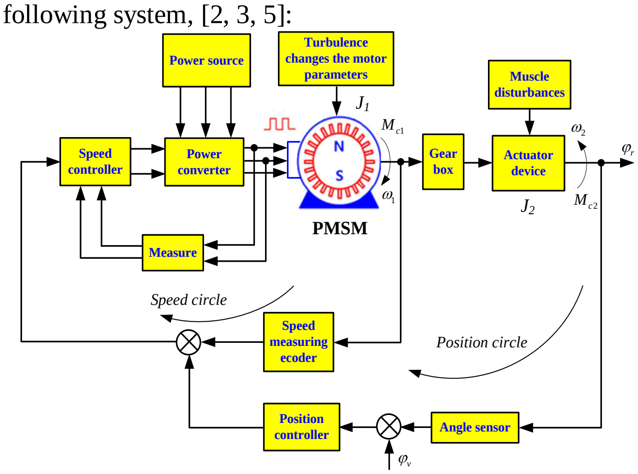


Fig. 1 The electromechanical tracking drive system diagram working in slow mode

In the content of this paper, the synthesis of the position control tracking system according to the principle of system synthesis with dependent loops. The system includes two speed and position control loops. The speed loop is based on adaptive sliding mode techniques to ensure that the engine speed is always in line with the set speed when taking into account the model's nonlinear uncertainties such as changes in engine parameters, variability friction torque, as well as when set values and load noise are changed. The position loop is based on a synthesis technique of linear control systems that combines identification with a state observer to evaluate the nonlinear uncertainty components of the object model. We have a block diagram of the structure of the drive system following the position as shown in Figure 1.

II. THE DYNAMIC MODEL OF THE TRACKING DRIVE SYSTEM USING PMSM MOTOR

The building the model of electromechanical tracking control system working at slow speeds always contains many parts, including electrical and mechanical parts, including motors to control speed, joints movement traditions, working structures, etc. These systems always exist in industrial machines, tracking control systems for robots, CNC cutting machines, weapon systems military (ship artillery), etc.

A. Building an electromechanical tracking system model

The objects of the electromechanical tracking drive system include motors, actuators, and working machines. The mechanical mass diagram of the tracking drive system working in slow mode is shown in figure 2, [2, 3, 5, 14].

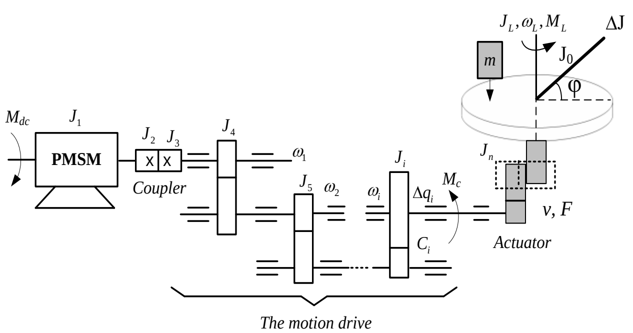


Fig. 2 The dynamic diagram shows the relationships of the elements in the tracking drive system

In general, the mechanical part of the tracking drive system consists of many units that are elastic together and then converted to the motor shaft, normally using a two-object model [2, 5].

$$J\frac{d\omega}{dt} = M_d - B_m\omega - M_L \quad (1)$$

Here J is the sum of the moment of inertia of the motor, and the other parts are converted to the motor shaft, M_d is the motor torque, B_m is the friction coefficient of the speed dependent friction component. Component M_L is The sum of the resistance torque types acting on the motor shaft and the resistance torque converted to the motor shaft. M_L is a complex nonlinear function that depends on engine speed, friction, the elasticity of drive axes, etc.

The mathematical model of the PMSM three-phase synchronous motor in the d-q coordinate system is written as follows, [3, 7]:

$$\begin{aligned}
V_{ds} &= R_s I_{ds} + L_{ds}\frac{dI_{ds}}{dt} - P\omega L_{ds} I_{qs} \\
V_{qs} &= R_s I_{qs} + L_{qs}\frac{dI_{qs}}{dt} + P\omega L_{qs} I_{ds} + P\omega\lambda_m \\
M &= \frac{3}{2}P\lambda_m I_{qs} + \frac{3}{2}P(L_{ds} - L_{qs}) I_{ds} I_{qs} \\
M_e &= M_L + B\frac{2}{p}\omega + J\frac{2}{p}\dot{\omega}
\end{aligned} \quad (2)$$

In which the components V_d, V_q are the stator voltage of the d-axis and the q-axis, respectively; current I_{ds}, I_{qs} is the value of current in the d and q axis, R_s is the stator resistance, L_d, L_q is the d axis inductance and the d and q axis stator inductance, M_e is the electromagnetic moment, J torque Rotor inertia, B is the viscosity coefficient of friction, p is the number of magnetic poles, ω is the angular (electrical) speed of the rotor, λ_m is the magnetic flux linkage.

