

# Adaptive Control of the Mechanical Part of the Electric Drive System Using a Reference Model of Neuro-Fuzzy Logic

Marinka Baghdasaryan<sup>1</sup>, Azatuhi Ulikyan<sup>2</sup>, Vardan Hovhannisyan<sup>1</sup>

**Abstract** – The introduction of new generation mechanisms in technological processes poses the tasks of ensuring their control, which require urgent solutions. For this reason, solving tasks that meet the arising challenges that have arisen and are aimed at improving the efficiency of control systems for electric drives of mechanisms becomes a priority. This paper presents a new approach to adaptive control of the mechanical part of the electric drive system of mechanisms operating in uncertain conditions. The proposed approach is modeled in the MATLAB software environment and provides high control speed, accuracy, adaptability and the ability to expand capabilities. This is achieved due to the fuzzy reference model used in the system and the coordinated operation of the PID controller, as well as the neural network's ability to learn quickly and accurately. The observations and studies necessary for the development of the control model were carried out for both the two-mass and three-mass mechanical parts of the electric drive system. This took into account the possible changes in connection stiffness that occur in mechanical parts and the ability of the control system to adapt to them. Tests of the model show that it suppresses the elastic vibrations of the mechanical part. **Copyright** © 2024 Praise Worthy Prize S.r.l. - All rights reserved.

**Keywords:** Fuzzy Logic, Regulator, Adaptive, Two-Mass and Three-Mass, Electric Drive, Connection Stiffness

## Nomenclature

$J_1$	Moment of inertia of the first mass
$J_2$	Moment of inertia of the second mass
$J_3$	Moment of inertia of the third mass
$M_D$	Torque of the motor
$M_{12}$	Elastic torque
$M_{23}$	Elastic torque between the gearbox and the technological mechanism
$\omega_1$	Angular velocity of the first mass
$\omega_2$	Angular velocity of the second mass
$\omega_3$	Angular velocity of the third mass
$c$	Stiffness of the elastic link connection
$c_{12}$	Connection stiffness between the drive and the gearbox
$c_{23}$	Connection stiffness between the gearbox and the technological mechanism
$M_c$	Torque of the load resistance
$\omega_0$	Set value of the motor rotation speed

## I. Introduction

The efficiency of modern industries, transport and life support is determined by the quality of management of the electric drive system used in them [1]-[3]. The synthesis of an electric drive control system is based on the requirements set to the system and changes in operating conditions determined by the application purpose of the controlled object. Some mechanisms operate under conditions of random changes in the technological process

[4]-[8]. During the operation of a number of technological mechanisms, due to elastic vibrations of the mechanical parts of the electric drive system, their transmission elements can be destroyed, deformed or gradually wear out [9]-[11]. They occur during electrical transients, as well as under the influence of sharply changing loads.

Elastic vibrations have a negative impact on the performance of the electric drive system, causing an increase in dynamic loads on the elements and a decrease in productivity [12], [13]. The ineffective operation of the electric drive system of such mechanisms leads to dangerous operating conditions or premature failure, as well as to a decrease in the product quality. Obviously, for reliable operation of the electric drive system, there is a need to limit elastic vibrations in the transmissions of its mechanical part. For the effective operation of technological mechanisms operating under the above-mentioned hard conditions, it becomes necessary to ensure such control of its electric drive system, which would allow adapting the operation of the electric motor to the current situation. Due to their versatility, simplicity and reliability [14], [15], standard controllers are used in dynamic object control systems. Proportional Integral Differential (PID) regulators are still used to control the mechanical part of various electric drive systems. A large number of studies are known in which the use of a PID controller has made it possible to provide the expected indicators [16]-[20]. In order to improve the functioning of control systems in [21], the PID controller has been used in combination with Model Predictive Control

(MPC). The approach described above with standard controllers is applicable to the electric drive systems operating in a predictable mode. The use of traditional methods of controlling the electric drive system is especially ineffective in cases of the technological mechanisms operating with a random change in load [22], [23]. In order to solve this problem, the idea of replacing the linear regulators with nonlinear ones is applied. There are known studies in which controllers of artificial neural networks are used to control an electric drive [24]-[26].

[24] has presented a speed controller developed on the basis of a neural network and it has been tested on a synchronous drive. The results obtained provide an accurate assessment of the load and shaft rotation signals for a two-mass system. The author of the paper proposes an optimal neural network control system depending on the operating modes of the equipment [25]. In this work, interconnected electric motors are controlled individually by using a neural network controller for each electric drive. [26] has presented an adaptive neural network controller for direct control of the torque of the power part of an electric vehicle. The proposed INS tool optimizes the parameters of a Proportional Integral (PI) controller with real-time data and provides excellent dynamic stability.

