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Sliding mode control for the speed loop combined with adaptive coefficients for urban trains' load variations of Nhon – Hanoi Station Metro line

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ABSTRACT

Electric trains are becoming increasingly popular due to their environmental protection and ability to transport a large number of passengers. Alongside this trend, traction motors for electric trains have become diverse thanks to the rapid development of power electronics. Among them, the permanent magnet synchronous motor (PMSM) stands out with advantages such as high efficiency, high torque-to-current ratio, and compactness compared to other motors of the same power, making it the top choice. However, PMSM motors are nonlinear objects, so the nonlinear control technique of sliding mode control has been applied to the speed loop in this paper. Additionally, electric trains' inertial torque and load torque vary due to changes in the number of passengers during peak and off-peak hours and weather conditions. Therefore, this paper introduces two adaptive coefficients to account for these variations. Simulation results show that the sliding mode control technique for the speed loop circuit provides a faster and more accurate speed response. Meanwhile, the two parameters also adapt to the inertial and load torque variations. This ensures the safety and efficiency of the electric train system, contributing to the advantages of this mode of transportation.

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1. INTRODUCTION

Over the past two centuries, environmental pollution and climate change have emerged as significant global challenges. Among them, pollution indices in the transportation sector represent a considerable portion. Therefore, to mitigate pollution, electric trains have become one of the best means of transportation to reduce emissions into the environment, reduce traffic congestion, and save fossil energy [1], [2].

Electric trains are gradually becoming popular and developing in many countries, including Vietnam. Vietnam is constructing electric train lines in two major cities, Hanoi and Ho Chi Minh City [3]. The traction motors such as direct current (DC) motors, alternating current (AC) motors, and linear motors play an extremely crucial role in operating a train fleet [4]. Thanks to advancements in power electronics, AC traction motors are being applied more extensively in electric trains [5]–[7]. Guzinski *et al.* [8] used induction motors (IM) and developed a load observer for electric trains. Trabelsi and Brahim and designed backstepping control for the speed loop and observer to estimate rotor flux for induction motors (IM) [9], [10]. However, IM have drawbacks such as copper losses and low efficiency, while permanent magnet synchronous motors (PMSM) offer many advantages. PMSMs have high efficiency, no copper losses, high power density, and low maintenance requirements, and are more compact and lightweight than IMs of the same power. Therefore, PMSMs are widely applied in various fields, especially in the electric train sector [11]–[14]. However, the PMSM is a physical object with nonlinear characteristics, so applying control techniques such as backstepping, sliding mode control, intelligent control, and adaptive control [15]–[17].

The application of control techniques combined with methods such as field-oriented control (FOC) and direct torque control (DTC) [18], [19] helps improve the stability of motors and has been mentioned in many research papers. Several studies [20]–[22] have researched sliding mode control for the speed loop of PMSM motors in electric trains. Sun *et al.* [23] have researched sliding mode control for the speed loop, proposing new laws that improve noise compensation performance in the speed loop. Iqbal and Memon [24] have researched backstepping for the speed loop circuit and high gain observer to accurately eliminate noise parameters, aiding in more efficient motor operation. Zhou and Wang [25] have researched backstepping for the speed loop circuit of PMSM motors for electric trains. They have developed an uncertain nonlinear model of PMSM, ensuring parameters related to torque disturbance noise.

However, the authors above did not address the variations in inertial and load torque during operation due to weather effects on train tracks, wind resistance, and the dynamic changes when passengers get on and off the train. This paper utilized the sliding mode control technique for the speed loop to mitigate the motor's nonlinearity, introducing adaptive parameters for both inertial and load torque. The results demonstrated on MATLAB software showed fast output responses and system stability. The adaptive parameters are adjusted to the inertial and load torque variations.