From equation (2), component M represents the electro-magnetic moment produced by the magnetic flux linkage, and the component representing the reactive torque generated by the difference inductance between the d-axis and the q-axis of a PMSM motor. Then we replace M for M_e, and we obtain the dynamic equation of motor speed as follows:

$$\begin{aligned}
\dot{\omega} &= \frac{3}{2}\frac{p^2}{4}\frac{\lambda_m}{J} I_{qs} - \frac{B}{J}\omega - \frac{p}{2J} M_L + \\
&+ \frac{3}{2}\frac{p^2}{4}\frac{(L_d - L_q)}{J} I_{ds} I_{qs}
\end{aligned} \quad (3)$$

The derivative of the PMSM motor rotor position is calculated by the following formula: $\dot{\theta} = \omega$. Here we assume that θ, ω, and M_L of unknown components; Components I_{ds}, I_{qs} are measurable. The time derivative of the set rate (ω_d) is zero because the set rate cannot change dramatically in a short sampling interval, then $\dot{\omega}_d = 0$.

Based on the equations (1) - (3) above, the dynamics of the PMSM motor considering the non-measurable component influence with the parameter can be written as follows:

$$\begin{aligned}
\dot{\theta} &= \omega \\
\dot{\omega} &= k_1 I_{qs} - k_2\omega + k_{11} I_{ds} I_{qs} - k_3 d_1 \\
\dot{I}_{ds} &= -k_7 I_{ds} + k_8 V_{ds} + k_9 \omega I_{qs} - k_8 d_3 \\
\dot{I}_{qs} &= -k_4 I_{qs} - k_5\omega + k_6 V_{qs} - k_{10}\omega I_{ds} - k_6 d_2
\end{aligned} \quad (4)$$

there, $k_1 = \frac{3}{2}\frac{1}{J}\frac{p^2}{4}\lambda_m, k_2 = \frac{B}{J}, k_3 = \frac{p}{2J}, k_4 = \frac{R_s}{L_q},$

$$k_5 = \frac{\lambda_m}{L_q}, k_6 = \frac{1}{L_q}, k_7 = \frac{R_s}{L_d}, k_8 = \frac{1}{L_d}, k_9 = \frac{L_q}{L_d},$$

$$k_{10} = \frac{L_d}{L_q}, k11 = \frac{3p^2}{8}\frac{1}{J}(L_d - L_q).$$

where components d_1 , d_2, and d_3 are written:

$$d_1 = -\frac{3p}{4}\Delta\lambda_m I_{qs} + \frac{2}{p}\Delta B\omega +$$

$$-\frac{3p}{4}(\Delta L_d - \Delta L_q) I_{ds} I_{qs} + M_L + \frac{2\Delta J}{p}\dot{\omega},$$

$$d_2 = \Delta R_s I_q + \Delta\lambda_m \omega + \Delta L_d \omega I_d + \Delta L_d \dot{I}_q,$$

$$d_3 = \Delta R_s I_q - \Delta L_q \omega I_q + \Delta L_d \dot{I}_d.$$

From the definition of d_1, d_2, and d_3, we find that since L_d, L_q, R_s, I_{ds}, and I_{qs} are quite small, the variation of L_d, L_q, and Rs has little effect on the characteristic of the system. Therefore, for the simplicity of the analysis and for the design of the nonlinear state observer, within the framework of this paper, the aforementioned parameters are assumed to be constant. Therefore, we have:

$$d_1 = -\frac{3p}{4}\Delta\lambda_m I_{qs} + \frac{2}{p}\Delta B\omega + M_L + \frac{2\Delta J}{p}\dot{\omega} \quad (5)$$

$$d_2 = \Delta\lambda_m \omega, d_3 = 0.$$

The tracking drive system model is a combination of the mechanical drive system and the actuator dynamic model. When considering the tracking drive system, it is necessary to consider the nonlinearity factor and the variable parameters caused by the mechanical part of the system. Therefore, a state observer is required to evaluate the uncertainties [1, 3, 5, 7, 9, 14, 15].

B. Design state observation with uncertain nonlinear parameters

In rotor flux-based control, information about the angular position of the rotor must always be provided for the conversion of the coordinate axis. In this section, a nonlinear state observer will be presented to accurately estimate the rotor position and speed, taking into account the influence of component parameters that cannot be measured in both low and high speed regions. The nonlinear state observer design sequence is divided into two steps. First, the kinetic model (4) of the engine is transformed to bring it back to the desired form for the state observation design [10].