Although neuroregulators provide high speed and high control efficiency, one of their disadvantages is that the neural network controller is mainly designed and adapted for a specific control object. In addition, it is difficult from an implementation point of view. The use of fuzzy logic capabilities is of particular importance for controlling electric drives operating under uncertain conditions [27]-[30], which reduces the complexity of control algorithms, the design and the execution time. Controllers built based on fuzzy logic are especially effective in control systems for complex technological processes. The authors of [28] have managed to suppress significantly elastic vibrations of a two-mass system by using an adaptive fuzzy controller. In this case, the Petri transition has been used.

A fuzzy control system for a two-mass electric drive, in which classical linear and nonlinear functions are used for the fuzzification process, is known. In order to find optimal values of the membership function parameters, a genetic algorithm is used [29]. A model of nonlinear control of a rolling ball is considered by using a PID controller and two different fuzzy logic controllers in the Matlab Simulink environment. In order to obtain a complete understanding of the simulation results, the application possibilities of various controllers are analyzed. Finally, conclusions are drawn about the advantages and the disadvantages of each control strategy [30]. In [31], the characteristics of traditional PID controllers, direct-coupled PID controllers and fuzzy PID controllers have been considered for temperature control.

Recommendations on the feasibility of using direct-coupled PID controllers and fuzzy PID controllers are proposed. In order to improve the frequency stability of the microgrid, S. Romfochai has proposed an adaptive neuro-fuzzy controller [32]. It is found out that the proposed method improves frequency stability during

disturbances, reduces transient time, and operates smoothly and with high performance. The adaptive control approach presented in [33], based on the use of a reference model, is of particular interest. Control is carried out by internal and external loops. The system provides such design of input data that corresponds to the description of the reference model [33]. The effectiveness of adaptive control of fuzzy systems is mainly determined by the correspondence of the membership functions of the input variables to the numerical value of the output variable. Some researchers have addressed the issue of creating a rule base. Ignatyev V. et al. have developed a base of optimal rules, which is formed automatically based on the knowledge of the object obtained under the control of the classical regulator [34]. The task of optimization is solved by using the method of grouping the values of input and output signals in order to reduce the number of rules and increase the speed of the control system. The analysis shows that, although the results obtained in the field of electric drive control are of great practical importance, they are nevertheless focused on individual special cases of the control of the electric drive system. They lack the ability to return quickly to the steady state of the system with high performance and accuracy after the disappearance of the external influence and the completion of the transition process. Although adaptive control capabilities make it possible to record significant successes in solving control tasks, there is still a significant reserve for their improvement, which can be provided by using intelligent approaches. By taking into account the peculiarities of controlling the mechanical part of the electric drive system of mechanisms operating with uncertain changes in technological conditions and the possibility of its improvement, it can be stated that the synthesis of a regulator taking into account their fuzzy characteristics is an urgent task of scientific and technical interest, on the basis of which the purpose of the study is formed. The goal of the study is to develop an adaptive control system for the mechanical part of the electric drive of mechanisms used in technological processes operating under uncertain conditions with the help of which the system can independently adapt to changes in external conditions and function effectively in various situations.

The paper is organized as follows. Section II presents the structure of the two-mass and three-mass mechanical parts, its mathematical description. The changes in angular velocities and elastic torques of two-mass and three-mass electric drive systems operating with dynamic load in transients, in the systems without a regulator and with a PID controller are presented. A block diagram of the proposed control system and an algorithm for its implementation are presented. Section III presents adaptive control models for two-mass and three-mass electric drive systems and the characteristics obtained as a result of their testing. The construction and training algorithm of the reference model of the fuzzy controller is considered. The results of training a neural network using the input and output signals of a fuzzy model are evaluated. Section IV presents the discussion. Finally,

Section V presents the conclusions.

## II. Materials and Methods

### II.1. Statement of the Problem and Justification of the Methodology

In practice, mechanisms of different power, different types and structures are used, and their electric drives use different approaches to energy transfer [35], [36]. Two types of energy transmission from the drive motor to the technological mechanism are widely used: with a gearbox and without a gearbox, in which a clutch is mainly used.

