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PANTOGRAPH DRIVEN WITH A LINEAR INDUCTION MOTOR WITH ADAPTIVE FUZZY CONTROL

PANTOGRAF GNAN Z LINEARNIM INDUKCIJSKIM MOTORJEM S PRILAGOJENIMI KRMILNIMI TEHNIKAMI

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Abstract

This article presents an adaptive fuzzy control for a linear induction motor, which is used to control the vertical movement of a pantograph, which supplies an electric locomotive from a contact line. The system has the goal of eliminating all the discontinuity on the route, the resonance phenomenon, the separation of the pantograph head from the contact wire, and electric arches. The simulations demonstrate functional control of the pantograph driven with a linear induction motor system using fuzzy control techniques.

Povzetek

V članku je predstavljeno prilagodljivo mehko krmiljenje linearnega indukcijskega motorja, ki se uporablja za krmiljenje navpičnega gibanja odjemnika toka, ki napaja električno lokomotivo iz kontaktne linije. Cilj sistema je odpraviti vse prekinitve na poti, resonančni pojav, ločitev glave odjemnika toka od kontaktnega vodnika in električnih lokov. Simulacije prikazujejo funkcionalno kontrolo odjemnika toka, ki se poganja z linearnim indukcijskim motornim sistemom z uporabo mehkih krmilnih tehnik.

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1 INTRODUCTION

A critical problem of the electric supply of a high-speed locomotive is maintaining the contact force between the pantograph head and the contact line as constant and pursuing the trajectory of the contact point *[1, 2]*. The dynamic of the pantograph under the influence of the disruptive factors and perturbations is the decisive criteria in the estimation of the energy transfer quality from the contact line to electric vehicles. The contact line (the catenary) and the power supply system of the train (the pantograph) are in a highly dynamic interaction, which is influenced by the speed, the vehicle type, the structure of the catenary and the mechanical tension in the wire, the weather conditions, the structure and the mass of the pantograph and the oscillations and perturbations of the vehicle while moving.

The conventional methods to drive the pantograph use systems with compressed air or with springs. The control system can be based on different actuator types (hydraulic, pneumatic, electric), and for different actuator positions (strips suspension, air spring, or frame).

The use of the active control strategies for the pantograph *[3, 4]* may lead to an improvement of contact *[5]*. New mathematical models for the pantograph-catenary interaction have been developed in *[6, 7]*, as the basis for the control principles. The pantograph-catenary system is also analysed by using the finite element method *[8-11]*, the results being compared with results from the real tests. The damper system of the catenary is analysed by recording the accelerations of the pantograph *[12]*, while in *[13]* a control is proposed to reduce the oscillations of the pantograph-catenary system. The advanced active control of the pantograph includes the analysis of the vertical body vibration, as in *[14]*. According to *[15]*, the proposed controller can improve the contact quality, leading to a reduction of the standard deviation of the pantograph-catenary contact force by more than 40% compared to the non-controlled system.

The drive and the control of the pantograph head trajectory can be made by using a linear induction motor *[16]*. The patent *[16]* relates to a pantograph current collector to be used in locomotives or electric trains, for collecting power from an electric contact line placed along the railway. In addition to the mechanical resort that develops a lifting force and a force for pressing the contact shoe against the contact wire, the pantograph is provided with a supplementary assembly of a linear induction motor providing a supplementary mechanical effort, which is to be added to the mechanical effort achieved by a mechanical resort in order to adapt the resulting effort intended to push the pantograph's shoe. Thus, in parallel with the elastic spring of the pantograph or even independently, a linear induction motor that drives the pantograph head with the aim of pursuing the geometry of the contact line can be used. The linear motor can be controlled with the adaptive fuzzy control technique. Different articles have examined the fuzzy control approach for dynamics of the pantograph-catenary interaction *[17, 18]* and for the linear induction motors *[19-23]*.

This article presents the fuzzy adaptive control for a pantograph driven by a linear induction motor system used to supply an electric locomotive from a contact line. A mathematical model of the motor and the methodology for the motor control are presented. Simulations are made in Matlab-Simulink software, and data analyses are discussed.

2 PANTOGRAPH DRIVEN WITH A LINEAR INDUCTION MOTOR – SYSTEM DESCRIPTION

The main characteristic of a railway pantograph is to assure good current collecting, without interruptions of the current, regardless of the height of the pantograph and train movement. For this, it is necessary for the pantograph to have a permanent contact, regardless of the movement of the mechanically articulated system, as well as good lateral and transversal stability, to achieve contact pressure, regardless of the height in static and dynamic conditions.

