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Designing A Synthesizing Adaptive Backstepping Sliding Mode Controller for Drive Systems Tracking Electric Mechanisms Using Synchronous Ac Motors

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Abstract: In this paper, we present a synthesis method adaptive backstepping sliding mode controller for drive systems tracking electric mechanisms working at slow speed using synchronous AC motors which has been commonly used in the industrial and military applications. The issues such as determining non-linear and changing parameters of the model, building adaptive law to determine parameter uncertainties and building the sliding mode observer to estimate the torques (load torque and friction torque) and disturbances are taken into account. A controller design is proposed to improve the quality of electric mechanisms systems while sticking to the components listed above nonlinear uncertainty. The calculation and design of this controller is based on the basis of speed synchronous AC motors. The research results can be used as the ground for establishing control algorithms and designing systems of electric drives in industry and military.

Keywords: Tracking system, adaptive control, backstepping sliding mode control, nonlinear systems, slow speed, synchronous AC motor.

I. INTRODUCTION

The attached-mode electric-mechanism actuators at slow work speed requiring high precision and quality have been popularly used in many industrial and military applications. The permanent magnet synchronous motor (PMSM) is one of the most popular AC motors in industry because of good controllability and high efficiency. In industrial PMSM drive applications, PID or linear quadratic regulator (LQR) has been extensively adopted since its implementation is low-cost [7]. However, these linear control methods cannot assure high control performance (e.g., fast transient response, zero steady-state error, and robustness) because they are highly vulnerable to parameter variations and external disturbances. Consequently, it is quite challenging to precisely and quickly control the PMSMs with the nonlinear dynamic model. Recently, to cope with the limitations of the linear control methods, many researchers have proposed various nonlinear control techniques such as adaptive control [1, 4], fault-tolerant control [6], robust control [4, 12], intelligent control [10], adaptive backstepping control [1], sliding mode control [2, 3], direct torque control [13], model predictive control [11], and fuzzy control [4]...

In this paper, a nonlinear optimal controller based on an adaptive backstepping sliding mode control is proposed to control the speed of the IPMSM. In addition, an optimal load torque observer is designed to supply the controller with the load torque information to improve quality control in the drive system and stick it in the industry and military.

II. MODELLING OF NONLINEAR ELECTRICAL TRANSMISSION DRIVERS

Subjects controlling the electric mechanisms can drive the system including the engine, transmission and producer. The block diagram of the mechanical drive system is shown in Figure 1. An overview of the mechanical drive system includes many mass linked with each other by elasticity or by using two elastic organism model then converted to the motor shaft. Dynamical mechanism of the drive system is described by the following equation:

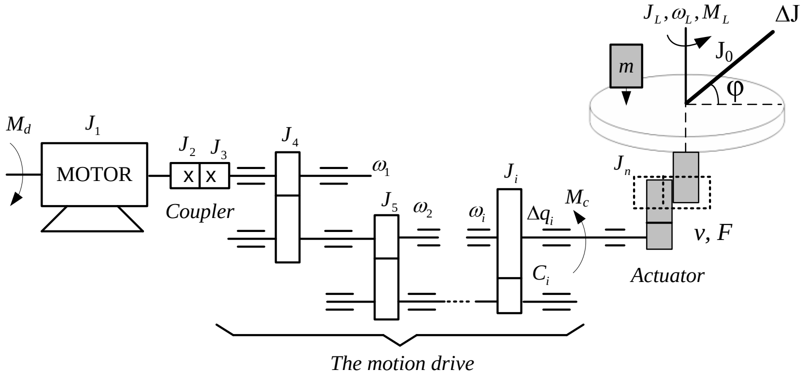


Fig 1. Block diagram of the mechanical drive system tracking nonlinear

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

where J is the total moment of inertia of the motor and other parts reduced on the motor shaft, M_d is the moment of the motor, B_m is the viscous friction coefficient depending on the engine speed, M_L is the sum of form load torque acts on the motor shaft and load torque converted to motor shaft. M_L is a nonlinear function complex depending on engine speed, friction, elasticity of the transmission shaft...

Mathematical modeling of the mechanical drive system tracking nonlinear using 3-phase motor PMSM in coordinate axes d-q is written as follows:

$$\begin{aligned} v_d &= r_s i_d + L_d\frac{di_d}{dt} - P\omega L_q i_q \\ v_q &= r_s i_q + L_q\frac{di_q}{dt} + P\omega L_d i_d + P\omega\lambda_m \\ M_d &= \frac{3}{2}P\lambda_m i_q + \frac{3}{2}P(L_d - L_q)i_d i_q \\ J\frac{d\omega}{dt} &= M_d - B_m\omega - M_L \end{aligned} \quad (2)$$

where, v_d, v_q direct-and quadrature-axis stator voltages, i_d, i_q direct-and quadrature-axis stator currents, L_d, L_q direct-and quadrature-axis inductance, r_s stator resistance, $\frac{d}{dt}$ is the differential operator, P number of poles, ω is the motor speed, M_L is the load torque, J Moment of inertia, B_m is viscous friction coefficient, and λ_m is flux linkage.

we representation the state vector as follows:

$$x = \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} = \begin{pmatrix} i_d \\ i_q \\ \omega \end{pmatrix}, \; g_1 = \begin{pmatrix} 1/L_d \\ 0 \\ 0 \end{pmatrix}, \; g_2 = \begin{pmatrix} 0 \\ 1/L_q \\ 0 \end{pmatrix}, \quad (3)$$

The nonlinear state equation of an IPMSM in the d-q reference frame can be written as follows:

$$\frac{dx}{dt} = f(x) + g_1 v_d + g_2 v_q \quad (4)$$

where,

$$f(x) = \begin{pmatrix} f_1(x) \\ f_2(x) \\ f_3(x) \end{pmatrix} = \begin{pmatrix} -\frac{r_s i_d}{L_d} + \frac{PL_q i_q\omega}{L_d} \\ -\frac{PL_d i_d\omega}{L_q} - \frac{r_s i_q}{L_q} - \frac{P\omega\lambda_m}{L_q} \\ \frac{3Pi_q\lambda_m + 3P\left(L_d - L_q\right)i_d i_q}{2J} - \frac{\omega B_m}{J} - \frac{M_L}{J} \end{pmatrix} \quad (5)$$