2. MODEL OF PMSM

The PMSM is a synchronous motor that uses the FOC method. This method includes inner-current loops with PI controllers, the outer-speed loop with the sliding mode controller, and increasing the speed of the PMSM quicker than the rated speed by controlling traction motors in the weakening flux region. The control structure is constructed as in Figure 1. The mathematical equations of the PMSM motor based on the *d-q* coordinate system are represented in (1).

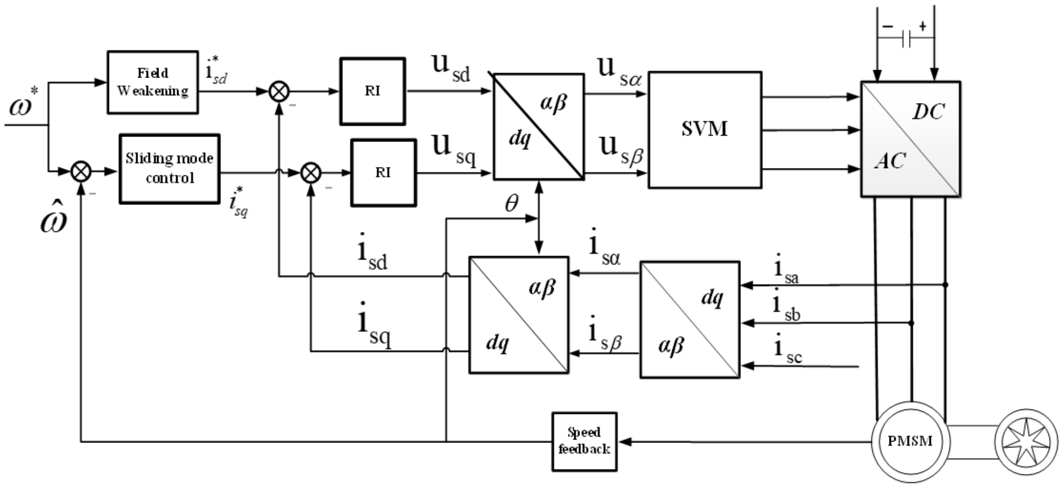

Figure 1. FOC control structure for PMSM motor

$$\begin{cases} \frac{di_{sd}}{dt} = -\frac{1}{T_{sd}} i_{sd} + \omega_s \frac{L_{sq}}{L_{sd}} i_{sq} + \frac{1}{L_{sd}} U_{sd} \\ \frac{di_{sq}}{dt} = -\omega_s \frac{L_{sq}}{L_{sd}} i_{sd} - \frac{1}{T_{sq}} i_{sq} + \frac{1}{L_{sq}} U_{sq} - \omega_s \frac{\psi_p}{L_{sq}} \\ \psi_{sd} = L_{sd} i_{sd} + \psi_p \\ \psi_{sq} = L_{sq} i_{sq} \\ T_e = \frac{3}{2} Z_p [\psi_p i_{sq} - i_{sd} i_{sq} (L_{sd} - L_{sq})] \\ T_e = T_L + \frac{J}{p_p} \frac{d\omega}{dt} \end{cases} \tag{1}$$

where i_{sd} and i_{sq} are the stator current on the d-q axis, u_{sd} and u_{sq} are the stator voltage on the d-q axis, ω_s is the rotor speed, L_{sd} and L_{sq} are the stator inductance on the d-q axis, ψ_p is the flux linkage, Z_p is the number of pole pairs, T_e is the electromagnetic torque, T_L is the load torque, J is the moment of inertia with $J = J_m + J_{eq}$, in there $J_{eq} = \frac{1}{4}\frac{M}{N}\left(\frac{D_{wh}}{\tau}\right)^2$, M is the mass of the train, N is the number of motors, and D_{wh} is the wheel diameter.