The proposed solution is to use a linear induction motor (LIM) to drive the pantograph, a solution that is patented. Using this solution *[16],* (Figure 1), pantograph detachments will be prevented, and the electric traction equipment will be supplied in good conditions.

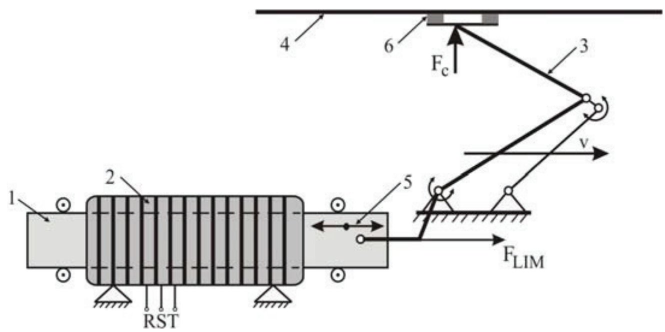

Figure 1: *Pantograph driven by a linear induction motor*

The linear induction motor (LIM) is three-phased and composed of a mobile plate armature (1) and two fixed inductors (2) with windings placed in 24 slots. The mobile armature is connected to the railway pantograph (3) and acts over it with force F_{LIM}. The pantograph pushes the contact line (4) with a contact force F_c. The mobile armature has a maximum oscillation motion (5) of 140 mm. The contact is assured by the skates (6).

3 MODEL OF THE SYSTEM

3.1 Model of the linear induction motor (LIM)

The dynamic model of the linear induction motor can be described with the following equations *[21, 24, 25]*:

$$\begin{cases} \dot{i}_{qs} = -\left(\frac{R_s}{\sigma \cdot L_s} + \frac{1-\sigma}{\sigma \cdot T_r}\right) \cdot i_{qs} + \frac{L_m}{\sigma \cdot L_s L_r T_r} \cdot \Phi_{qr} - \frac{n_p L_m \pi}{\sigma \cdot L_s L_r \tau} \cdot v\Phi_{dr} + \frac{1}{\sigma \cdot L_s} V_{qs}; \\ \dot{i}_{ds} = -\left(\frac{R_s}{\sigma \cdot L_s} + \frac{1-\sigma}{\sigma \cdot T_r}\right) \cdot i_{ds} + \frac{n_p L_m \pi}{\sigma \cdot L_s L_r \tau} \cdot v\Phi_{qr} + \frac{L_m}{\sigma \cdot L_s L_r T_r} \cdot \Phi_{dr} + \frac{1}{\sigma \cdot L_s} V_{ds}; \\ \dot{\Phi}_{qr} = \frac{L_m}{T_r} i_{qs} - \frac{1}{T_r} \Phi_{qr} + n_p \frac{\pi}{\tau} v\Phi_{dr}; \\ \dot{\Phi}_{dr} = \frac{L_m}{T_r} i_{ds} - n_p \frac{\pi}{\tau} v\Phi_{qr} - \frac{1}{T_r} \Phi_{dr}; \\ F_e = K_f\left(\Phi_{dr} i_{qs} - \Phi_{qr} i_{ds}\right). \end{cases} \tag{3.1}$$

where: T = L_r/R_r is the time constant for the secondary circuit of the LIM;

$\sigma = 1 - \left(\frac{L_m^2}{L_s L_m}\right)$, dispersion coefficient of the LIM;

$K_f = \frac{3 n_p \pi L_m}{2 \tau L_r}$, is constantly used in the formula of the linear induction motor force, F_{LIM}.

3.2 The model of the pantograph – linear induction motor system

The mechanical equilibrium equation can be written as *[20]*:

$$F_e - F_r = M\frac{dv}{dt} = -Mv\frac{ds}{dt}. \tag{3.2}$$

The resistant force F_r is the necessary force to lift and to maintain the pantograph at the optimal height to follow the trajectory of the contact line (which is supposed to be sinusoidal) and to assure a constant contact force. Thus, the pantograph will have some vertical oscillations along the contact line and during the vehicle movement. It will be considered as positive (+) for the lift motion and negative (-) for the down motion *[26].*

To compensate these oscillations movements and to assure a constant contact force, the linear induction motor will operate as an electromagnetic resort *[16]* having a short oscillating movement and a relatively low speed. The resistant force is given by the equation:

$$F_r = \pm\mu_0 \frac{P_0 d_0}{2} \pm M_0 \omega^2 y \tag{3.3}$$

The pantograph-linear induction motor system will be described by the mechanical equilibrium equation, *[21, 22]*:

$$F_e = K_f\left(\Phi_{dr} i_{qs} - \Phi_{qr} i_{ds}\right) = M\dot{v} + Dv + F_r. \tag{3.4}$$

4 CONTROL METHODOLOGY FOR THE LINEAR INDUCTION MOTOR

Figure 2 presents the position control system for the linear induction motor *[19, 23, 24]*, with the following parameters:

$$F_e = K_f u_T \quad (4.1)$$

$$H_p(s) = \frac{1}{Ms + D} = \frac{b}{s + a} \quad (4.2)$$

where: $H_p(s)$ - transfer function of the motor; u_T - control signal; s- Laplace operator; a, b – constants.