It is then converted back to the desired form to design the observer so that it is suitable for the drive controller model. To evaluate convergence estimation error to zero is best. Assume that the non-measurable components of the system d_1 and d_2 change very slowly, and their derivatives over time are zero. To obtain the state model of the motor, taking into account the non-measurable component, we perform a few simple transforms as follows:

$$\dot{\theta} = \omega$$

$$\dot{\omega} = k_1 I_{qs} - k_2\omega + k_{11} I_{ds} I_{qs} - k_3 d_1$$

$$I_{qs} = -k_4 I_{qs} - k_5\omega + k_6 V_{qs} - k_{10}\omega I_{ds} - k_6 d_2 + \theta - \theta \quad (6)$$

$$\dot{d}_1 = 0$$

$$\dot{d}_2 = d_2 - d_2$$

In the system of equations above (6), we can write in the form of a state observer model as follows:

$$\dot{x} = Ax + f(x,u) + g(x)u$$
$$y = h(x) \quad (7)$$

where $x \in R^n$ is an n-dimensional space vector, $u, y \in R$ is the control signal at the controller inputs and outputs respectively, $x = [\theta\ \omega\ I_{qs}\ d_1\ d_2]^T$, $y = I_{qs}, u = [I_{ds}\ V_{qs}]^T$.

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ 0 & -k_2 & k_1 & -k_3 & 0 \\ 1 & -k_5 & -k_4 & 0 & -k_6 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}, C = \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \\ 0 \end{bmatrix}^T,$$

$$f(x,u) = \begin{bmatrix} 0 \\ 0 \\ -k_{10}\omega I_{ds} - \theta \\ 0 \\ d_2 \end{bmatrix}, g(x) = \begin{bmatrix} 0 & 0 \\ k_{11} I_{qs} & 0 \\ 0 & k_6 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}.$$

We can easily see that matrix pairs (A, C) are observable and that the model to estimate the nonlinear state (7) is to be estimated. Nonlinear state observers are used to calculate and estimate the rotor position (θ), rotor speed (ω), and unmeasured components of the system (d1, d2). We can then calculate and obtain by doing the following: Assume that Iqs is available and that LMI (Linear matrix inequality) is satisfied for $Y \in R^{5\times1}, P \in R^{5\times5}$, some values of $\rho > 0$.

$$\begin{bmatrix} \Omega & P & PE \\ P & \frac{-1}{\gamma_1^2 \gamma_2^2} I & 0 \\ E^T P & 0 & -\rho I \end{bmatrix} < 0 \quad (8)$$

There, $\Omega = A^T P - C^T Y^T + PA - YC + I + \rho N^T N$, and $E \in R^{5\times5}, N \in R^{5\times5}$, I is a 5x5 matrix, and ρ, γ_1, γ_2 are constants.

Then we consider the nonlinear state observer in the general form as follows:

$$\begin{aligned} \dot{\hat{x}} &= A\hat{x} + f(\hat{x},u) + g(\hat{x})u + L(y - C\hat{x}) \\ y &= I_{qs} \end{aligned} \quad (9)$$

Where, $\hat{x} = [\hat{\theta}\ \hat{\omega}\ \hat{I}_{qs}\ \hat{d}_1\ \hat{d}_2]^T$, $L = P^{-1}Y$ then the estimated error vector component e below is asymptotic stability written as follows: $e = x - \hat{x}$. To prove this problem has been presented carefully in section [22, 24, 30].

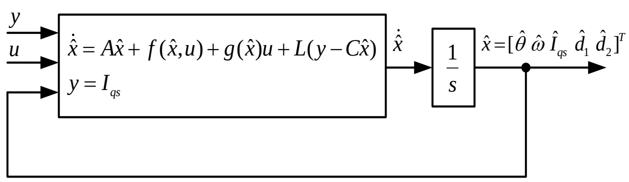


Fig. 3 Block diagram of a nonlinear state observer

Figure 3 shows a block diagram of a nonlinear state observer. The estimated values of the rotor speed component and the system non-measurable component are used to improve the quality of the speed controller; meanwhile, the estimated rotor position is used to convert the coordinate system.

III. THE RESEARCH CONTROLLER SYNTHESIS

A. The adaptive sliding mode speed controller

When synthesizing speed control loop with nonlinear control object, the system of equations of control object exists as the equation of state; contains matrices with nonlinear elements, [1, 5, 8]. Therefore, the use of traditional linear controllers such as PID has not overcome the effects of nonlinear factors and variable parameters on the working quality of the system [3, 9, 15, 23]. By synthesizing the adaptive slip controller, the effects of uncertain nonlinear factors such as friction, elasticity on the quality of the drive system have been resolved [12, 14, 28]. The document [19] has presented very carefully the synthetic method of adaptive slip controller for speed control loop using PMSM motor.