2.3. Load modeling

The resistance force acting on the train includes frictional resistance, wind resistance, gradient resistance, and curve resistance.

$$F_{grad} = mg\, sin\, \alpha \tag{2}$$

With m (kg) being the mass of the train, g (m/s^2) being the acceleration due to gravity, α being the gradient angle in thousandths. The curve resistance force:

$$(Farc): F_{arc} = \frac{A}{R} \tag{1}$$

where A is a coefficient determined experimentally in the range from 450 to 800, $R(m)$ is the radius of the most minor curve. The basic equation calculated through experimental testing represents the resistance forces and is estimated as a quadratic function called the Davis.

$$\omega_0 = a + bv + cv^2 \tag{2}$$

where v is the velocity and the coefficients $a\,(N), b\,(\,N\,s/m)$, and $c(N\,s^2/m^2)$ are provided by the manufacturer.

3. CONTROL DESIGN

Traction motor-PMSM is a non-linear object using the FOC method with three control loops. To overcome the nonlinearity of this motor, the sliding mode control technique is applied for the speed loop because sliding mode controller (SMC) can resist disturbances and ensure stability under all operating conditions. Furthermore, a predictive observation of inertial and load torque via two coefficients, a_1, a_2 was added to the motion (1).

3.1. Designing a sliding mode control for the speed loop incorporating adjustable coefficients due to inertial and load torques

Choosing a control law [26]:

$$\dot{s} = -\varepsilon\, sgn(\,s), \varepsilon > 0 \tag{3}$$

Designing the sliding surface $s = e = \omega - \omega^*$ where ω^* is the set value. Taking the derivative of s we obtain

$$\dot{s} = \dot{\omega} - \dot{\omega}^* = \frac{Z_p}{J}(T_e - T_L) - \dot{\omega}^* \tag{4}$$

According to (5), we obtain the sliding mode control signal as (7):

$$T_e = \frac{-J}{Z_p}\left(-\frac{Z_p}{J}T_L - \dot{\omega}^* + \varepsilon\, sgn(\,s)\right) \tag{5}$$

To ensure system stability $\dot{V} \leq 0$. We perform stability analysis and obtain:

$$\dot{V} = s.\dot{s} = s\dot{e} = s(\dot{\omega} - \dot{\omega}^*) = s\left[\frac{Z_p}{J}(T_e - T_L) - \dot{\omega}^*\right] = s\left[\frac{Z_p}{J}\left(\frac{-J}{Z_p}\left(-\frac{Z_p}{J}T_L - \dot{\omega}^* + \varepsilon\, sgn(\,s)\right) - T_L\right) - \dot{\omega}^*\right] = s(-\varepsilon\, sgn(\,s)) = -(\varepsilon|s|) \leq 0 \tag{6}$$

The system is stable. However, both the inertial and load torque fluctuate during operation. Therefore, we need to adjust these two parameters. Consequently, (7) is rewritten as:

$$T_e = \frac{-a_1}{Z_p}\left(-\frac{Z_p}{a_1}a_2 - \dot{\omega}^* + \varepsilon\, sgn(s)\right) \tag{7}$$

Proving stability:

$$\dot{V} = s.\dot{s} = s\dot{e} = s(\dot{\omega} - \dot{\omega}^*) = s\left[\frac{Z_p}{a_1}(T_e - a_2) - \dot{\omega}^*\right] = s\left[\frac{Z_p}{a_1}\left(\frac{-a_1}{Z_p}\left(-\frac{Z_p}{a_1}a_2 - \dot{\omega}^* + \varepsilon\, sgn(s)\right) - a_2\right) - \dot{\omega}^*\right] = s(-\varepsilon\, sgn(s)) = -(\varepsilon|s|) \leq 0 \tag{8}$$

Thus, the system has achieved stability with the two adaptive parameters a_1, a_2

3.2. Designing PI controllers for the current loop

Starting from the two equations of (1). To simplify, we omit the cross-channel component, resulting in (11):

$$\begin{cases} \frac{di_{sd}}{dt} = -\frac{1}{T_{sq}}i_{sd} + \frac{1}{L_{sq}}u_{sd} \\ \frac{di_{sq}}{dt} = -\frac{1}{T_{sq}}i_{sq} + \frac{1}{L_{sq}}u_{sq} \end{cases} \tag{11}$$

Taking the Laplace transform of both sides of each equation and transforming, we obtain the transfer function of each component. After Laplace transformation and transformation combined with the application of the optimal magnitude and cross-channel compensation, we get the control loop structure, as shown in Figure 2.