In Figure 2, the parameter d_m is the desired position, and the parameter v_m is the desired speed.

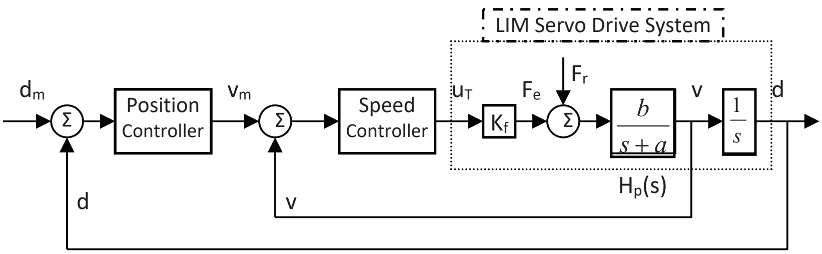

Figure 2: *Simplified position control system*

To obtain the control signal, a fuzzy adaptive regulator is proposed *[26]*.

4.1 Fuzzy adaptive regulator

The design of the fuzzy adaptive regulator is based on the aspects developed into the specific literature *[27-31]*. Hence, in this article, only the necessary steps to implement the fuzzy adaptive regulator are presented using Matlab-Simulink software. In Figure 3, a schematic for the fuzzy adaptive regulator is presented *[27, 28].*

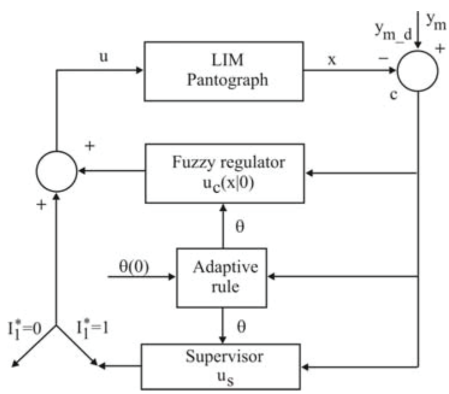

Figure 3: *Schematic of the fuzzy adaptive regulator*

Considering the signal u_c as a fuzzy system, the fuzzy adaptive regulator is designed as follows:

Step 1: *Preprocessing [27, 28].* There are specify $k_1,\dots,k_n$ so that all the roots of the equation $s^n + k_1 s^{n-1} + \cdots + k_n = 0$ to be in the open left half plane. The positive definite *n x n* matrix *Q* is specified. The Lyapunov equation $\Lambda_c^T P + P\Lambda_c = -Q$, *Q*>0 is solved to obtain a symmetrical matrix *P*>0. The design parameters M_θ, M_x and σ are described based on practical constraints.

Step 2: Initial controller design *[28, 29]*:

u_c as a fuzzy system is considered.

$$u_c(\underline{x}|\underline{\theta}) = \frac{\sum_{i=1}^{M} \overline{y}^l \left[\prod_{i=1}^{n} \exp\left(-\left(\frac{x_i - \overline{x}^l}{\sigma_i^l} \right)^2 \right) \right]}{\sum_{i=1}^{M} \left[\prod_{i=1}^{n} \exp\left(-\left(\frac{x_i - \overline{x}^l}{\sigma_i^l} \right)^2 \right) \right]}; \tag{4.3}$$

where θ represents some adjustable parameters $\overline{y}^l, \overline{x}_i^l$ and σ_i^l.

The command u_c is designed according to the relation (4.3) based on *M* rules characterized by the Gaussian membership functions:

$$\mu_{F_i^l}(x_i) = \exp\left(-\left(\frac{x_i - \overline{x}^l}{\sigma_i^l} \right)^2 \right); \tag{4.4}$$

where *l* = 1,2,…,M and *i*= 1,2 …n.