When taking into account the uncertainty of the model (the change in the motor parameters, the parameter mechanical and load torque in the working process), then (4) is rewritten as follows:

$$\frac{dx}{dt} = (f_o(x) + \Delta f(x)) + (g_{1o} + \Delta g_1)v_d + (g_{2o} + \Delta g_2)v_q \quad (6)$$

where,

$$f_o(x) = \begin{pmatrix} f_{1o}(x) \\ f_{2o}(x) \\ f_{3o}(x) \end{pmatrix} = \begin{pmatrix} -\frac{r_{so} i_d}{L_{do}} + \frac{P_o L_{qo} i_q\omega}{L_{do}} \\ -\frac{P_o L_{do} i_d\omega}{L_{qo}} - \frac{r_{so} i_q}{L_{qo}} - \frac{P_o\omega\lambda_{mo}}{L_{qo}} \\ \frac{3P_o i_q\lambda_{mo} + 3P_o\left(L_{do} - L_{qo}\right)i_d i_q}{2J_o} - \frac{\omega B_{mo}}{J_o} - \frac{\hat{M}_L}{J_o} \end{pmatrix} \quad (7)$$

$$g_{1o} = \begin{pmatrix} 1/L_{do} \\ 0 \\ 0 \end{pmatrix}, \; g_{2o} = \begin{pmatrix} 0 \\ 1/L_{qo} \\ 0 \end{pmatrix} \tag{8}$$

$$\Delta f(x) = \begin{pmatrix} \Delta f_1(x) \\ \Delta f_2(x) \\ \Delta f_3(x) \end{pmatrix}, \; \Delta g_1 = \begin{pmatrix} \Delta_1 \\ 0 \\ 0 \end{pmatrix}, \; \Delta g_1 = \begin{pmatrix} 0 \\ \Delta_2 \\ 0 \end{pmatrix} \tag{9}$$

where, with the subscript "$_o$" denoting the nominal value of some interested coefficient, $\hat{M}_L$ value estimate load torque of outside the motor, Δ symbolizing the system uncertainties including parameter variations and load estimation error, and Δ_1, Δ_2 representing unknown but bounded constants. Reformulating (6), one can obtain:

$$\frac{dx}{dt} = f_o(x) + g_{1o}v_d + g_{2o}v_q + F \tag{10}$$

where,

$$F = \begin{pmatrix} F_1 \\ F_2 \\ F_3 \end{pmatrix} = \begin{pmatrix} \Delta f_1(x) + \Delta_1 v_d \\ \Delta f_2(x) + \Delta_2 v_q \\ \Delta f_3(x) \end{pmatrix}, \; |F| < \bar{F} = \begin{pmatrix} \bar{F}_1 \\ \bar{F}_2 \\ \bar{F}_3 \end{pmatrix} \tag{11}$$

with $\bar{F}$ being the upper bound of the lumped uncertainty F assuming the lumped uncertainty F and the external load M_L are unknown constants. As a result, the lumped uncertainty F and the external load M_L can be approximately estimated by adaptive laws and a load torque estimator, respectively.

III. DESIGN OF ADAPTIVE BACKSTEPPING SLIDING MODE CONTROLLER

The problem of controller synthesis system is the problem of define control laws for v_d, v_q ensure a stable working system, the tracking errors quickly reduced to zero.

When building speed tracking systems, we define the error as follows:

$$e_1 = \omega_d - \omega \tag{12}$$

$$e_2 = i_{dd} - i_d \tag{13}$$

where, ω_d and i_{dd} is the set value corresponding of rotor speed and d-axis currents is set non-zero, with, [10]:

$$i_{dd} = \frac{-\lambda_{mo}}{2(L_{do} - L_{qo})} - \sqrt{\frac{\lambda_{mo}^2}{4(L_{do} - L_{qo})^2} + i_q^2} \tag{14}$$

From (12) - (13), combined with (10) and (11), we built a system of differential equations for the errors is:

$$\dot{e}_1 = \dot{\omega}_d - \dot{\omega} = \dot{\omega}_d - f_{3o}(x) - F_3 \tag{15}$$

$$\dot{e}_2 = \dot{i}_{dd} - f_{1o} - F_1 - v_d / L_{do} \tag{16}$$

The design procedure of the proposed control scheme can be generalized as follows:

Step 1: Using the form surface slip differential for the sliding surface s_q sliding surface for sliding surface PI with s_d errors is selected as follows, [1, 2, 3]:

$$\begin{aligned} s_q &= \dot{e}_1 + k_1 e_1 \\ \dot{s}_q &= k_1\dot{\omega}_d - k_1(f_{3o} + F_3) + \ddot{\omega}_d + (f_{3o} + F_3)M_3 - M_2(f_{2o} + \\ &\quad + F_2 + v_q / L_{qo}) - M_1(f_{1o} + F_1 + v_d / L_{do}) \end{aligned} \tag{17}$$

where,

$$M_1 = \frac{3P_o(L_{do} - L_{qo})i_q}{2J_o}, \; M_2 = \frac{3P_o\lambda_{mo} + 3P_o(L_{do} - L_{qo})i_d}{2J_o}, \; M_3 = \frac{B_{mo}}{J_o}. \tag{18}$$

$$\begin{aligned} s_d &= e_2 + k_{sd}\int_0^t e_2 dt \\ \dot{s}_d &= \dot{e}_2 + k_{sd}e_2 = \dot{i}_{dd} - f_{1o} - F_1 - v_d / L_{do} + k_{sd}e_2 \end{aligned} \tag{19}$$

where, k_{sd}, k_1 are strictly positive constants. To design the backstepping control scheme, the Lyapunov function with sliding manifold information is selected as:

$$V_1 = \frac{1}{2}s_d^2 + \frac{1}{2}s_q^2 \tag{20}$$

Computing the derivative of the Lyapunov function, one can obtain:

$$\begin{aligned}\dot{V}_1 &= s_d\dot{s}_d + s_q\dot{s}_q \\ &= s_d\left(\dot{i}_{dd} - f_{1o} - F_1 - v_d / L_{do} + k_{sd}e_2\right) + \\ &+ s_q\begin{bmatrix} k_1\dot{\omega}_d - k_1(f_{3o} + F_3) + \ddot{\omega}_d + (f_{3o} + F_3)M_3 - M_2(f_{2o} + \\ + F_2 + v_q / L_{qo}) - M_1(f_{1o} + F_1 + v_d / L_{do}) \end{bmatrix}\end{aligned} \tag{21}$$