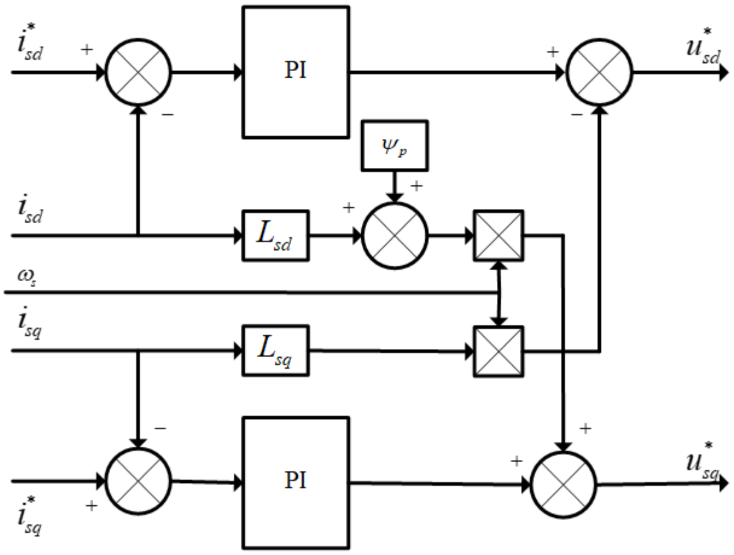

Figure 2. Current controller

4. SIMULATION RESULTS

The sliding mode control technique for the speed loop and the coefficients a1 and a2 are adaptive with load and inertial torque changes. The simulation parameters were collected from urban electric trains and traction motors at the Nhon—Hanoi station Metro line, shown in Table 1 and Table 2. This metro has a total length of 12.5 km and 12 stations. Responses include speed, load torque, power, and motor torque.

Figure 3 shows the speed responses with the SMC controller as the load changes in Figure 4. In this situation, with/without adaptive factors a_1 and a_2 affect the speed curve's quality. The speed curve in green without a_1, a_2 has occurred the error compared to reference speed; meanwhile, thanks to a_1, a_2, the speed curve in red track closely set speed in blue. The responses demonstrate that a_1, a_2 have effectively adapted to the fluctuations and changes in load and inertial torque during operation. Thus, it shows that the SMC controller effectively controls the motor speed, unaffected by external disturbances or factors.

Table 1. Train parameters

Setting up the train	3M1T	
Loaded train mass (*M*)	[kg]	192,000
Number of motors (*N*)		12
Maximum speed (*vmax*)	[km/h]	60
Basic speed (*vb*)	[km/h]	40
Acceleration when the train is running (0-40km/h)	$[m/s^2]$	0.83
Acceleration when the train is running (0-80km/h)	$[m/s^2]$	≥ 0.5
Maximum deceleration during normal braking	$[m/s^2]$	≥ 1
Maximum deceleration during emergency braking	$[m/s^2]$	≥ 1.25
Resistance coefficient *a*	[KN]	0.0115070
Resistance coefficient *b*	[kg/s]	0.0003494
Resistance coefficient *c*	[kg/m]	0.00005497
Wheel diameter (D_{wh})	[m]	0.84
Gear ratio (i)		9.5:1
Gearbox efficiency(η_{mech})		0.9
Motor efficiency (η_{em})		0.95
Train inertial torque (*Jeq*)	[kg. m^2]	31.272