Step 3. Design of the adaptive block *[27-29]:*

With the next algorithm, the relation $\frac{\partial u_c(\underline{x}|\underline{\theta})}{\partial \overline{y}^l}$ is derived:

$$\frac{\partial u_c}{\partial \overline{y}^l} = \frac{b^l}{\sum_{i=1}^{M} b^l}, \tag{4.5}$$

$$\frac{\partial u_c}{\partial \overline{x}_i^l} = \frac{\overline{y}^l - u_c}{\sum_{i=1}^{M} b^l} b^l \frac{-2\left(x_i - \overline{x}_i^l\right)}{\left(\sigma_i^l\right)}, \tag{4.6}$$

$$\frac{\partial u_c}{\partial \sigma_i^l} = \frac{\overline{y}^l - u_c}{\sum_{i=1}^{M} b^l} b^l \frac{-2\left(x_i - \overline{x}_i^l\right)^2}{\left(\sigma_i^l\right)^3}; \tag{4.7}$$

where:

$$b^{l} = \prod_{i=1}^{n} \exp\left(-\left(\frac{x_i - \bar{x}^{l}}{\sigma_i^{l}} \right)^2 \right). \tag{4.8}$$

The above relations are obtained considering the equations in (4.3) and the control u_s is given by *[13, 17]:*

$$u_s(\underline{x}) = I_1^{*} \operatorname{sgn}\left(\underline{e}^{T} P \underline{b}_c\right) \cdot \left[|u_c| + \frac{1}{b_L}\left(f^{U} + \left|y_m^{(n)}\right| + \left|\underline{k}^{T} \underline{e}\right| \right) \right], \tag{4.9}$$

where: $I_1^{*} = 1$ if $V_e > \bar{V}$ and $I_1^{*} = 0$ if $V_e \le \bar{V}$ *[15, 16]*.

The control u (Figure 3) is applied *[14, 15]*:

$$u = u_c(\underline{x}|\underline{\theta}) + u_s(\underline{x}), \tag{4.10}$$

where u_c is given by the relation (4.3) and u_s is given by the relation (4.9).

To adjust the vector $\underline{\theta}$, the next adaptive law is used:

if $\sigma_i^{l} = \sigma$, the following equation is used:

$$\dot{\sigma}_i^{l} = \begin{cases} \gamma \underline{e}^{T} \underline{p}_n \dfrac{\partial u_c}{\partial \sigma_i^{l}} & if \quad \underline{e}^{T} \underline{p}_n \dfrac{\partial u_c}{\partial \sigma_i^{l}} < 0 \\ 0 \quad if \quad \underline{e}^{T} \underline{p}_n \dfrac{\partial u_c}{\partial \sigma_i^{l}} \ge 0 \end{cases}; \tag{4.11}$$

Otherwise, the following equation is used:

$$\underline{\dot{\theta}} = \begin{cases} \gamma \underline{e}^{T} \underline{p}_n \dfrac{\partial u_c}{\partial \sigma_i^{l}} & if \quad \left(|\underline{\theta}| < M_{\theta}\right) \quad or \quad \left(|\underline{\theta}| = M_{\theta} \quad and \quad \underline{e}^{T} \underline{p}_n \underline{\theta}^{T} \dfrac{\partial u_c}{\partial \sigma_i^{l}} \ge 0\right) \\ \gamma \underline{e}^{T} \underline{p}_n \dfrac{\partial u_c}{\partial \sigma_i^{l}} - \gamma \underline{e}^{T} \underline{p}_n \dfrac{\theta \theta^{T}}{|\underline{\theta}|^2} \dfrac{\partial u_c}{\partial \underline{\theta}} & if \quad \left(|\underline{\theta}| = M_{\theta} \quad and \quad \underline{e}^{T} \underline{p}_n \underline{\theta}^{T} \dfrac{\partial u_c}{\partial \sigma_i^{l}} < 0\right) \end{cases}. \tag{4.12}$$

5 SIMULATIONS AND DATA ANALYSIS

For the simulations, a three-phased, bilateral, linear induction motor is used; it has the following parameters: V_F = 230V; I_f = 5A; R_s = 5.3Ω; R_r = 13.8Ω; L_m = 0.037H; L_r = 0.041H; L_s = 0.051H; K_f = 231.15 N/A; a = 23.741 ; b = 0.319; D = 57.1 kg/s; F_e = 150N; M = 12kg; v = 3m/s; τ = 0.027. The contact line considered for the simulations has the following parameters: span is 60m, deflection is 0.454m. The main pulsation of the contact line for a locomotive speed of 100km/h is ω = 2.907 1/s. Figure 4 presents the Matlab-Simulink schematic for the fuzzy adaptive regulator.

