International Journal of Engineering Trends and Technology
ISSN: 2231 – 5381 / https://doi.org/10.14445/22315381/IJETT-V70I6P234

Volume 70 Issue 6, 331-336, June 2022

Original Article

Design of Sliding Mode Control for an Induction Motor using in Railway Traction

Vo Thanh Ha[1], Nguyen Van Hai[1], Vo Quang Vinh[2], Vo Thu Ha[3]

[1] *Faculty of Electrical and Electrical Engineering, University of Transport and Communications, VietNam*
[2]*Faculty of Control and Automation, Electric Power University, Vietnam*
[3]*Faculty of Electrical Engineering, University of Economics - Technology for Industries, Vietnam.*

vothanhha.ktd@utc.edu.vn

Received: 20 April 2022 Revised: 05 June 2022 Accepted: 09 June 2022 Published: 29 June 2022

Abstract *- A sliding mode control design for a railway traction induction motor is presented in this research. In addition, this paper discusses modeling, load torque, control design, and simulation using a field-oriented control (FOC) structure with a voltage source inverter and space vector modulation. The usefulness of speed control design over the operating range of IM with constant, changing, and uncertain parameters will be demonstrated by comparing SMC and PI controllers. The MATLAB simulation results will illustrate the efficiency of the traction motor SMC controller when the motor settings are updated and stable with the rotor flux set.*

Keywords *- Sliding Mode Control, PI controller Induction motor, Field oriented control, Railway traction (RT).*

1. Introduction

Three-phase induction motors began to replace DC motors in railway traction motors in the 1990s. Because the IMs are less expensive, more durable, and better suited to the characteristics of railway traction motors [1]. According to the study [2], the railway traction driver will demand torque at a given speed. This torque demand is determined by the current limit of the motor stator, pulse modulation, and inverter and is restricted by saturation and available DC link voltage. Furthermore, changing the stator voltage frequency will result in the torque and speed required for railway traction motors. The available voltage three-phase inverter supply is used to control the IMs speed.

Further, the IM slip-on features allow many motors with varying speeds and wheel sizes to be fed by a single inverter [3]. The advancements in asynchronous driver control technologies are reassuring. Today's control techniques for a railway traction motor include u/f control, direct torque control (DTC), and field-oriented control (FOC). As a result of the advantage of field-oriented control, the two stator currents at the d and q axes have been separated. The stator current on the d-axis controls the rotor flux, whereas the current on the q-axis controls the torque. Hence the IM is handled similarly to DC motors. The FOC control, in particular, allows IMs to operate in the flux weakling zone.

Therefore, the flux must be reduced in this circumstance [4,5]. In addition, load torque must be factored into the load model while designing a controller. The parameters of friction forces characterize train motion. Hence, the speed model shown by load torque [6] must be added. Linear methods such as proportional-integral (PI) controller using space vector modulation (SVM) section voltage module and nonlinear techniques such as flatness based on control, backstepping, exact nonlinear, sliding mode control (SMC)...have been documented in the literature as well as experimental research for IM speed control strategies [4,5]. In the meantime, regardless of the drive system parameters, the PI controller has a basic design. It's created using an optimal control strategy. However, the driver system's robustness is compromised because the PI controller is the single operating point [7]. Nonlinear control with rapid hardware changes is increasingly being studied in practical applications. For speed and flux control, the flatness-based control approach is applied. The planned speed and flux reference trajectories can be chosen based on the amplitude constraint of current by simply decreasing the order of the governing equations [8,9,10]. In addition, the backstepping control approach [11], which ensures that the error between set values and actual values satisfies Lyapunov's stability, is also used for speed and flux loops, despite the IM model being a stringent feedback type. In another study, slide mode control (SMC) is a simple and effective nonlinear control approach. However, this controller must know the object model's parameters and the component's upper limitations.

On the other hand, this controller must be mindful of the object model's parameters and the upper bounds of the elements on the model's uncertainty. SMC is represented by an sgn(.) function and asserts chatter around the slip surface [12,13]. Evaluation of dynamic response between different speed control structures based on speed and ripple torque performance [14,15,16,17]. Thus, the paper presents the speed control design of IM for railway traction motor based on FOC construction. The speed and torque responses of the railway traction motor can be improved by using the sliding mode controller. The proposed controller will be compared with a speed proportional-integral (PI) controller for speed and torque responses.