The problem of synthesizing the controller for the speed control ring is the problem of determining the control law for V_{ds}, V_{qs} to ensure that the tracking drive system works stably and the tracking error quickly decreases to zero. When constructing the speed control loop, we define the tracking error as follows, [12, 19]:

$$e_1 = \omega_d - \omega \quad (10)$$

$$e_2 = i_{dd} - I_{ds} \quad (11)$$

In which, I_{ds} and i_{dd} are set values of rotor speed and axis current, respectively. Because PMSM motors have a hidden polar form, permanent magnet excitation has some reactive torque. The d-axis current is set to nonzero and is written as follows, [12, 13, 19]:

$$i_{dd} = \frac{-\lambda_m}{2(L_d - L_q)} - \sqrt{\frac{\lambda_m^2}{4(L_d - L_q)^2} + I_{qs}^2} \quad (12)$$

Where λ_m is the rated loop flux, L_d; L_q is the nominal d-axis inductance and the rated q-axis inductance, respectively. Therefore here, we will synthesize the position control loop on the basis of the described adaptive sliding speed controller, synthesized as shown in [19].

B. The position controller uses a PMSM motor based on the adaptive sliding speed controller

When solving the positional ring synthesis problem in the speed loop using the adaptive sliding mode method in [19], taking into account the load observer, the control problem will be simpler. Based on the position controller block diagram of electromechanical tracking drive system working in slow mode using PMSM motor as shown in figure 1 above.

When conducting position controller synthesis, we assume that the speed controller synthesized in [19] is good. The position control loop has the main control object, the speed ring. Through experimental investigation and simulation, we can see that the speed loop has dynamic properties equivalent to the second order stage. So when synthesizing the position controller, we proceed to identify the parameters of the model and consider the speed loop equivalent to a quadratic stage. The main task now is to synthesize the position controller in the directions. French classics.

Perform position controller synthesis on the basis that speed loops have been synthesized at. Its kinetics is equivalent to the quadratic stage whose transfer function is, [2, 5]:

$$W_{K_\omega} = \frac{K_\omega}{(T_1 s + 1).(T_2 s + 1)} \quad (13)$$

The parameters of this transfer function have been determined experimentally, as shown in [5]. Position controller synthesis can be done in the following ways:

- Synthesis of the position controller according to the module optimization standard or the symmetry optimization method has been presented in the document [5, 32, 33].
- Synthesize the position controller according to the Ziegler-Nichols method or the method using PID Design controller design software as shown in the document [5], etc., to design the PID position controller.

Thus the positional controller synthesis problem is synthesized in two steps: step 1 is to identify the parameters of the positional loop object (determine the parameters of the transfer function (13)), step 2 is PID controller parameter determination according to the classic method.

When synthesizing according to the symmetry optimization criteria, according to the method presented in the document [5], we convert the denominator of the transfer function (13) as follows:

$$MS = (T_1 s+1).(T_2 s+1) = T_1 T_2.s^2 + (T_1+T_2)s+1 \quad (14)$$

Ignore the high order number in the denominator, and we have an approximate transfer function of $W_{K_\omega} = K_\omega /(T_\omega s+1)$, with $T_\omega = T_1 + T_2$. Then the structure diagram is transformed into a diagram as follows:

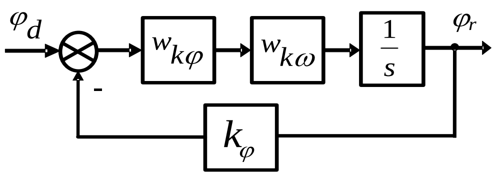


Fig. 4 The Structural diagram of positional tracking drive system

Continuing to transform the block diagram, we have the following diagram:

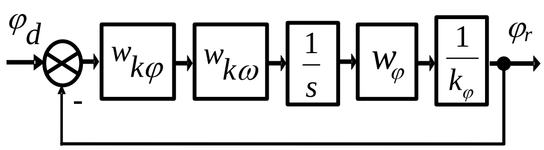


Fig. 5 The alteration of the structure diagram of the positional tracking drive system

In figure 4, we consider the simplified $W_{k\omega}$ speed loop circuit to be equivalent to an inertial stage, which is the speed controller that we synthesized according to the adaptive sliding mode control method [19]. At this point, the position controller that needs to be considered is the dynamic stage $W_{k\varphi}$. So for the positional loop, the object transfer function has the following form:

$$W_{o\varphi} = W_{K_\omega}.K_\varphi(1/s) \quad (15)$$

Where K_φ is the transmission coefficient of the measuring part (or K_{do}) $W_{K_\omega} = K_\omega/(T_\omega s+1)$ is the speed-loop transfer function that has been approximated simply and ignores the high order number in the denominator.

We use the method of synthesizing the position controller according to the symmetry optimization standard, then the desired transfer function of the open system has the form:

$$W_{H\varphi} = \frac{2a_\varphi T_\omega s+1}{2a_\varphi T_\omega s}.\frac{1}{a_\varphi T_\omega s(T_\omega s+1)} \quad (16)$$

The function that passes the position regulator is then:

$$W_\varphi = \frac{W_{H\varphi}}{W_{0\varphi}} = \frac{K_\omega}{K_\varphi a_\varphi T_\omega} + \frac{K_\omega}{2K_\varphi a_\varphi^2 T_\omega^2 s} \quad (17)$$

Let $K_{d\varphi} = K_\omega/(K_\varphi a_\varphi T_\omega)$, we obtain the positional transmitter transfer function:

$$W_\varphi = K_{d\varphi} + \frac{K_{d\varphi}}{2a_\varphi T_\omega s} \quad (18)$$

This is the integral rate controller. When synthesizing the PID position controller, we use specialized software PID Design in [5] to calculate.