To satisfy $\dot{V}_1 \le 0$, the backstepping sliding mode control laws are designed as:

$$v_d = L_{do}\left(\dot{i}_{dd} - f_{1o} - F_1 + k_{sd}e_2 + k_d s_d + \left(\bar{F}_1 + \eta_d\right)sgn(s_d)\right) \tag{22}$$

$$\begin{aligned}v_q = \frac{L_{qo}}{M_2}\Big(& k_1\dot{\omega}_d - k_1(f_{3o} + F_3) + \ddot{\omega}_d + f_{3o}M_3 - M_1 f_{1o} - M_1 v_d / L_{do} + k_q s_q + M_3 f_{3o} + \\ & - M_2 f_{2o} + k_q s_q + \left|M_1\bar{F}_1 + M_2\bar{F}_2 + M_3\bar{F}_3 + k_1\bar{F}_3 + \eta_q\right| sgn(s_q)\Big)\end{aligned} \tag{23}$$

where, η_d, η_q are positive constants. Substituting (17) and (18) into (16), one can obtain:

$$\dot{V}_1 \le -k_d s_d^2 - k_q s_q^2 - \eta_d\left|s_d\right| - \eta_q\left|s_q\right| \le 0 \tag{24}$$

As one can observe, the derivative of the Lyapunov function is less or equal to zero, and it means that the backstepping sliding-mode control system is stable.

Step 2: Then, the Lyapunov function can be rewritten as:

Assume that the lumped uncertainties F_1, F_2, and F_3 can be approximately estimated by adaptive laws under a fixed sampling interval. These functions are determined by the construction of the adaptive law. Then, the Lyapunov function can be rewritten as:

$$V_2 = V_1 + \frac{1}{2\gamma_1}\tilde{F}_1^2 + \frac{1}{2\gamma_2}\tilde{F}_2^2 + \frac{1}{2\gamma_3}\tilde{F}_3^2 \tag{25}$$

where, $\tilde{F}_1 = \hat{F}_1 - F_1, \tilde{F}_2 = \hat{F}_2 - F_2, \tilde{F}_3 = \hat{F}_3 - F_3$, and $\gamma_1, \gamma_2, \gamma_3$ are adaptive gains.

The derivative of the Lyapunov function (25) can be expressed as:

$$\begin{aligned}\dot{V}_2 &= \dot{V}_1 - \frac{1}{\gamma_1}\tilde{F}_1\dot{\hat{F}}_1 - \frac{1}{\gamma_2}\tilde{F}_2\dot{\hat{F}}_2 - \frac{1}{\gamma_3}\tilde{F}_3\dot{\hat{F}}_3 = \\ &= s_d\left(\dot{i}_{dd} - f_{1o} - F_1 - v_d / L_{do} + k_{sd}e_2\right) + s_q\big(k_1\dot{\omega}_d - k_1(f_{3o} + F_3) + \ddot{\omega}_d + \\ &- M_1(f_{1o} + F_1 + v_d / L_{do}) - M_2(f_{2o} + F_2 + v_q / L_{qo}) + M_3(f_{3o} + F_3)\big) + \\ &- \frac{1}{\gamma_1}\tilde{F}_1\dot{\hat{F}}_1 - \frac{1}{\gamma_2}\tilde{F}_2\dot{\hat{F}}_2 - \frac{1}{\gamma_3}\tilde{F}_3\dot{\hat{F}}_3.\end{aligned} \tag{26}$$

Substituting $F_1 = \tilde{F}_1 + \hat{F}_1, F_2 = \tilde{F}_2 + \hat{F}_2, F_3 = \tilde{F}_3 + \hat{F}_3$, we have the following $\dot{V}_2$ values as follows

$$\begin{aligned}\dot{V}_2 = &s_d\left(\dot{i}_{dd} - f_{1o} - \tilde{F}_1 - \hat{F}_1 - v_d / L_{do} + k_{sd}e_2\right) + s_q\big[k_1\dot{\omega}_d - k_1(f_{3o} + F_3) + \ddot{\omega}_d + \\ &- M_1(f_{1o} + v_d / L_{do}) - M_2(f_{2o} + v_q / L_{qo}) + M_3 f_{3o} + \\ &- k_1(\tilde{F}_3 + \hat{F}_3) - M_1(\tilde{F}_1 + \hat{F}_1) - M_2(\tilde{F}_2 + \hat{F}_2) + M_3(\tilde{F}_3 + \hat{F}_3)\big] + \\ &- \frac{1}{\gamma_1}\tilde{F}_1\dot{\hat{F}}_1 - \frac{1}{\gamma_2}\tilde{F}_2\dot{\hat{F}}_2 - \frac{1}{\gamma_3}\tilde{F}_3\dot{\hat{F}}_3.\end{aligned} \tag{27}$$

According to (21), we design the adaptive backstepping sliding mode control laws v_d, v_q as follows:

$$v_d = L_{do}\left(\dot{i}_{dd} - f_{1o} - \hat{F}_1 + k_{sd}e_2 + k_d s_d + \eta_d sgn(s_d)\right) \tag{28}$$

$$v_q = \frac{L_{qo}}{M_2}\Big[k_1\dot{\omega}_d - k_1(f_{3o}+F_3) + \ddot{\omega}_d - M_1(f_{1o} + v_d / L_{do}) - M_2 f_{2o} + M_3 f_{3o} + \\ - M_1\hat{F}_1 - M_2\hat{F}_2 + M_3\hat{F}_3 - k_1\hat{F}_3 + k_q s_q + \eta_q sgn(s_q)\Big]. \tag{29}$$