The following parts will present the paper's content. The induction motor and load model is created first, and then the speed control loop is created using sliding mode control. Matlab/Simulation is then used to demonstrate the effectiveness of the control mechanism. Finally, various conclusions and points of view are offered.

2. The mathematical of the three-phase induction motor and load

2.1. The three-phase induction motor

According to the FOC method, IM's mathematical model is described by the following equations Eq(1).

With $\omega_s = \omega + \omega_r = \omega + \frac{L_m}{T_r}\frac{i_{sq}}{\psi_{rd}}; k_\omega = \frac{3}{2}\frac{z_p^2 L_m^2}{L_r J}$

In which, $i_{sd}; i_{sq}$ are dq in the stator current; is electromagnetic currents; w, w_s are mechanical and synchronous speed, respectively; y'_{rd}, y'_{rq} are dq is the rotor flux; is total leakage factor; T_r is rotor time constant; u_{sd}, u_{sq} are dq is the stator voltage; L_s is stator inductance, L_m, L_r are mutual, rotor inductance, m_L : torque load. Eq. (1), the initial state is bilinear and of the fourth order, as may be observed.

$$\begin{cases} \frac{di_{sd}}{dt} = -\left(\frac{1}{s T_s} + \frac{1-s}{s T_r}\right) i_{sd} + w_s i_{sq} + \frac{1-s}{s T_r} + \frac{1}{s L_s} u_{sd} \\ \frac{di_{sq}}{dt} = -w_s i_{sd} - \left(\frac{1}{s T_s} + \frac{1-s}{s T_r}\right) i_{sq} - \frac{1-s}{s} w i_m + \frac{1}{s L_s} u_{sq} \\ \frac{dy_{rd}}{dt} = -\frac{1}{T_r} y_{rd} + \frac{L_m}{T_r} i_{sd} \\ \frac{dw}{dt} = k_w y_{rd} i_{sq} - \frac{z_p}{J} m_L \end{cases} \quad (1)$$

The mechanical equation for an IM is as follows:

$$m_M = m_L + \frac{Jd\omega}{dt} \quad (1)$$

Where J is inertia torque constant; m_L is load torque; ω is the rotor

2.2. The load model of the railway traction motor

The load model of the railway traction motor must add train resistance. It's the total amount of resistance to the train's motion. It's the total of the resistance forces opposing an electric train's movement. Train resistance includes rolling resistance due to friction between the wheels and rails, sliding resistance due to friction between the belt wheel and rail, and air resistance. Since the controller is designed by simulation, we need to include the train resistance. Train resistance is calculated by the following as Eq. (2)

$$\begin{aligned} F(t) = {} & a_{11}M + a_{12}n + a_2 M\upsilon(t) + a_3 Ak\upsilon(t)^2 \\ & + Mg\sin\alpha \end{aligned} \quad (2)$$

Where, M, n, A, k, α are represent the weight of the train, the shaft, the track and gear specifications, and the surface area in the displacement direction determine train speed.

3. Sliding mode controller design (SMC)

The SMC is effectively used for nonlinear systems, load torque disturbance, and parameter variation changes. The speed control for railway traction motor is designed to follow these steps:

$$\dot{\omega} + \frac{1}{J} m_L = \frac{1}{J} m_M \quad (3)$$

Where:

$$m_M = \frac{3}{2}\frac{L_m^2}{L_r} p\psi_{rd} \frac{i_{sq}}{L_m} = k_\omega i_{sq}; k_\omega = \frac{3}{2}\frac{L_m}{L_r} p\psi_{rd}$$

Second, we add the following mechanical uncertainties to Eq. (5). Eq. (5) may so be rewritten as Eq. (6):

$$\dot{\omega} = -(a + \Delta a) + (b + \Delta b) i_{sq} M, n, A, k, \alpha \quad (4)$$

Where $\Delta a, \Delta b$ are the uncertainties parameters

Then, the speed error can be calculated as:

$$e(t) = \omega(t) - \omega^*(t)\Delta b \quad (5)$$

Where ω^* is the conference speed.