IV. THE RESEARCH RESULTS

A. The Simulation

The simulation of the nonlinear tracking drive system with position controller based on adaptive sliding mode method using PMSM motor.

The motor parameters used in the simulation are as follows: the PMSM of YaKawa, rated power P_{rated} = 0,45KW, Number of poles is 4, rated speed nrated = 1500 r/min, I_{rated} = 3,8A, rated voltage U = 220 V, R_s = 2.5 Ω, L_s = $94e^{-3}$ H, L_d = $75e^{-3}$ H, L_q = $114e^{-3}$ H, λ_m = 0.193V.s/rad, J = $1.5e^{-4}$ Kg.m^2, B = 0,0001 N.m.s/rad, K_I = 8500; K_P = 2900 and $K_\omega = 0,002$; $K_{do} = 0,1$; $T_\omega = 0,079$.

Simulation of the nonlinear tracking drive system with position controller based on an adaptive sliding method using PMSM motor. We conduct research on the simulation of the tracking drive system on the basis of the adaptive sliding method built above. From the given parameters, we proceed to build a simulation model on the basis of Matlab / Simulink the PI controller as shown in Figure 6:

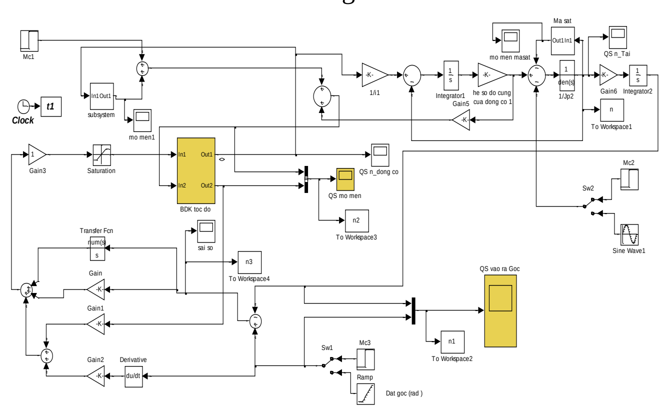


Fig. 6 The simulation diagram of the tracking drive system is built on Matlab/Simulink

The Matlab / Simulink simulation diagram built-in in figure 6 is a nonlinear tracking drive system with a position controller taking into account the friction torque nonlinear factor and the state observer using the kinematic stage PI.

Case 1: When input the ladder function X_v = 0.1 rad, the load moment does not change amplitude M_{cmax} = 0.5Nm. The change increases the moment of inertia by 50% from the original value. With the initial value (J_2 = 6Kgm^2); The new value (J_2 = 9Kgm^2), the simulation results are as follows:

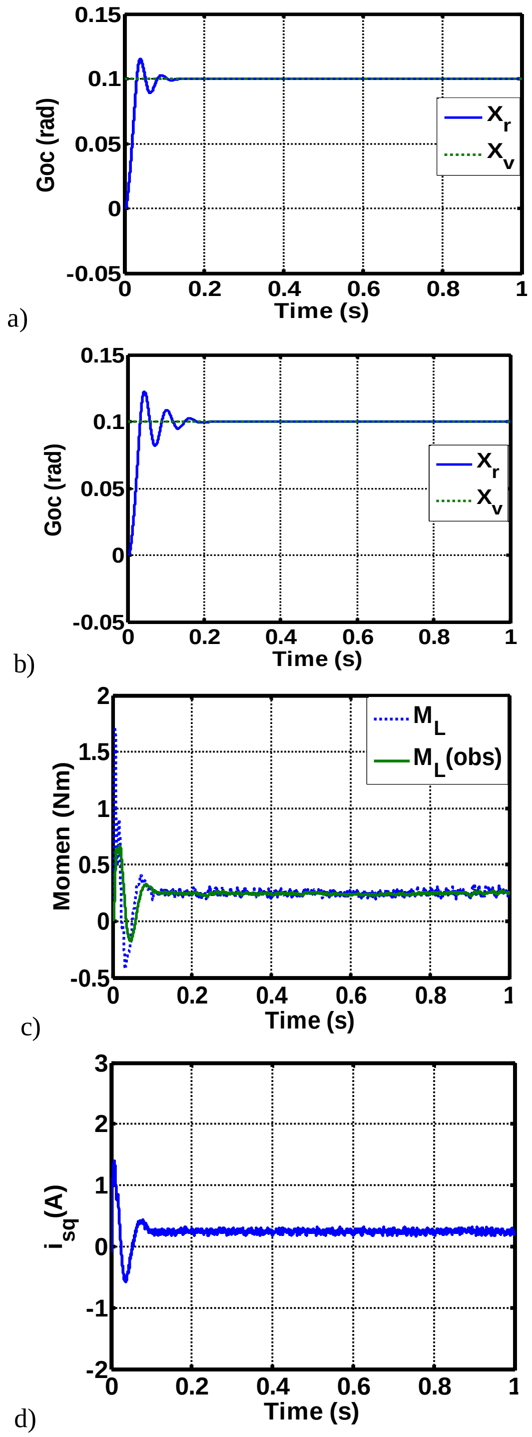


Fig. 7 Results simulation of case 1 the response in and out at the angle of the initial value: a) J2 = 6Kgm2, b) new value J2 = 9Kgm2, c) response to state observer, d) current response Iqs in case 1

In this case, the results show that when the moment of inertia increases, the oscillation of the system increases (initial value "J_2 = 6Kgm^2" number of oscillations = 1; the following value "J_2 = 9Kgm^2" number times of oscillation = 2), the output still tracking follows the input amount in the equilibrium process, meeting the updated observer with full information about the controller, moreover, the current value I_{sq} also shows system workflow correctly.

Case 2: Studying the reaction of the system when the applied angle changes according to the function X_v = V.t, (V = 1rad / s), the constant load moment M_c = 0.5Nm.

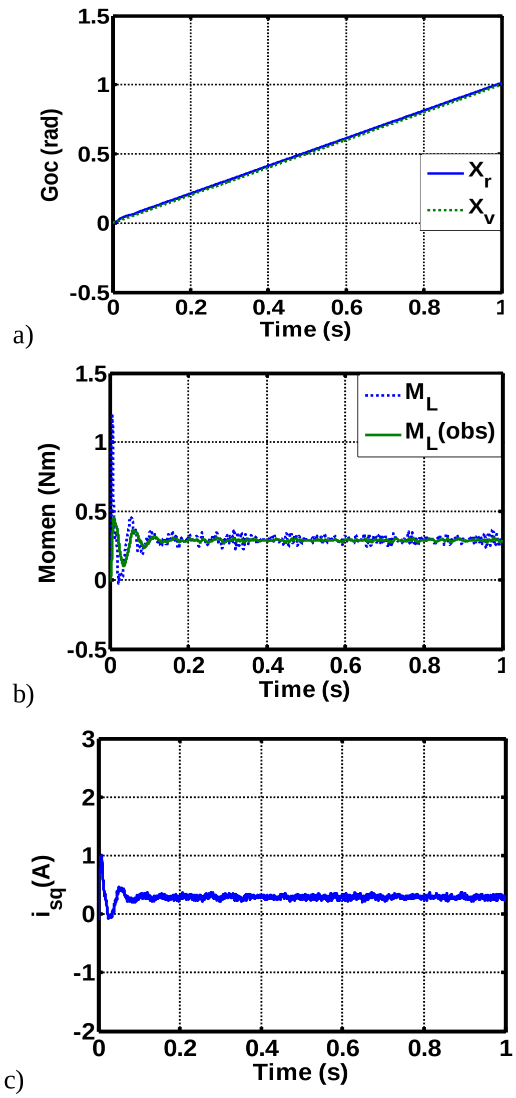
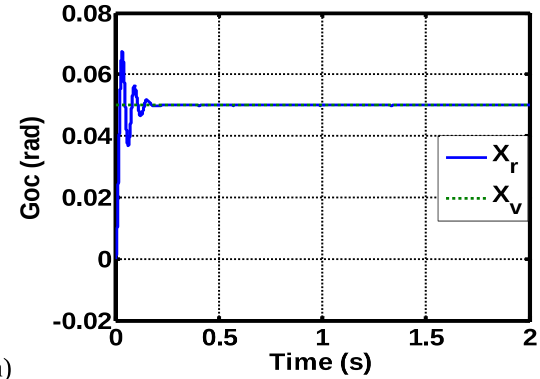


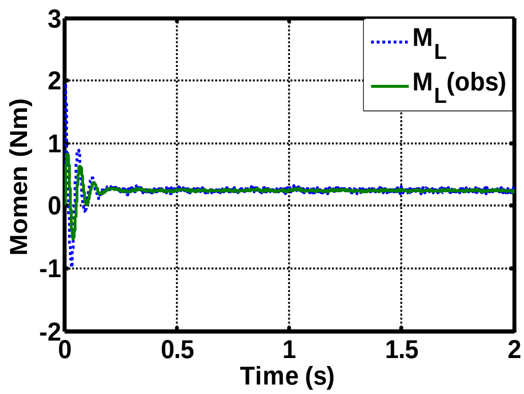
Fig. 8 Results simulation of case 2: a) the response in and out at the angle, b) response to state observer, c) current response Iqs in case2

When the set angle is a function V, time reaches a small equilibrium value. Adjacent error is zero; we see that the load torque observer responds to the relatively fast time; Provides full load information for the controller.