The first of them is used in the drive systems of mechanisms with high (more than 1000 kW) power, and the second one with low (up to 1000 kW) power. By considering that both types of transmission are used in dynamic systems operating under uncertain conditions, it becomes necessary to consider issues of improving the efficiency of control of the electric drive systems both with and without a gearbox. The mechanical part of the electric drive system without a gearbox is two-mass, and there is an elastic connection between the motor and the mechanism (Fig. 1). The mechanical part of the electric drive system with a gearbox is three-mass, and there are elastic connections between the motor and the gearbox, as well as between the gearbox and the mechanism (Fig. 2).

A mathematical model describing the dynamics of the mechanical part of a two-mass electric drive system is presented by the following differential equation:

$$\begin{cases} M_D - M_{12} = J_1 \frac{d\omega_1}{dt} \\ M_{12} - M_c = J_2 \frac{d\omega_2}{dt}, \quad \frac{dM_{12}}{dt} = c(\omega_1 - \omega_2) \end{cases} \quad (1)$$

The mathematical model characterizing the dynamics of the mechanical part of the three-mass electric drive system is presented by the following differential equation:

$$\begin{cases} M_D - M_{12} = J_1 \frac{d\omega_1}{dt} \\ M_{12} - M_{23} = J_2 \frac{d\omega_2}{dt}, \quad \frac{dM_{12}}{dt} = c_{12}(\omega_1 - \omega_2) \\ M_{23} - M_c = J_3 \frac{d\omega_3}{dt}, \quad \frac{dM_{23}}{dt} = c_{23}(\omega_2 - \omega_3) \end{cases} \quad (2)$$

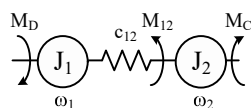


Fig. 1. The two-mass system

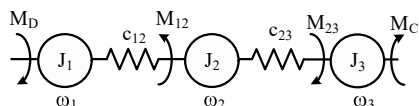


Fig. 2. The three-mass system

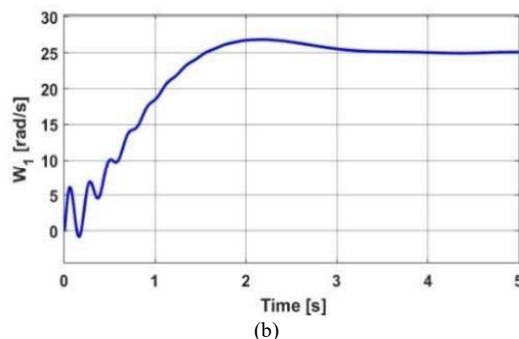
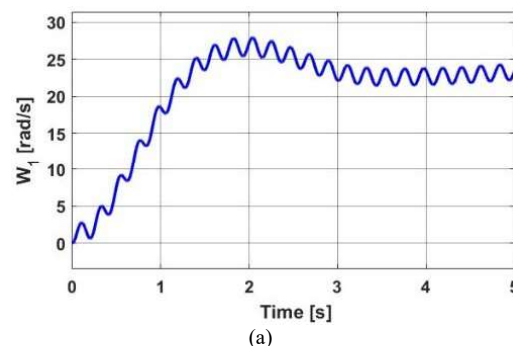
By taking into account the fact that the change in the elastic torque of the mechanical part is manifested in a change in the connection stiffness, various values of the connection stiffness are considered when developing the control model. The importance of such consideration is due to the fact that during operation, elastic links can deform, wear out, causing a change in the stiffness of the connection. Developing a control system capable of adapting to these changes is at the basis of the adaptive control proposed in this paper. Transients in the mechanical part of the electric drive system are studied by using a system of differential equations (1) and (2).

### II.2. Characteristics of the Transients of the Mechanical Part

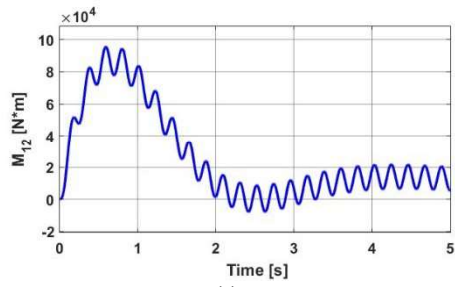
Figures 3-8 show the changes in the angular velocities and the elastic torque in two-mass and three-mass systems of electric drives with dynamic load in transients for systems without a regulator and with a PID controller.

From the given characteristics, it is clear that the angular speeds of rotation and elastic torques of the mechanical parts of a two- and three-mass electric drive without a regulator do not enter a steady state during the observed period.