Taking the derivative of the previous Eq. (5) concerning time yields, Eq. (5) becomes as:

$$\dot{e}(t) = u(t) + d(t) \quad (6)$$

Where:

$$\begin{cases} u(t) = bi_{sq}(t) - a(t) - \dot{\omega}^{*}(t) \\ d(t) = \Delta bi_{sq}(t) - \Delta a(t) \end{cases}$$

In the third step, we'll define the sliding surface variable s(t) as follows:

$$s(t) = e(t) - \int_{0}^{t} (k-c)e(t)dt = 0 \qquad (7)$$

With c is a typical motion under sliding mode control to zero.

Next, the variable structure speed controller is designed as:

$$u(t) = ke(t) - \beta \operatorname{sgn}(s) \qquad (8)$$

The gain defined before with k is k<0 to $(k-c) < 0$. The switching gain must be selected to $\beta \geq d(t)$, sgn(.) is the switching function.

Then, define the Lyapunov function and derivate it in eq. (9)

$$V(t) = \frac{1}{2} s(t)s(t) \qquad (9)$$

The derivative Eq. (11) is then calculated as:

$$\dot{V}(t) = s[d - \beta \operatorname{sgn}(s) + ce] < 0 \qquad (10)$$

In Eq.(10) $\dot{V}(t) < 0$, that means the design of SMC and the conditions of SMC. Therefore, the SMC for the system can be determined as:

$$i^{*}_{sq}(t) = i_{sq}(t) = \frac{1}{b}[ke - \beta \operatorname{sgn}(s) + a + \dot{\omega}^{*}] \qquad (11)$$

4. Simulation Results

Figure 1 shows the sliding mode control for an IM in a railway traction system, and table 1 shows the simulation using the IM's parameters for a railway traction motor.

Table 1. Simulation with IM's parameters used railway traction motor

Parameters	***Symbol***	***Value***
Power	P_{dm}	270 kW
Rated speed	n_{dm}	2880 rpm
Rated voltage	U_{dm}	400V
Pole pair	p	1
Power factor	$\cos\varphi$	0.9
Stator resistance	R_s	0.0138
Rotor resistance	R_r	0.00773
Rotor inductance	L_r	0.0078H
Mutual inductance	L_m	0.0077H
Voltage		750 VDC
Maximum speed for the train		80km/h

In Fig.1, the stator current controller is PI with $K_p = 0.385; T_i = 0.052$ coefficients. With these coefficients, the current controller response is perfect.

The following simulation scenario investigates some of the typical working modes of the SMC.

+ From t = 1s to t=3s, the IM is operating at the pull process with parameters:

$t_{1s} = 0(km/h)$ $t_{2s} = 40(km/h)$; $t_{3s} = 70(km/h)$.

+ From t = 3s to t=6s, the IM operates at the coasting process with parameters: $t_{6s} = 60(km/h)$.

+ From t = 6s to t=8s, the IM is operating at the braking process with parameters:

$t_{7s} = 5(km/h)$, $t_{8s} = 0(km/h)$

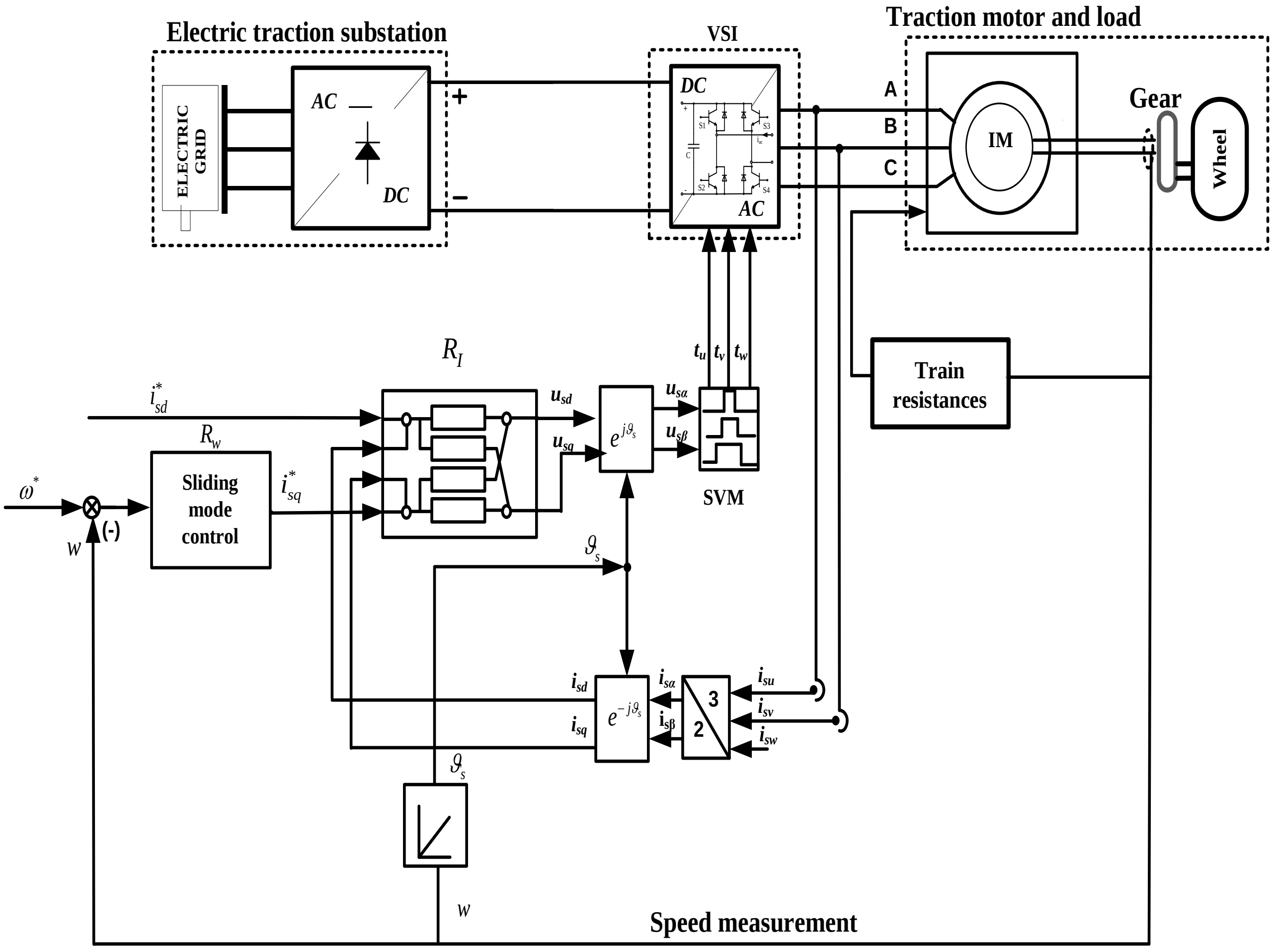


Fig. 1 The speed sliding mode control construction for an IM used in the RT system

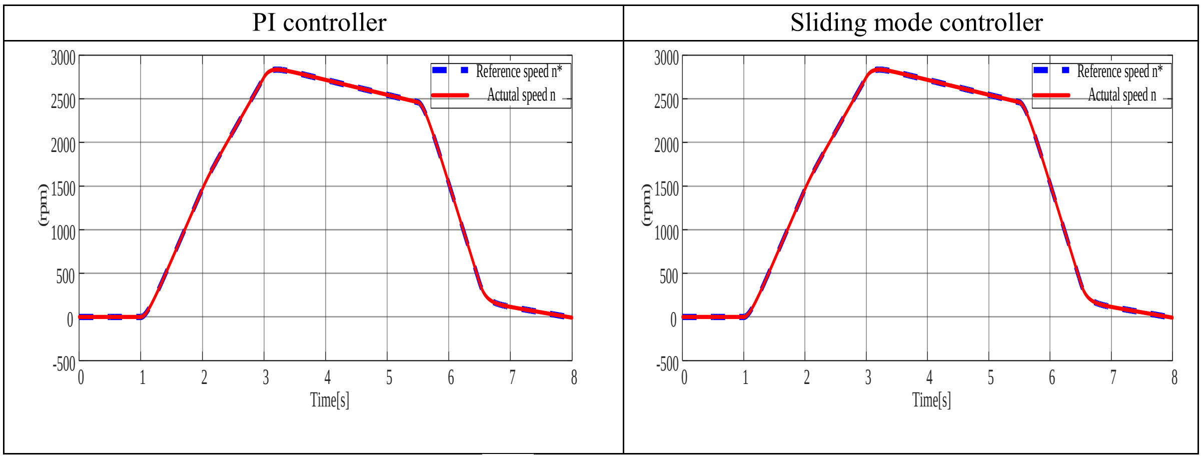
The research compares employing the PI speed control in two scenarios, where the rotor resistance parameters are left unchanged and increased, to evaluate the effectiveness of the suggested speed sliding mode control.