Substituting (28) and (29) into (27) the following adaptive laws can be obtained:

$$\begin{aligned} \dot{V}_2 &= s_d\left(-\tilde{F}_1 - k_d s_d - \eta_d sgn(s_d)\right) + s_q\left(-M_1\tilde{F}_1 - M_2\tilde{F}_2 + M_3\tilde{F}_3 - k_q s_q - \eta_q sgn(s_q)\right) + \\ &\quad - \frac{1}{\gamma_1}\tilde{F}_1\dot{\hat{F}}_1 - \frac{1}{\gamma_2}\tilde{F}_2\dot{\hat{F}}_2 - \frac{1}{\gamma_3}\tilde{F}_3\dot{\hat{F}}_3 \\ &= s_d\left(-k_d s_d - \eta_d sgn(s_d)\right) + s_q\left(-k_q s_q - \eta_q sgn(s_q)\right) + \\ &\quad - \tilde{F}_1\left(s_q M_1 + \frac{1}{\gamma_1}\dot{\hat{F}}_1 + s_d\right) - \tilde{F}_2\left(s_q M_2 + \frac{1}{\gamma_2}\dot{\hat{F}}_2\right) - \tilde{F}_3\left(-M_3 s_q + k_1 + \frac{1}{\gamma_3}\dot{\hat{F}}_3\right) \end{aligned} \tag{30}$$

From there, the parameter adaptation laws are then written as follows:

$$\dot{\hat{F}}_1 = -\gamma_1\left(s_q M_1 + s_d\right) \tag{31}$$

$$\dot{\hat{F}}_2 = -\gamma_2 s_q M_2 \tag{32}$$

$$\dot{\hat{F}}_3 = -\gamma_3\left(k_1 - M_3\right)s_q \tag{33}$$

Substituting (31) - (33) into (27), one can satisfy:

$$\dot{V}_2 \le -k_d s_d^2 - k_q s_q^2 - \eta_d\left|s_d\right| - \eta_q\left|s_q\right| \le 0 \tag{34}$$

From (34), we can see that the designed adaptive backstepping sliding mode control can ensure system stability. By increasing the controller gains η_d and η_q in (30) and (28), one can improve the robustness. In fact, larger values of the controller gains η_d and η_q will lead to more chattering in the control inputs. To reduce the chattering, the chattering phenomenon can be reduced by replacing the discontinuous sign function by a continuous function approximation $s/(|s|+\mu)$, where μ is a positive constant. We know that when $\mu \to 0$, the characteristics of the controller will close approximation to the characteristics of the original controller [6], [9].

With the use of function approximation as above, the controller (28) and (29), the adaptive backstepping sliding mode control laws v_d and v_q becomes:

$$v_d = L_{do}\left(\dot{i}_{dd} - f_{1o} - \hat{F}_1 + k_{sd}e_2 + k_d s_d + \eta_d s_d / (\left|s_d\right| + \mu_d)\right) \tag{35}$$

$$v_q = \frac{L_{qo}}{M_2}\Big[k_1\dot{\omega}_d - k_1(f_{3o}+F_3) + \ddot{\omega}_d - M_1(f_{1o} + v_d / L_{do}) - M_2 f_{2o} + M_3 f_{3o} + \\ - M_1\hat{F}_1 - M_2\hat{F}_2 + M_3\hat{F}_3 - k_1\hat{F}_3 + k_q s_q + \eta_q s_q / (\left|s_q\right| + \mu_q)\Big]. \tag{36}$$

The whole speed control system is shown in Figure 2,

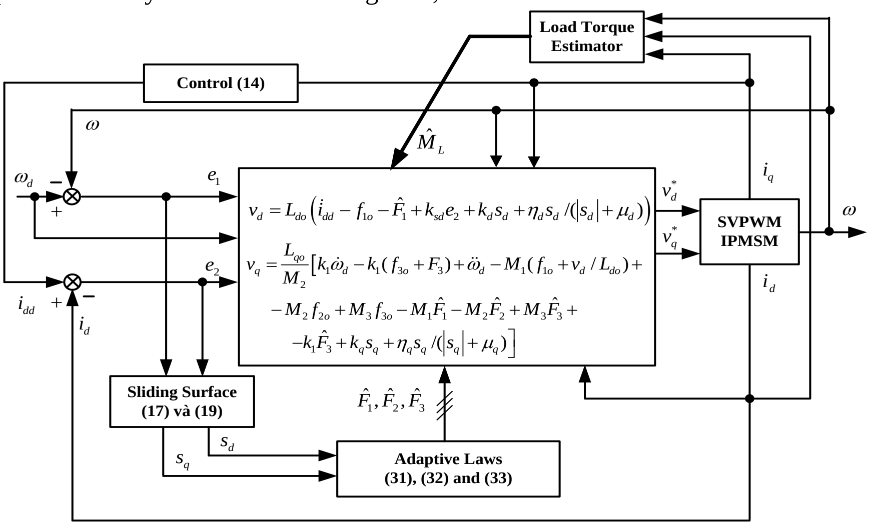


Fig. 2. The system calculates adaptive backstepping sliding controller.

Step 3: Load torque and disturb observer design

As expected previously, the proposed adaptive backstepping sliding mode control law (35) includes the load torque M_L term. It means that the control performance can be severely affected by the load torque variations if M_L is not properly observed. In this section, a simple observer is utilized to know its information. In this part, a load torque observer based on sliding method is used to estimate the load torque, [8, 10].

From dynamical equations of motor speeds that we have chosen is written as follows:

$$\dot{\omega} = k_1 i_{sq} - k_2\omega + k_{11} i_{sd} i_{sq} - k_3 M_L \tag{37}$$

where, $k_1 = \frac{3}{2}\frac{1}{J_o}\frac{p^2}{4}\lambda_{mo}$, $k_2 = \frac{B_{mo}}{J_o}$, $k_3 = \frac{p}{2J_o}$, $k_{11} = \frac{3}{2}\frac{1}{J_o}\frac{p^2}{4}(L_{do} - L_{qo})$.