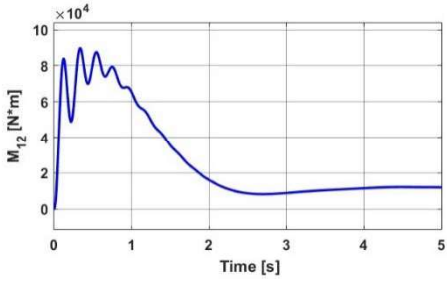
An unstable change in elastic torques in the transient process over a long period will lead to deformation and wear of individual units of transmission links, which leads to an emergency situation and unnecessary losses of transmitted energy. When using a PID controller, the characteristics of the system are stabilized with some delay. The construction method of an adaptive model with a double tuning is presented.



Figs. 3. Changing the rotation speed of the first mass of the two-mass electric drive system (a) without a regulator, (b) using a PID controller

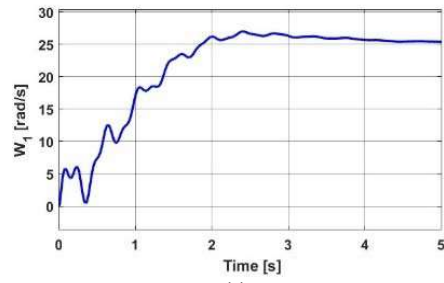


(a)

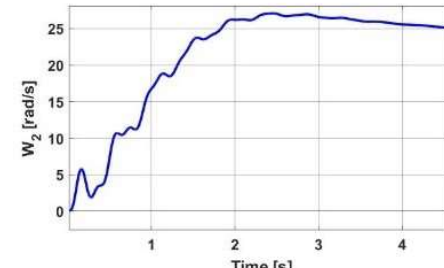


(b)

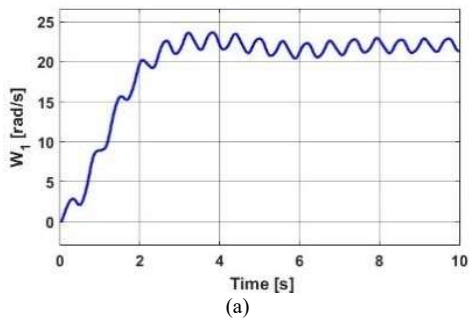
Figs. 4. The elastic torque of a two-mass electric drive system, changes in transients (a) without a regulator, (b) with a PID controller



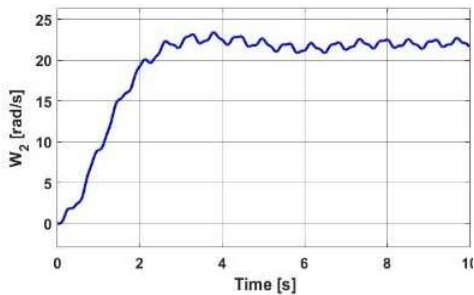
(a)



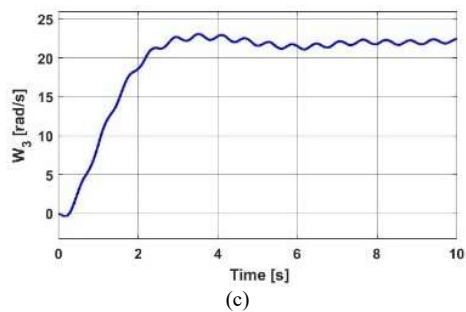
(b)



(a)

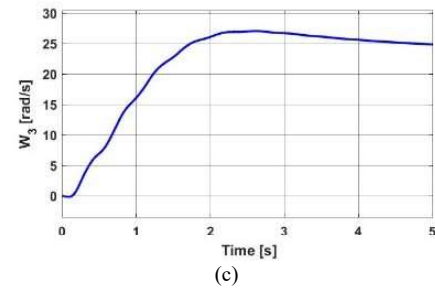


(b)



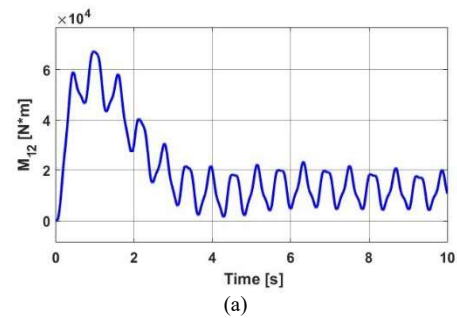
(c)

Figs. 5. Changes in the angular velocities of the three-mass electric drive system, (a) the first (b) the second, (c) the third masses in transients without the use of a regulator