Case 1: In simulation as the rotor resistance parameters are constant. Figures 2 and 3 demonstrate the simulation results.

The results of IM speed control using both methods (SMC and PI) at high and low-speed zones are shown in Fig.3. The measured velocities follow the reference speeds when the reference speeds are adjusted. However, the torque responses for SMC and PI in Fig 3 indicate a high ripple torque with THD%= 30%, indicating that a better solution is required

Case 2: Furthermore, increasing rotor resistance demonstrates the railway traction drive's resilience. This parameter is directly linked to the IM's dynamic reaction, affecting the rotor time constant as R_r increases. When the value of Rr was raised by 50% of the nominal amount, the torque and speed were reduced. Figures 4 and 5 depict the findings.

In comparison to the other two approaches, Fig. 4 and 5 indicate that the configuration of the speed loop with sliding mode control gives higher system resilience against rotor resistance change than PI control. The PI control's speed response has a sizeable actual speed reduction than the reference speed response at t=3s. The systems are due to the significant ripple torque in the torque with THD%= 30%.


PI controller

Sliding mode controller

Fig. 2 Speed responses

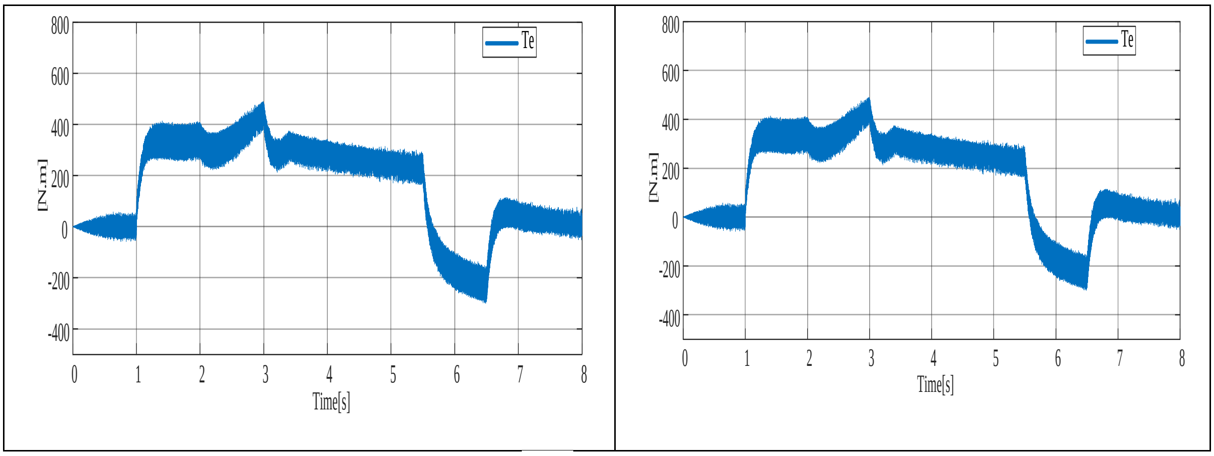
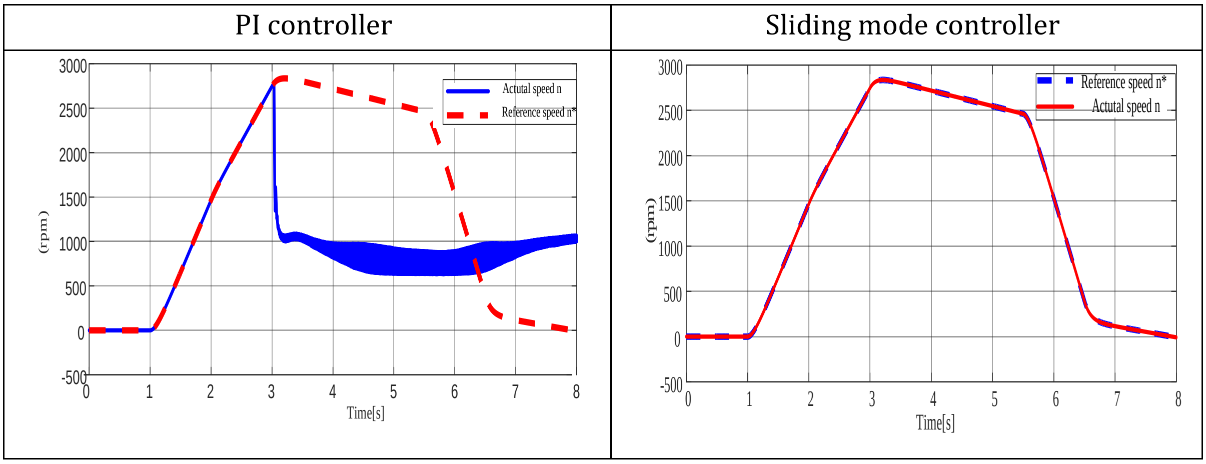