In order to design the estimate for uncertain nonlinear components, firstly we define a sliding surface as follows:

$$s_o = \omega - \hat{\omega} \tag{38}$$

where, $\hat{\omega}$ is the estimated value of the rotor speeds is calculated as follows:

$$\dot{\hat{\omega}} = k_1 i_{sq} - k_2\omega + k_{11} i_{sq} i_{sd} + l\,\mathrm{sgn}(\omega - \hat{\omega}) \tag{39}$$

with $l > 0$.

The error dynamics of the slide mode observe can be obtained as follows:

$$\dot{s}_o = \dot{\omega} - \dot{\hat{\omega}} = -k_3 M_L - l\,\mathrm{sgn}(s_o) \tag{40}$$

where, $s_o = \dot{s}_o = 0$. Therefore:

$$k_3 M_L \approx -l\,\mathrm{sgn}(s_o) \tag{41}$$

The value of the load torque estimate can be rewritten as follows:

$$\hat{M}_L = -\frac{1}{1+s\tau_o}\frac{l}{k_3}\mathrm{sgn}(s_o) \tag{42}$$

where, τ_o is a constant inertial the filter; l is the amplification factor.

We have block diagram of the load torque observer as follows:

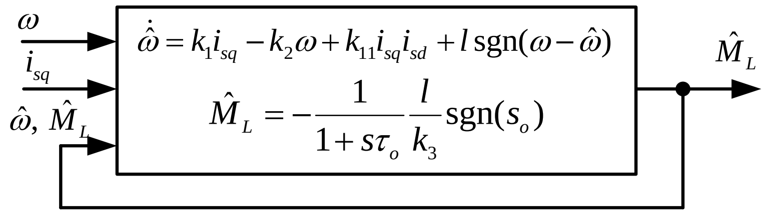


Fig. 3. Block diagram of the load torque observer

The composition load torque estimated here include: inertial torque, friction torque, drag torque... is the uncertain nonlinear composition, often appearing in the gearbox. Therefore the traditional PID controller cannot overcome their effects on the quality of work of the system, [12, 13]. By synthetic methods this adaptive backstepping slide mode control, the negative impact of nonlinear uncertain factors on the quality of the drive systems have been resolved.

IV. THE SIMULATION AND EXPERIMENTAL

4.1. Simulation results

Block diagram of system structure tracking nonlinear, designed by the method of adaptive backstepping sliding mode controller shown in figure 4:

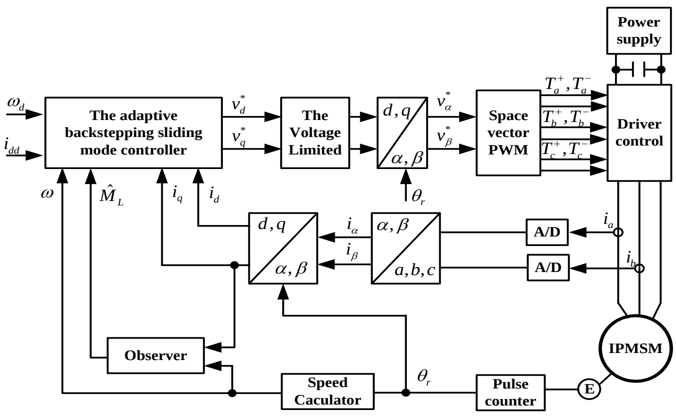


Fig. 4. Block diagram system structure tracking nonlinear

To evaluate the performance of the proposed control system design, let us consider a prototype IPMSM used on simulation and experimental with the flowing nominal parameters: the IPMSM of YaKawa, rated power P_{rated} = 0,45KW, Number of poles is 4, rated speed n_{rated} = 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, l_m = 0.193V.s/rad, J = 1.5e^{-4} Kg.m^2, B = 0,0001 N.m.s/rad.

The selected parameter in the controller is: $k_1 = 1250,\ k_d = 50;\ k_q = 30,\ \eta_d = 270,$

$$\eta_q = 130,\ k_{sd} = 1.e^4,\ \gamma_1 = 0.067,\ \gamma_2 = 0.01,\ \gamma_3 = 0.01.$$

We have simulated the model controller for IPMSM motors in Matlab/Simulink as follows:

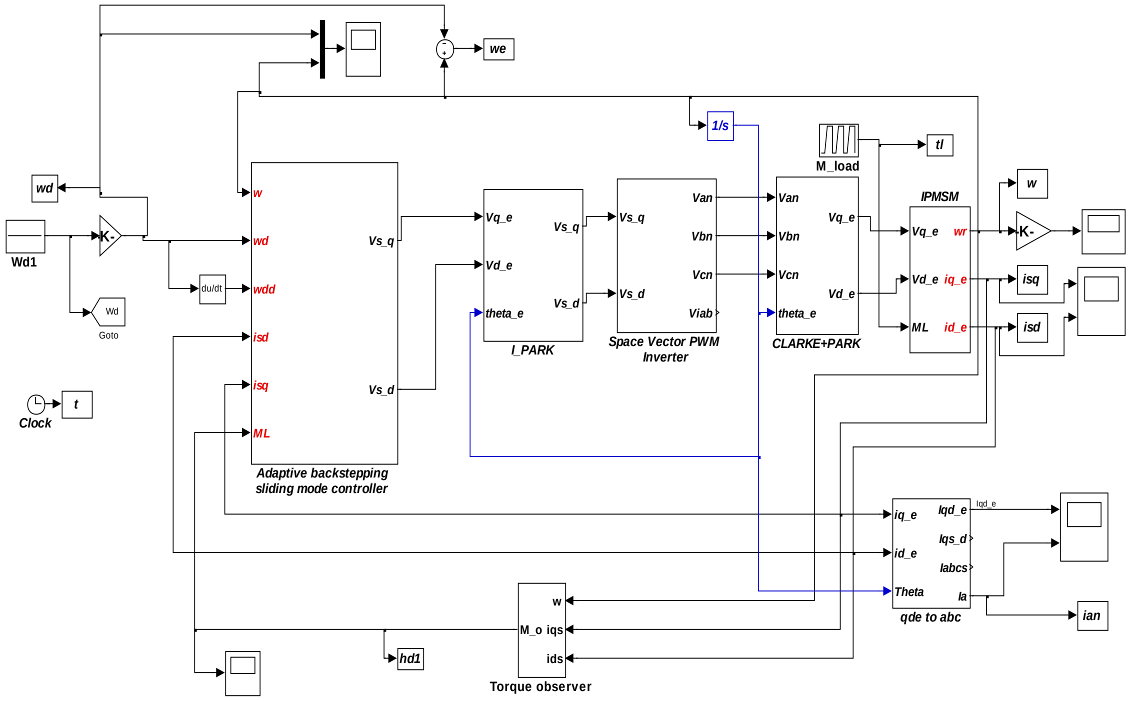
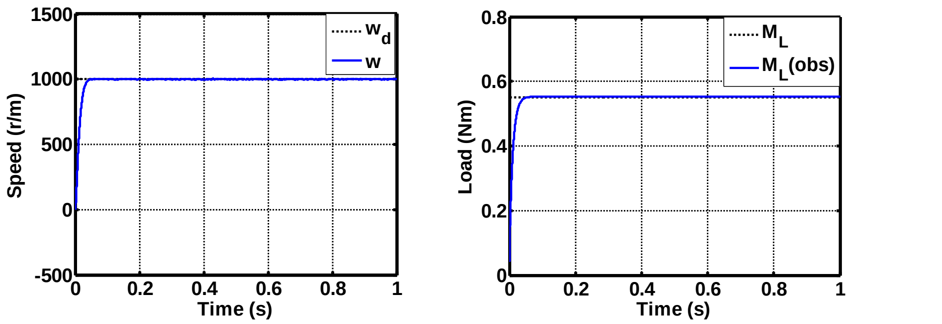