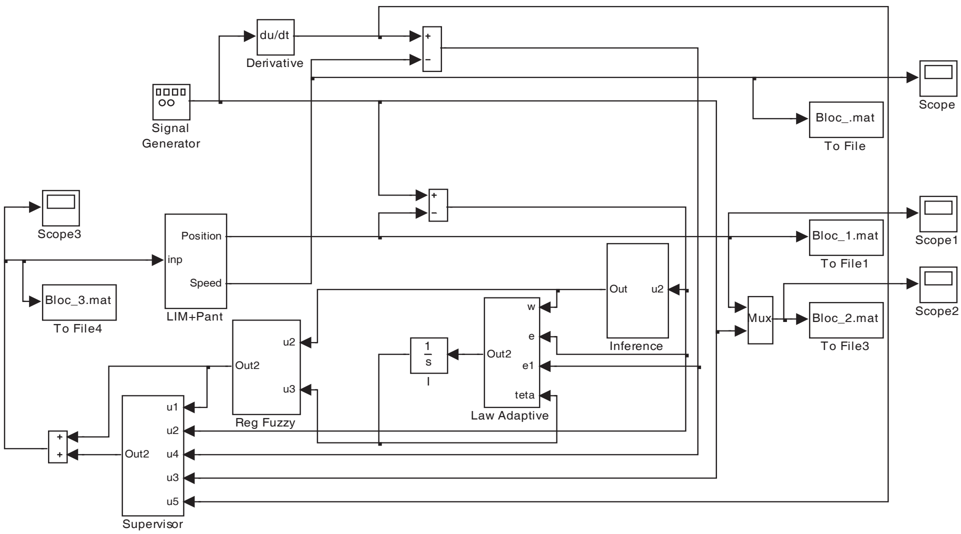

Figure 4: *Matlab-Simulink schematic for the fuzzy adaptive regulator*

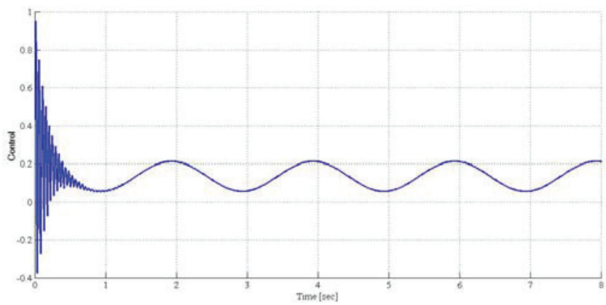

Figure 5: *Control signal variation*

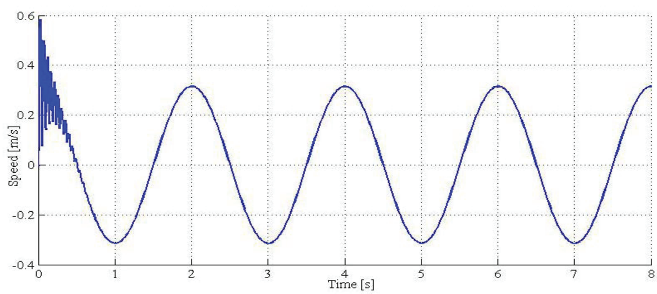

Figure 6: *Speed variation of the linear induction motor*

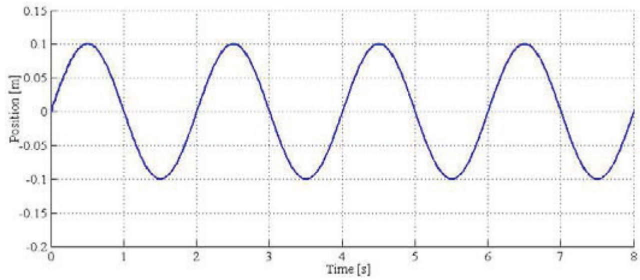

Figure 7: *Mobile armature motion (motor position)*

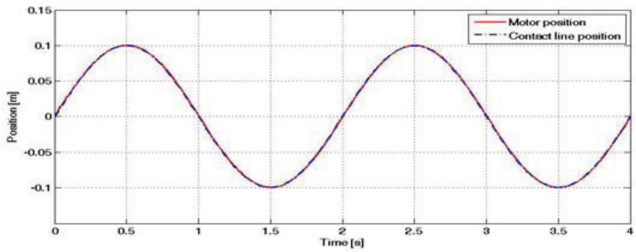

Figure 8: *Motor's movement and contact line position*

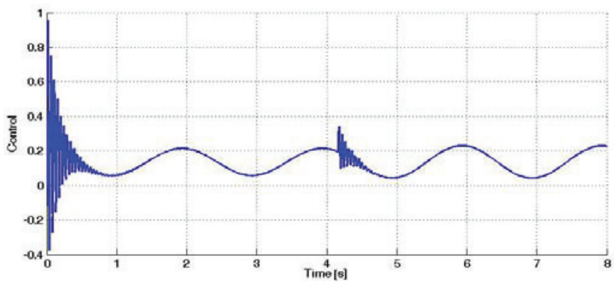

Figure 9: *Control signal variation with a supplementary, incidental force*

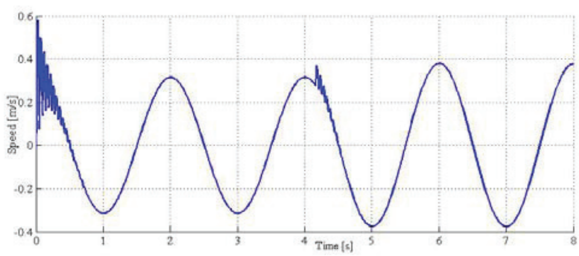

Figure 10: *Speed variation of the linear induction motor with supplementary, incidental force*

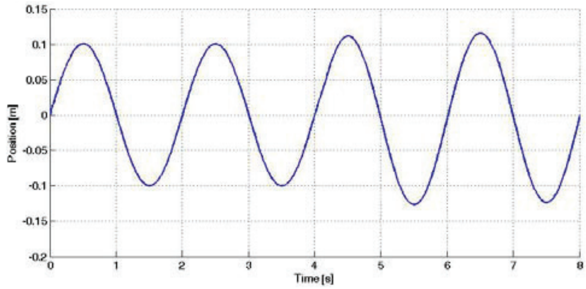

Figure 11: *Mobile armature motion (motor position) in case of the incidental force*

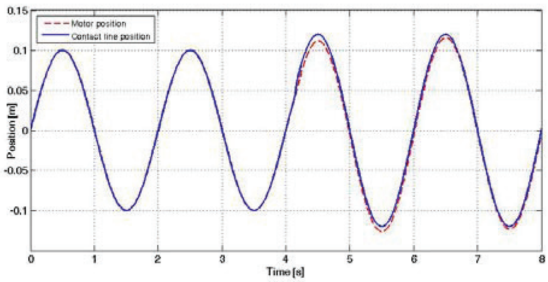

Figure 12: *Motor's movement and contact line position in case of the incidental force*

Figures 5 to 12 present the simulations of the pantograph driven by the linear motor system using a fuzzy adaptive regulator. Figure 5 presents the variation of the control signal, and Figure 6 presents the speed variation of the LIM and, accordingly, the vertical speed variation of the pantograph. The speed of the system has a variation of ±0.314 m/s.

Figure 7 presents the movement of the mobile armature (the plate) of the LIM, of the ±0.100 m. These variations are in accordance with the prescribed values of ±0.454 m.