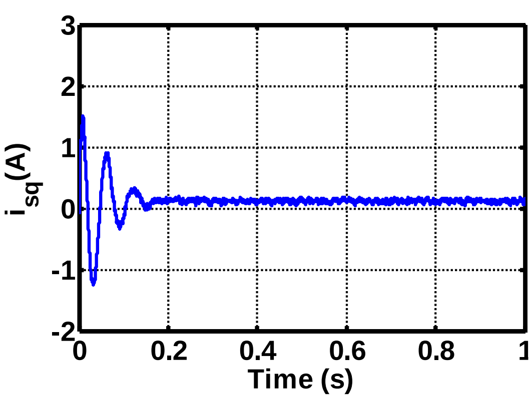
Case 3: When the angle at the baby X_v = 0.05 rad, the transmission system works in slow mode. Then we consider the influence of friction torque on the motor shaft and friction torque on the load side in this case. We have some simulation results as follows:



a)



b)



c)

Fig. 9 Results simulation of case 3: a) the response in and out at the angle, b) response to state observer, c) current response Iqs in case 3

In this case, the simulation results with the baby input X_v = 0.05 rad, the system works in slow mode. The output of the system has a change during the transition when the friction torque on the motor shaft and the friction torque on the load side is variable "as shown in Figure 9b and Figure 9c; the system variation has a number of oscillations = 2 times; transient time t_{qd} = 0.16s; The output is still closely related to the amount applied in the equilibrium process. The controller ensures stable working for the system.

Observing the simulation results of the cases, we see: although the load inertia moment changes, the system still operates stably, but in some cases, when the moment of inertia of the load is large, the transition time bigger. Furthermore, the positional controller here considers the changes of elastic and frictional moments to the system. This shows the robustness of the control law against uncertain nonlinear component effects. The built-in control system is always stable with load noise and stable with the change of set speed; the system works stably.

Comparing the results with the studies in [26, 28] and in previous studies [21, 29], the results that the paper achieved better than the previous works with the time to reach an equilibrium value. Small in both the value of current, preset angle value, the response of the observer, the following error is very small. The tracking drive system works in slow mode, always tracking to the original value, and the system works stably. This confirms that this system can be applied in practical industrial and military production.

V. CONCLUSION

The slow-motion position tracking drive system for industrial and military subjects that require high reliability and precision, replacing DC motors with rotating motors Dimensional PMSM is essential. The paper presented the new asymptotic approach to the combination of the tracking drive system working in slow mode using a PMSM engine with a nonlinear model and variable parameters, taking into account the state observer. The system has been built on the basis of a combination of adaptive sliding mode speed control and classic controls that give us the right direction and have created the position controller for the electric drive system. Mechanics are being used a lot in practice. The obtained theoretical and simulation results have proven the correctness of the algorithm, and the results of this study can be completely applied in practice for industrial and military electric drive systems.

ACKNOWLEDGMENT

This study was supported by the Faculty of Electrical Engineering, University of Economics - Technology for Industries, No. 353, Tran Hung Dao Road, Nam Dinh City of Viet Nam; http://www.uneti.edu.vn.

REFERENCES

[1] D. Phuoc. Nguyen, The Advanced control theory., Science and Technics Publishing House (in Vietnamese), Hanoi, Vietnam, (2016).

[2] Q. Khanh. Bui, V. Lien. Nguyen, Electric drive base. Science and Technics Publishing House (in Vietnamese), Hanoi, Vietnam, (2012).

[3] D. Chuyen. Tran, Electric drive. Science and Technics Publishing House (in Vietnamese), Hanoi, Vietnam, (2016).

[4] M. Chinh. Vo, Power electronics, Science and Technics Publishing House (in Vietnamese), Hanoi, Vietnam, (2015).

[5] H. Viet. Dao, Analysis, and synthesis of electric drive systems, People's Army Publishing House (in Vietnamese), Hanoi, Vietnam, (2010).

[6] P. Quang. Nguyen and Jörg-Andreas Dittrich., Intelligent electric drive, Science and Technics Publishing House, (in Vietnamese), Hanoi, Viet Nam, (2006).

[7] J. Chiasson, Modeling and high-performance control of electric machines. Wiley-IEEE Press. Published by Inc., Hoboken, New Jersey, Printed in the United States of America, (2005).

[8] P. Ioannou, and J. Sun, Robust Adaptive Control., University of Southern California, 6(2017).

[9] L. Keviczky, R. Bars, J. Hetthéssy, C. Bányász, and C. Engineering, MATLAB Exercises., Springer Nature Singapore Pte Ltd, USA ISSN 1439-2232, (2019).

[10] Andrea Bacciotti, Stability and Control of Linear Systems, Publishing Ltd; Springer Nature Switzerland AG (2019).