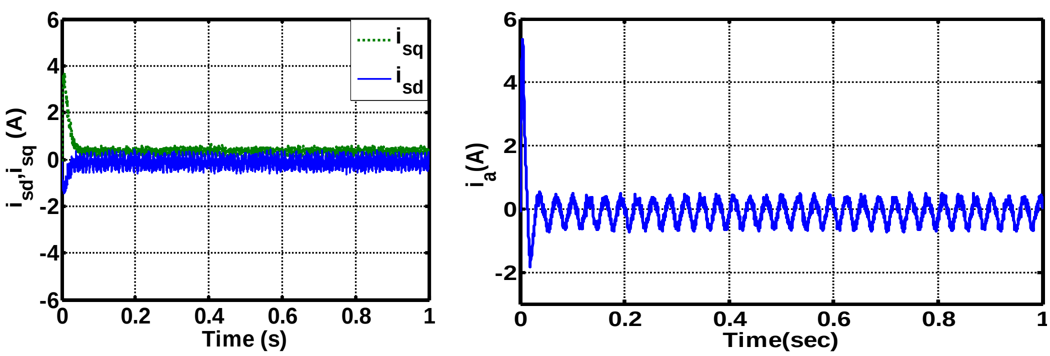
Fig 5. The simulation models in MATLAB SIMULINK

From simulation diagrams have the following results:



(a) (b)

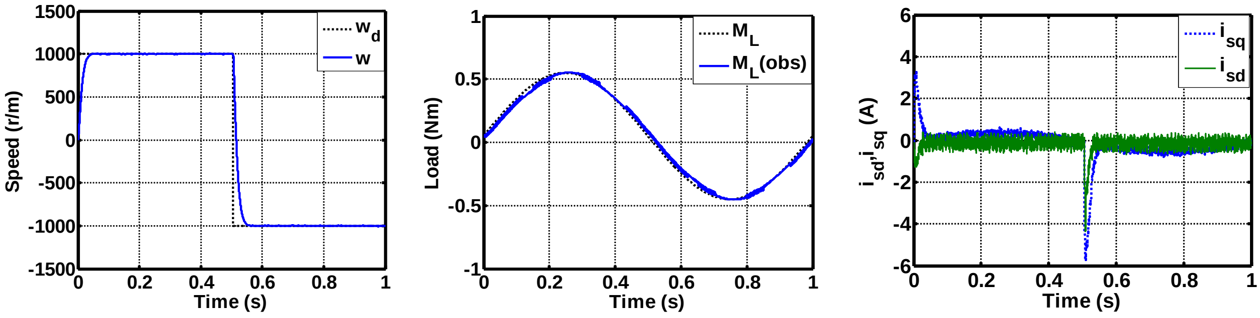
Fig. 6. Simulation results with the responding components: a) $\omega;\ \omega_d$, and b) $M_L;\ \hat{M}_L$



(a) (b)

Fig. 7. Responding current (a) i_{sd}, i_{sq} and (b) currents i_a from the controller

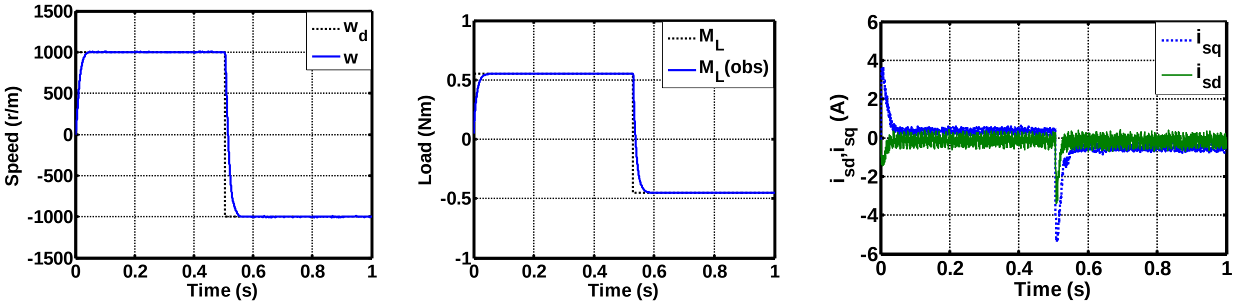
In Figure 6 presents the simulation results when the constant input, constant load torque effects on motor. The output sticking of the system on the input. Load observers accurately reflect effects load into the system. And Figure 7 is the response output currents i_a, i_{sd}, i_{sq} of the proposed controller.