Figure 8 presents the movement of the motor (red curve) and the position of the contact line (blue, dash curve) which must be followed by the pantograph. It can be observed that the two curves are very close, with differences of about (±0.1m), which demonstrate good control of the pantograph – linear motor system.

To estimate the operability of the system, a simulation for the overload was made, for the situation when the motor has to overcome a supplementary effort. For the simulation, the previous parameters are used, but, currently, a supplementary, incidental force is considered F_{1p}=20N.

Figure 9 describes the control signal with supplementary, incidental force F_{1p} at the moment t=4.16s, a force that modifies the shape of the control signal.

In Figure 10, the speed of the motor is depicted, with variations of ±0.314m/s in the first part of the simulation. When the supplementary force F_{1p} occurs, the variation speed becomes ±0.378m/s, with an increase of about 16%.

In Figure 11, it is observed that the variation of the position of the motor. When the supplementary force occurs, the position is modified from ±0.100m la ±0.117m.

Figure 12 shows the trajectory of the pantograph over the contact line when an incidental force appears. Thus, after the time t=4.163s, an increase also observed for the movement of the pantograph (red curve, ±0.1116m) and for the trajectory of the contact line (blue, dash curve, 0.12m). The difference between the two characteristics is of 0.0084m, which is about 7%; even in this situation, the system operates in the necessary conditions of the deflection of 0.454m.