Fig. 3 Torque responses


PI controller

Sliding mode controller

Fig. 4 The speed response with value of rotor resistance R_r increasing to 50%

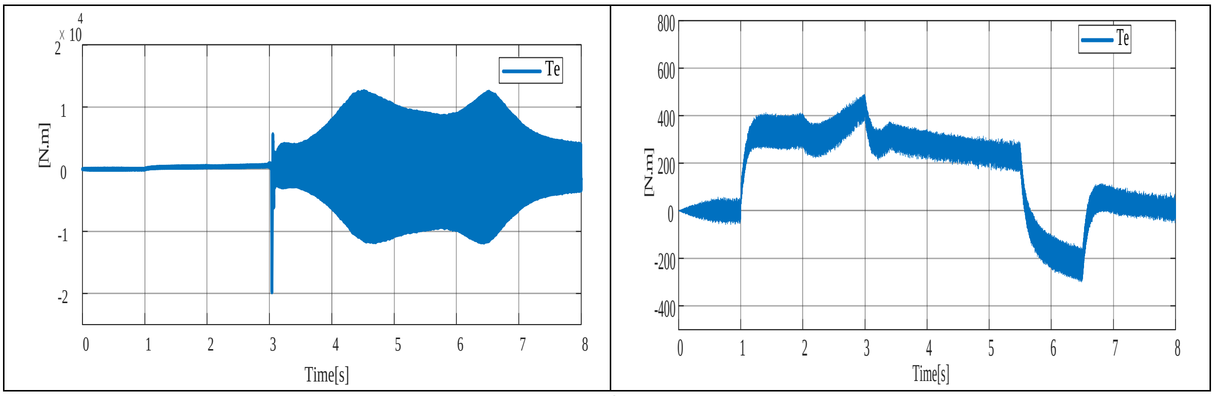


Fig. 5 The torque response with value of rotor resistance R_r increasing to 50%

6. Conclusion

This work investigated sliding mode control for railway traction motors based on the FOC control method. The dynamic reactivity and resilience of this control mechanism are excellent. When the motor parameters are altered and the rotor flux is set, the effectiveness of the traction motor SMC controller will be shown using MATLAB simulation data. This controller generates the desired response. Furthermore, this system required higher reference torque than a PI controller. However, torque response still has an ample ripple torque. Thus, we advocate using a multi-level inverter in combination with a novel pulse modulation for the inverter to increase torque response.

Acknowledgments

This project study was supported by all researchers and funding from the University of Transport and Communications.

References

[1] K. Maurya, M. Singh, and N. Jain, Real Time Vehicle Tracking System using GSM and GPS Technology-An Anti-Theft Tracking System, International Journal of Electronics and CompLfrederick, Copal K Dubey, AC Motor Traction Drives- A Status Review. (1997).

[2] Marian-Ștefan Nicolae, Iustin-Radu Bojoi, A Control Strategy for an Induction Motor Used for Vehicular Traction and/or Positioning Systems with Variable Speeds, 978-1-4673-1810-5/12/$31.00 IEEE. (2012).