[11] Andrzej Bartoszewicz, Sliding mode control, first published March Printed in India, (2011).

[12] Utkin, V., Guldner, J., Shi, J.: Sliding Mode Control in Electromechanical Systems. Published by CRC Press LLC, Boca Raton (1999).

[13] Vadim Utkin, Jürgen Guldner, Jingxin Shi, Sliding Mode Control in Electro-Mechanical Systems, Published by Taylor & Francis Group, LLC (2009). eBook Published (2017).

[14] Y.-C. Chang H.-M. Yen, Design of a robust position feedback tracking controller for flexible-joint, IET Control Theory Appl, (2011).

[15] Francis X. Govers, Artificial Intelligence for Robotics, Published by Packt Publishing Ltd. Livery Place. 35 Livery Street, Birmingham, B3 2PB, UK, (2018).

[16] CHIA-MING CHANG, CHANG-HUAN LIU., Adaptive Speed Sensorless Induction Motor Drive for Very-Low-Speed and Zero Stator Frequency Operation. Electric Power Components and Systems, 38(2010) 804-819.

[17] C. Uyulan., A robust-adaptive linearizing control method for sensorless high precision control of induction motor". Measurement and Control 2019, 52(2019) (5-6) 634-656.

[18] M. S. Zaky, M. Khater, Hyasin, and S. S. Shokralla, Very low speed and zero speed estmations of sensorless induction motor drivers, Electric Power Systems Research, 80(2010) 143-151.

[19] T. D. Chuyen et al. D. Q. Hiep, D. H. Du, Research to Improve the Quality Control for Drive System Tracking Electromechanical Takes into Account Nonlinear Undetermined Application in Industrial Production. The under exclusive license to Springer Nature Switzerland AG 2021, ICERA 2020, LNNS 178(2021) 708 – 723.

[20] Z. Li, J. Chen, G. Zhang, and M. Gan., Adaptive Robust Control of Servo Mechanisms With Compensation for Nonlinearly Parameterized Dynamic Friction, IEEE Transaction on Control Systems Technology, 21(1)(2013) 194-202.

[21] Kalyana C. Veluvolu, Dongik Lee., Sliding mode high-gain observers for a class of uncertain nonlinear systems., Applied Mathematics Letters 24(2011) 329–334.

[22] O. M. Kwon and J. H. Park, Exponential stability of uncertain dynamic systems including state delay., Applied Mathematics Letters, 19(9)(2006) 901-907.

[23] M. R. Msukwa, E. W. Nshama, and N. Uchiyama, Adaptive Sliding Mode Control With Feedforward Compensator for Energy-Efficient and High-Speed Precision Motion of Feed Drive Systems, IEEE Access, 8(2020) 43571-43581.

[24] M. N. Uddin and M. M. I. Chy, A novel fuzzy-logic-controller-based torque and flux controls of IPM synchronous motor, IEEE Trans. Ind. Appl., 46(3)(2010) 1220-1229.

[25] T. Zhang, Y. Yu, and Y. Zou., An Adaptive Sliding-Mode Iterative Constant-force Control Method for Robotic Belt Grinding Based on a One-Dimensional Force Sensor, Sensors, 19(7)(2019), Art. no. 1635.

[26] K.Sato, J. Shin, T. Koseki and Y. Aoyama, Basic Experiments for High-Torque, Low-Speed Permanent Magnet Synchronous Motor and a Technique for Reducing Cogging Torque., IEEE,(2010) 1- 6.

[27] Chee Pin Tana; Xinghuo Yub; Zhihong Manc., Terminal sliding mode observers for a class of nonlinear systems., Automatica 46(2010) 1401_1404.

[28] K. Akatsu and A. Kawamura., Sensorless very low-speed and zero-speed estimations with online rotor resistance estimation of induction motor without signal injection., IEEE Trans. on Industry Applications, 36(3)(2000) 764-771.

[29] H. Li, H.P. Xie, X. Yi, Y. Zheng., Research on low speed control of permanent magnet synchronous motor based on state observer, 4th International Conference on Biomedical Engineering and Informatics (BMEI 2011).

[30] Seong Ik Han, Chan Se Jeong; and Soon Yong Yang: "Robust sliding mode control for uncertain servo system using friction observer and recurrent fuzzy neural networks. Journal of Mechanical Science and Technology 26(2012) 1149-1159, 4.

[31] Jesús Linares-Flores, Carlos García-Rodríguez, Hebertt Sira-Ramírez, and Oscar David Ramírez-Cárdenas, Robust Backstepping Tracking Controller for Low-Speed PMSM Positioning System: Design, Analysis, and Implementation, IEEE Transactions on Industrial Informatics. 11(5)(2015) 1130-1141,.

[32] Б.К Чемоданов - Следящие приводы Т1, 2.- М.: Изд. МГТУ им Баумана, (1999).

[33] КлючевВ.И.Теория электропривода, Москва энергоатомиздт, (2001).