6 CONCLUSIONS

Assuring continuous power collection for railway vehicles is essential for a safe transportation system. Problems regarding power collection are related to the pantograph detachment from the contact line due to the oscillations and parasitic movement of the vehicles and their power-collecting equipment. In this article, a solution to improve the power supply of the electric locomotive by using a linear induction motor to drive the pantograph is presented and analyzed. A mathematical model for the linear induction motor and the motor-pantograph system are developed, considering a fuzzy control technique. Simulations are made for two cases, with and without supplementary incidental force acting over the pantograph. The speed and position of the pantograph are discussed. Furthermore, the trajectory of the pantograph head in concordance with the trajectory of the contact line is also analysed. The simulations demonstrate good control of the pantograph-linear induction motor system using a fuzzy control technique.

References

[1] **S. Walters, A. Rachid, A. Mpanda:** *On Modelling and Control of Pantograph Catenary Systems,* In: PACIFIC 2011, Amiens, France, 2011

[2] **C. Nituca, A. Rachid, L. Cantemir, G. Chirac, Alina Gheorghiu**: Constructive and experimental aspects regarding the electric power collecting for very high speed traction, In The 6th International Conference on Electromechanical and power systems, Chişinău, October 2007

[3] **A. Collina, A. Facchinetti, F. Fossati***: An application of active control to the collector of an high-speed pantograph: simulation and laboratory tests*, Proc.of the 44th IEEE Conf. on Decision and Control, and European Control Conference 2005 Seville, Spain, pp. 4602-4609, 2005

[4] **R. Garg, P. Mahajan, P. Kumar**: *Effect of Controller Parameters on Pantograph-Catenary System*, American Int. J. of Research in Science, Technology, Engineering & Mathematics, 2(2), March-May, 2013, pp. 233-239

[5] **M**. **Carnevale**: *Innovative Solutions for Improving Pantograph Dynamics and Current Collection*, Ph. D. Thesis, Politecnico di Milano, Milan, Italy, 2011

[6] **A. Pisano, E**. **Usai**: *Contact force regulation in wire-actuated pantographs via variable structure control and frequency-domain techniques*, Int. J. of Control, vol. 81 (11), pp. 1747-1762, 2008

[7] **A. Rachid:** *Pantograph catenary control and observation using the LMI approach*, 50th IEEE Conf. on Decision and Control and European Control Conf. Orlando, USA, pp. 2287-2292, 2011

[8] **J.W. Kim, H.C. Chae, B.S. Park, S.Y. Lee,** et. al., *State sensitivity analysis of the pantograph system for a high-speed rail vehicle considering span length and static uplift force*. J. of Sound and Vibration vol. 303, pp. 405–427, 2007

[9] **Y.H. Cho:** *Numerical simulation of the dynamic responses of railway overhead contact lines to a moving pantograph considering a nonlinear dropper.* J. Sound and Vibration vol. 315, pp. 433–454, 2008

[10] **A. Collina, S. Bruni**: *Numerical Simulation of Pantograph-Overhead Equipment Interaction*, Vehicle System Dynamics, Vol. 38, No. 4, pp. 261-291, 2002

[11] **N. Zhou, W. Zhang**: *Investigation on dynamic performance and parameter optimization design of pantograph and catenary system,* Finite Elements in Analysis and Design vol. 47, pp. 288–295, 2011

[12] **P. Nåvik, A. Rønnquist, S. Stichel:** *Identification of system damping in railway catenary wire systems from full-scale measurements*, Engineering Structures, vol. (113), pp. 71–78, 2016.

[13] **S. Liu, L. Wu, X. Zhu**: *Researchof Pantograph–Catenary Active Vibration Control System Based on NARMA-L2 Model*, Proc. of 2015 Int. Conf. on Electrical and Information Technologies for Rail Transportation, Vol. 377, pp. 803-810, 12 March 2016

[14] **M.A. Abdullah, A. Ibrahim, Y. Michitsuji, M. Nagai:** *Active control of high-speed railway vehicle pantograph considering vertical body vibration*, Int. J. of Mechanical Engineering and Technology (IJMET), Vol. 4, Issue 6, pp. 263-274, November - December 2013

[15] **D. Guida, C. M. Pappalardo**: *Development of a Closed-Chain Multibody Model of a High-Speed Railway Pantograph for Hybrid Motion/Force Control of the Pantograph/Catenary Interaction,* Int. J. of Mechanical Engineering and Industrial Design, vol. 3(5), pp. 45-85, 2013

[16] **L. Cantemir, A. Rachid, C. Nituca, C.I. Barbanta, G. Chiriac, A.P. Alexandrescu:** Patent No. 128199/28.02.2018, OSIM, Romania, *Echipament de actionare electromagnetic a unui culegator de curent de tip pantograph*, 2018