Table 2. Motor parameters

Parameters	Symbol	Value
Rated power	Pđm	185 kW
Rated current	Iđm	220 A
Rated torque	Mđm	836 Nm
Stator resistance	Rs	39.224 mΩ
Axis inductance d	Ld	1.997 mΩ
Axis inductance q	Lq	5.499 mΩ
Magnetizing field	ψ	0.5968 Wb
Number of pole pairs	Zp	3
Frequency	f	120 Hz
Rated power	Pđm	185 kW
Rated current	Iđm	220 A
Rated torque	Mđm	836 Nm
Stator resistance	Rs	39.224 mΩ
Axis inductance d	Ld	1.997 mΩ
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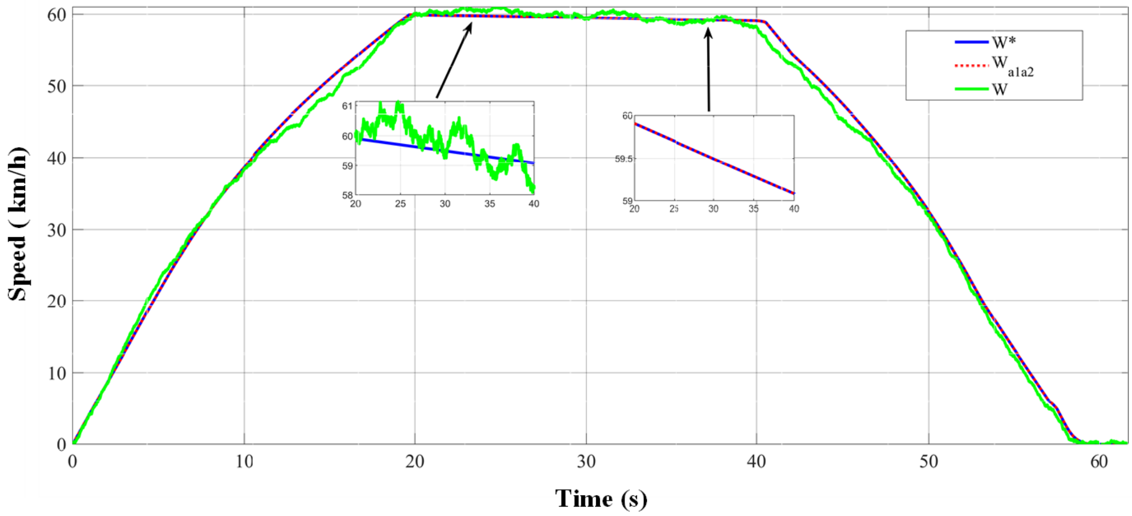

Figure 3. Speed responses when using the sliding mode control technique with changes in load