(a) (b) (c)

Fig. 8. The simulation results when load torque has sine waveform

In Figure 8 presents simulation results when the input of change the form of square pulses with amplitudes of 1000 r/m, torque interfere have sin waveform effects on the motor. The output tracking of the system on the input. The load observers measured accurately effects on the system.



(a) (b) (c)

Fig 9. The simulation results when the load inertia torque changes: a) speed ω; ω_d , b) load torque M_L; $\hat{M}_L$, c) currents i_{sd}, i_{sq}

In Figure 9 presents simulation results when the input of change the form of square pulses with amplitude of 1000 r/m, load torque of change the form of square pulses with amplitude of 0.5Nm effects on motor. Moment of inertia of the load increased by 50% compared with the initial value. The output of the system change in transient response, then still tracking the input balancing process.

4.2. Experimental results

Based on the adaptive backstepping sliding mode controller approach, a load-torque-observer based control design method was proposed for an IPMSM under model parameter and load torque variation. The proposed adaptive controller was implemented by using IPMSM driving system which consists of a three-phase inverter with TI DSP TMS230F28069 (fixed point DSP). The study, structural design model of experimental drive system is performed as follows:

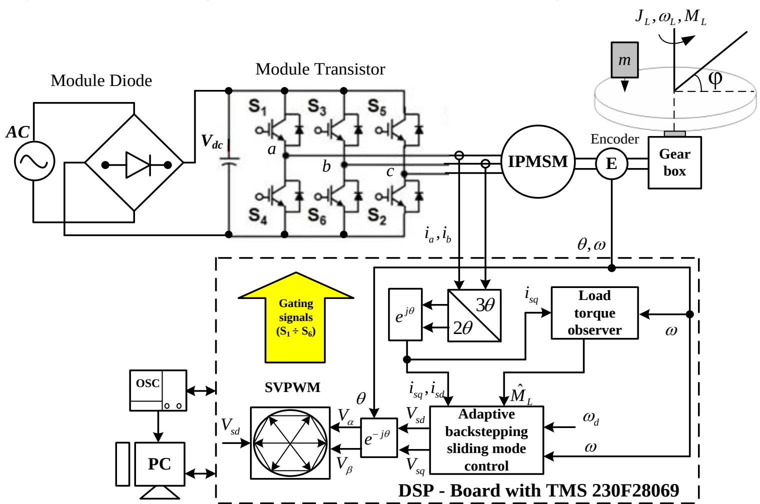


Figure 10: Overall block diagram of the proposed control system

And figure 11 shows the configuration of the experimental system includes the following equipment: 1- IPMSM, 2- encoder, 3- the disk to put the load, 4- the power supply, 5- gear box, 6- three phase PWM inverter with a DSP controller, 7- oscilloscope, 8- the computer.

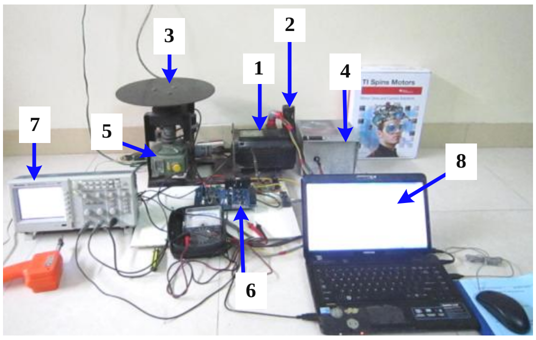
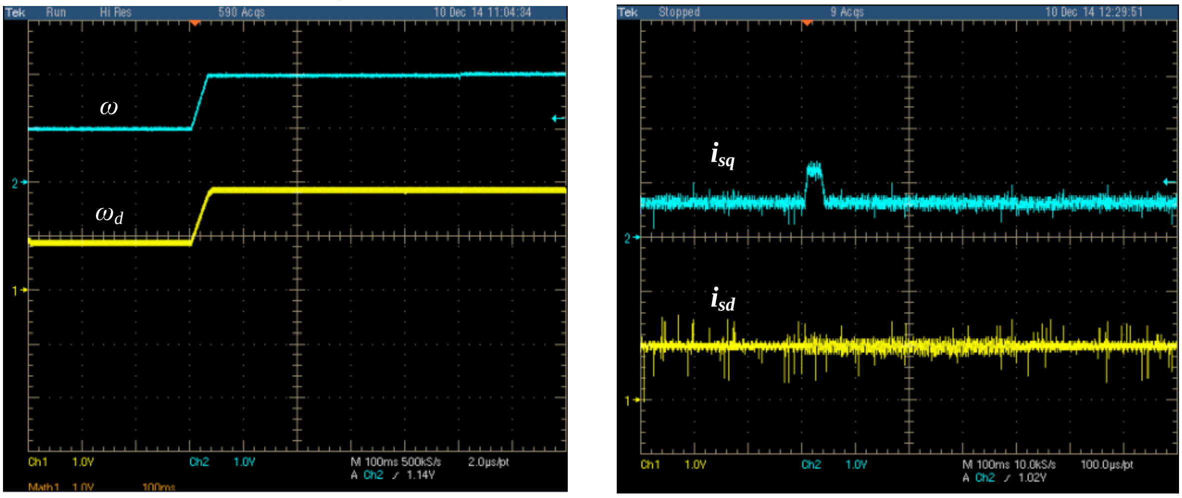


Figure 11: Configuration of experimental system

The experimental result: Three different control schemes have been simulation using Matlab Simulink, which is a very powerful simulation tool, under the flowing three cases:

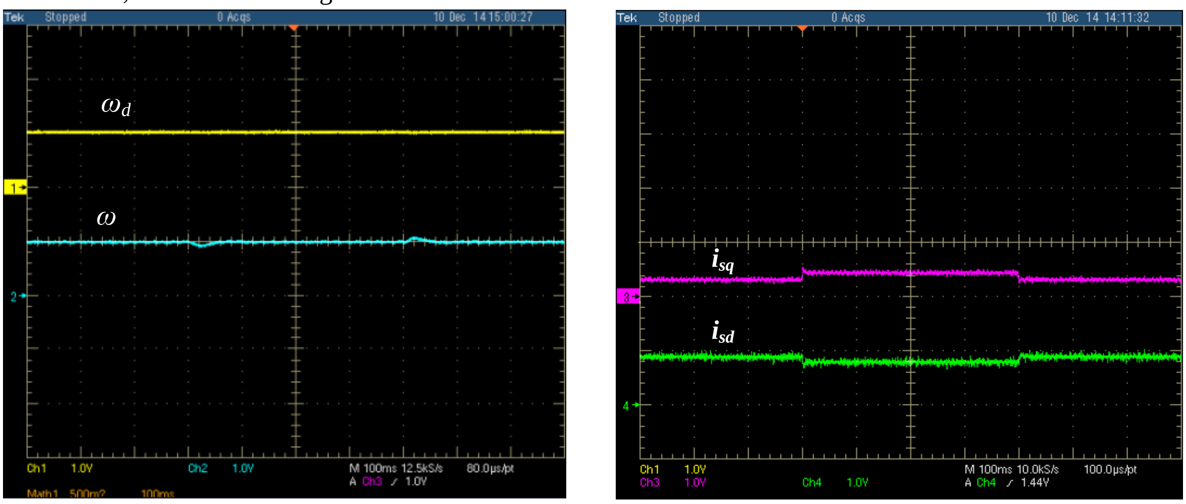
Case 1: Research during startup and speed up of the motor. The desired speed ω_d from 104,5 rad/s (500 r/min) to 209 rad/s (1000 r/min), with the following results:



(a) (b)

Figure 12: Experimental results of the proposed control method, a) Desired speed (ω_d), measured speed (ω), (b) q-axis current (i_{sq}), and d-axis current (i_{sd}) in case1

Case 2: Research the speed stability. Experimental results with constant speed and changing torque loads at the time of the 0.3s and 0.7s, with the following results:



(a) (b)

Figure 13: Experimental results of the proposed control method, a) Desired speed (ω_d), measured speed (ω), (b) q-axis current (i_{sq}), and d-axis current (i_{sd}) in case 2

Case 3: Research the engine brake and reverse. The speed changes ω_d from 209 rad/s to -209 rad/s (-1000 r/min), with the following results:

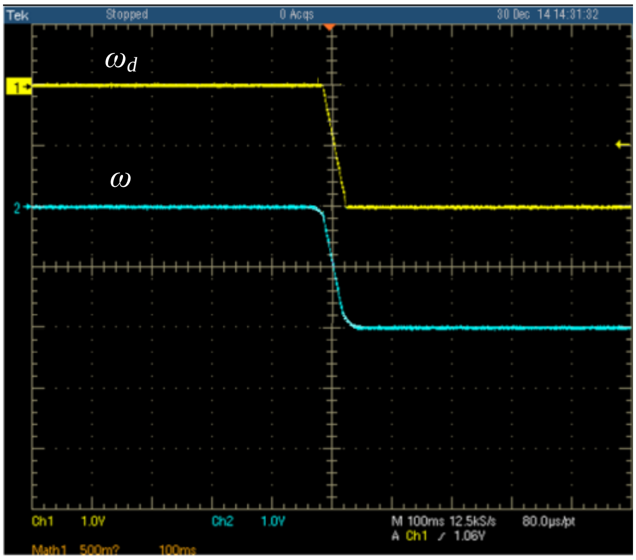


Figure 14: Experimental results of the case3, with desired speed (ω_d), measured speed (ω)

The proposed adaptive backstepping sliding mode controller is implemented on prototype IPMSM drive with TMS230F28069 as shown in Figure 12-14 show the experimental results about the speed response of the proposed control method. Figure 12(a) initial speed motor in 104,5 rad/s, at time t = 0,025s motor start up speed of 104.5 rad /s and to stabilize at this speed, show the measured speed (ω), the desired speed (ω_d), figure 12(b) show the q-axis current (i_{sq}) is measured initially 0,5A and speed change, starting current value increased to 1,2A in time 0,025s, and d-axis current (i_{sd}) is measured initially 0,95A. In case 2: Figure 13(a) motor is working at a steady rate is 209 rad/s, at time t = 0,3s make changes to increase the load set in the motor by creating friction force on the flywheel parts of the motor, the observed that the of motor speed reduced to the value of 170 rad/s. After a period of transition back recovery motor speed is 209 rad initial/s. At time t = 0,7s uninstall process the load parts effects of friction in flywheel, motor speed increased to 239 rad/s, after a period of transition back motor speed recovery time the first is 209 rad/s, figure 13(b) show the q-axis current (i_{sq}) is measured initially 0,5A and At time t = 0,3s make changes load the current increased to 0,75A to in time t = 0,7s uninstall process the load the current of the initial value 0,5A, so the controller has the ability to work well when the load changes. In case 3: Figure 14, first we set motor speed in the value of 209 rad/s, at time change t = 0,5s we reduce motor speed to -209 rad/s, reducer motor then turns around and increase the value of -209 rad/s is unchanged until the end of the process.

From the simulation and experimental results, it is definitely proven that the proposed adaptive backstepping sliding mode controller based near optimal control scheme can achieve better control performance such as no overshoot, zero steady-state error, and fast transient response in speed tracking than the linear conventional control methods such as LQR and PID controller with the presence of the motor parameter and load torque variations.

V. CONCLUSION

The adaptive backstepping sliding mode controller is proposed here work effectively throughout the speed range, from low speed to the rated speed. Moreover, it is also sustainable with the change of load torque and the motor parameters. The approximated control law is implemented to suppress the chattering effect which occurs in the original sliding control law. The simulation and experimental results have proved that the proposed control methodology can achieve not only the fast transient response but also the better robust control performance in comparison with the conventional adaptive backstepping sliding mode control. Simulation results show that both cases sustainability of control law before the impact of uncertain nonlinear composition. Sustainable with load noise and sustainable with the change of the desire speed, stable working system.

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