[17] **Y.J. Huang:** *Discrete fuzzy variable structure control for pantograph position control, Electrical Engineering*, vol. 86.3, pp. 171-177, 2004

[18] **E. Karaköse, M.T. Gençoğlu:** *Adaptive fuzzy control approach for dynamic pantograph-catenary interaction*, In: *MECHATRONIKA, 15th International Symposium*, IEEE, pp. 1-5, 2012

[19] **F.J. Lin, R.J. Wai**: *Hybrid Control Using Recurrent Fuzzy Neural Network for Linear-Induction Motor Servo Drive,* IEEE Transactions on Fuzzy Systems, Vol. 9, No. 1, pp. 102-115, 2001

[20] **Gh. Livinţ, M. Petrescu, P. Livinţi**: *Modeling and control for linear induction motor electrical drive;* Buletinul Institutului Politehnic Iaşi, Tomul XLVIII, (LII), Fasc. 5, 2002

[21] **C.I Huang, K.C. Hsu, H.H. Chiang, K.Y. Kou, T.T. Lee**: *Adaptive Fuzzy Sliding Mode Control of Linear Induction Motors with Unknown End Effect Consideration*, Proceedings of the 2012 International Conference on Advanced Mechatronic Systems, Tokyo, Japan, September 18-21, pp. 626-631, 2012

[22] **M.A. Nasr Khoidja, M.A. Ouaz, B. Ben Salah, P. Brochet:** *Control of Velocity for a Linear Induction Motor***,** International Conference on Machine Intelligence, Tozeur – Tunisia, pp. 91-95, November 5-7, 2015

[23] **F.L. Lin, P.K. Huang, W.D. Chou**: *Genetic Algorithm Based Recurrent Fuzzy Neural Network For Linear Induction Motor Servo Drive*, Journal of the Chinese Institute of Engineers, Vol. 30, No. 5, pp. 801-817, 2007

[24] **I. Boldea, S.A. Nasar**: Linear Motion Electromagnetic Devices, Taylor & Francis November 5, 2001

[25] **R.J. Wai**: *Development of Intelligent Position Control System Using Optimal Design Technique*, IEEE Transactions on Industrial Electronics, vol. 50, no. 1, pp. 218-231, Feb. 2003

[26] **C. Nituca:** *Probleme de captare a curentului electric de la linia de contact pentru vehicule acţionate electric*, Universitatea Tehnică ”Gheorghe Asachi” din Iaşi, 2003

[27] **L.X. Wang**: *Adaptive fuzzy systems and control: design and stability analysis*, Englewood Cliffs, N.J.: PTR Prentice Hall, 1994

[28] **L.X. Wang**: *A Course in Fuzzy Systems and Control*, Prentice Hall International Ed., 1996

[29] **L.X. Wang**: *Stable Adaptive Fuzzy Controllers with Application to Inverted Pendulum Tracking,* IEEE Transactions on Systems, Man, and Cybernetics-Part b: Cybernetics, vol. 26, no. 5, pp. 667-691, October 1996

[30] **F. Wan, L.X. Wang, Y. Sun**: *One-stepahead Adaptive Control for a General Class of Nonlinear Dynamic Systems based on Fuzzy Models*, Proceedings of the American Control Conference Arlington, VA, pp. 4782-4787, June 25-27, 2001

[31] **C.M. Lin, C.F. Hsu:** *Recurrent-Neural-Network-Based Adaptive-Backstepping Control for Induction Servomotors*, IEEE Transactions on Industrial Electronics, vol. 52, no. 6, pp. 1677- 1684, December 2005

Nomenclature

(Symbols)	(Symbol meaning)
d_0	diameter of the shaft load of the pantograph
D	viscous friction and iron-loss coefficient
F_e	electromagnetic force
F_r	external force disturbance
i_{qs}	q-axis primary current
i_{ds}	d-axis primary current
K_f	force constant
L_m	magnetizing inductance per phase
L_r	secondary inductance per phase
L_s	primary inductance per phase
M	total mass of the moving element
M_0	*t*otal mass of the pantograph related to the skate;
n_p	number of pole pairs
P_0	*t*he static equivalent load of the pantograph;
R_s	winding resistance per phase
R_r	secondary resistance per phase referred primary
T_r	secondary time-constant
v	mover linear velocity
V_{ds}	d-axis primary voltage
V_{qs}	q-axis primary voltage
y	amplitude of the catenary
σ	leakage coefficient
Φ_{dr}	d-axis secondary flux
Φ_{qr}	q-axis secondary flux
τ	pole pitch
μ_0	the friction coefficient in bearings
ω	catenary angular frequency