[3] Ahmed Fathy Abouzeid, Juan Manuel Guerrero, Aitor Endemaño, Iker Muniategui, David Ortega 2, Igor Larrazabal and Fernando Briz, Control Strategies for Induction Motors in Railway Traction Applications, Energies. 13 (2020) 700. Doi:10.3390/en13030700.

[4] Quag NP, Dittrich JA, Vector Control of Three-Phase AC Machines – System Development in the Practice, 2nd ed., Springer-Verleg Berlin Heidelberg. (2015).

[5] Leonhard W, Control of Electrical Drives, 3rd ed., Springer. (2001).

[6] Emre Dincel, Handan Nak, Şirin Akkaya, Mehmet Canevi, İlhan Mutlu, M. Turan Söylemez, Robust Control of Raiway Traction System, IFAC Papers Online. 51(25) (2018) 171-177.

[7] R. Gunabalan, V. Subbiah, Speed Sensorless Vector Control of Induction Motor Drive with PI and Fuzzy Controller, International Journal of Power Electronics and Drive System, IJPEDS. 5(3) (2015) 315-325. Doi: 10.11591/ijpeds. v5i3.6670.

[8] Dannehl J, Fuchs FW, Flatness-based Control of an Induction Machine Fed Via Voltage Source Inverter - Concept, Control Design and Performance Analysis, IECON - 32nd Annual Conference on IEEE Industrial Electronics. (2006) 5125-5130.

[9] Liping Fan, Liang Zhang, Fuzzy based Flatness Control of an Induction Motor, Procedia Engineering, Published by Elsevier Ltd. 23 (2011) 72-76.

[10] Berrezzek Farid, Bourbia Waffa and Bensaker Bachir, A Flatness Based Nonlinear Sensorless Control of Induction Motor System, Internationl Jounal of Power Electronics and Drive System. 7(1) (2016) 265-278.

[11] Berrezzek Farid, Bourbia Waffa and Bensaker Bachir, A Flatness Based Nonlinear Sensorless Control of Induction Motor System, Internationl Jounal of Power Electronics and Drive System. 7(1) (2016) 265-278.

[12] A. Ebrahim, G. Murphy, Adaptive Backstepping Control of an Induction Motor Under Time-Varying Load Torque and Rotor Resistance Uncertainty, Proceeding of the Thirty-Eighth Southeastern Symposium on System Theory. (2006).

[13] Othmane Boughazi, Abdelmadjid Boumedienne, Hachemi Glaoui, Sliding Mode Backstepping Control of Induction Motor, International Journal of Power Electronics and Drive Systems IJPEDS. 4(4) (2014) 481-488. Doi: 10.11591/ijpeds. v4i4.6532.

[14] Bui Thi Hai Linh, A Design of Fuzzy Sliding Mode Controller for DC Motor Drive Base on FPGA, SSRG International Journal of Electronics and Communication Engineering. 4(6) (2017) 12-17.

[15] José Rodríguez, Fellow, Ralph M. Kennel and José R. Espinoza, High-Performance Control Strategies for Electrical Drives: An Experimental Assessment, IEEE Transactions on Industrial Electronics. 59(2) (2012). Doi: 10.1109/TIE.2011.2158778.

[16] Vo Thanh Ha, Pham Thi Giang, Vu Hoang Phuong, T-Type Multi-Inverter Application for Traction Motor Control, Engineering, Technology and Applied Science Research, ETASR. 12(2) (2022) 8321-832. https://doi.org/10.48084/etasr.4776.

[17] Pham Thi Giang, Vo Thanh Ha, Vu Hoang Phuong, Drive Control of a Permanent Magnet Synchronous Motor Fed by a Multi-Level Inverter for Electric Vehicle Application, Engineering, Technology and Applied Science Research ETASR. 12(3) (2022) 8658-8666. https://doi.org/10.48084/etasr.4935.

[18] Mrs Ajaz Fatima, Mrs Ajaz Fatima, Mohammed Abdul Khader Aziz Biabani, Mohammed Imran, Sliding Mode Control of Induction Motor used in Traction, International Conference on Electrical, Electronics, and Optimization Techniques ICEEOT. (2016).