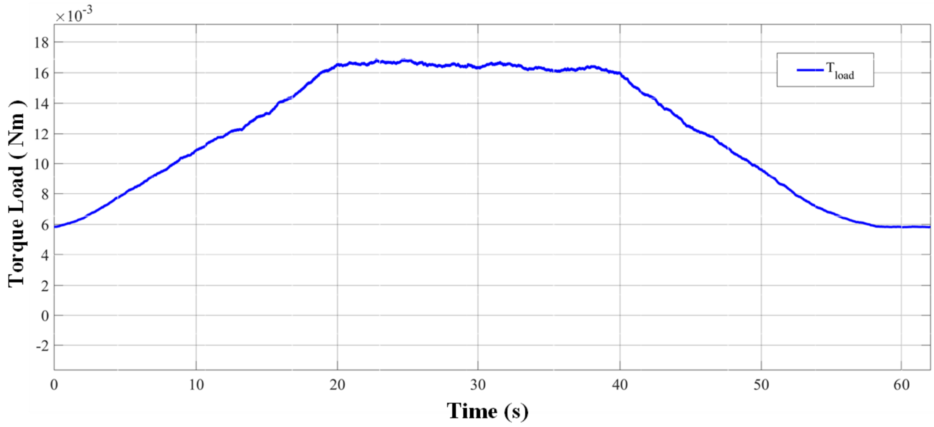

Figure 4. Load torque of the electric train

Figure 5 and Figure 6 show responses of torque and power in three phases. In the accelerating phase from 0 to the 19th second, the torque response is constant in the rated speed region and decreases in the weakening fux region to boost the speed higher than the rated speed while the power increases in the rated speed region, and is constant in the high-speed region. In the coasting phase from the 19th second to the 40th second: responses of torque, power are zero. In braking phase from the 40th second to 68th second: values of torque, power are negative in order to demonstrate traction motors working as generators to back regenerative energy to grid.

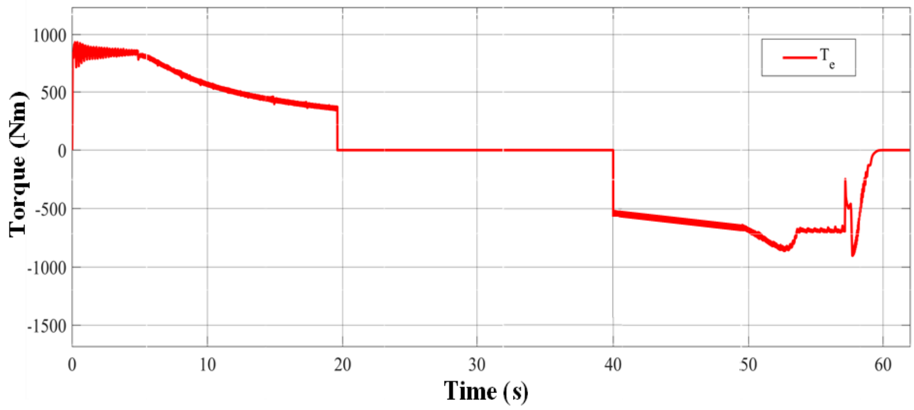

Figure 5. Torque response

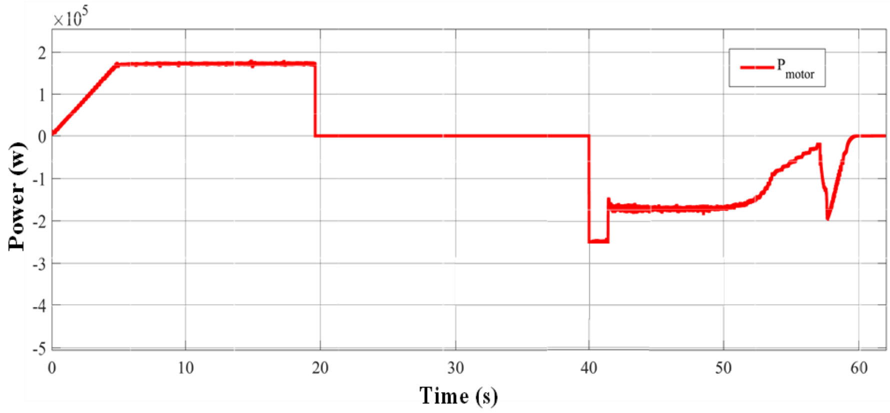

Figure 6. Response of the power

5. CONCLUSION

This paper introduced the sliding mode control method for the speed loop combined with two adaptive tuning coefficients for inertia and load torque to enhance the stability of PMSM motors for electric trains. The sliding mode control technique provided a robust controller to improve the stability of PMSM motor speed control and enhance the accuracy and stability of the system. In conjunction with this, coefficients a_1 and a_2 demonstrated excellent responses to inertia and load torque variations. The simulation results have shown the effectiveness of the controllers and tuning coefficients proposed in controlling the motor speed. Finally, this research also opens up a new approach for research in developing control techniques in the transportation field, particularly in electric trains.

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