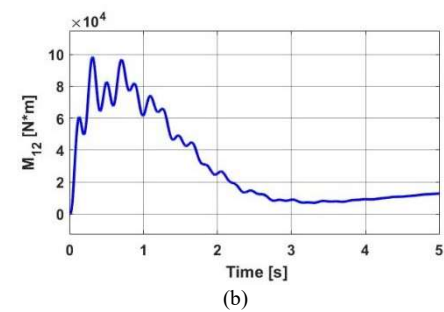


(c)

Figs. 6. Changes in the three-mass electric drive system, (a) in the first (b) in the second, and (c) in the third masses, changes in angular velocities when using the PID controller in transients

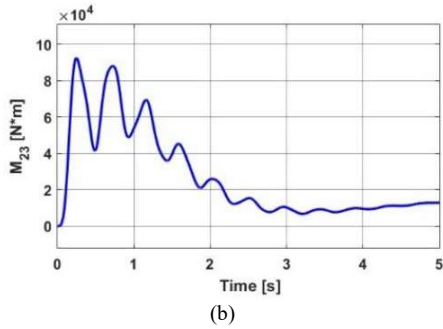
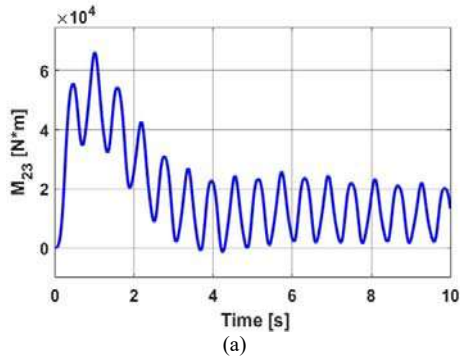


(a)



(b)

Figs. 7. The change in the elastic torque  $M_{12}$  of a three-mass electric drive system in transients (a) without a regulator (b) with a PID controller



Figs. 8. The elastic torque  $M_{23}$  of a three-mass electric drive system, changes in transients (a) without a regulator (b) with a PID controller

### II.3. An Adaptive Control System with Reference Model

A block diagram of the adaptive control model for the mechanical part of the electric drive of the technological mechanism is shown in Fig. 9.

It is a double tuning control system with one of the controllers serving as a reference model. In the proposed adaptive control system for the mechanical part of the electric drive, a fuzzy controller is used as a reference model.

This regulator generates the desired signal of the rotation velocity of the motor, which provides the best course of the technological mechanism operating under uncertain changes in working conditions, in accordance with the established quality criteria.

The signal received at the system output is subtracted from the output signal of the reference model, and the output signal of the reference model is added to the resulting error. The received signal is fed to the input of the system with negative feedback. This leads to improved system control indicators.

#### II.3.1. Neuro-Fuzzy Controller

The neuro-fuzzy system, created as a result of the joint use of a fuzzy logic system and a neural network has been widely used due to the following [37], [38]:

- It can have several input and output variables that are interconnected by rules and operate in parallel;
- It has a nonlinear structure, so it can work successfully under both linear and nonlinear external influences;
- High ability to learn a large amount of data.

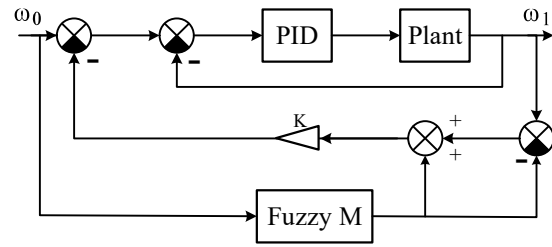


Fig. 9. A block diagram of the adaptive control

For the mechanical part of the electric drive system, a neuro-fuzzy controller of the rotation speed of the motor rotor with four input and one output variables is developed, which has a Sugeno type output [39], [40]. The Fuzzy Logic Toolbox environment of the MATLAB software package is used as a modeling tool. The Gaussian membership function [41], [42] is selected for the input variables, whose number is set in accordance with the number of points in the sequence of the input signal. A database of rules has been formed. Each rule establishes the correspondence of the membership functions of the input variables to the numerical value of the output variable. The fuzzy system is trained by using an algorithm developed based on a neural network. For this purpose, the Adaptive-Neuro-Fuzzy-Inference-System (ANFIS) of the MATLAB software package is used.

## III. Results

The model of the adaptive control of the mechanical part of the described two-mass and three-mass electric drive system is shown in Figures 10 and 11.

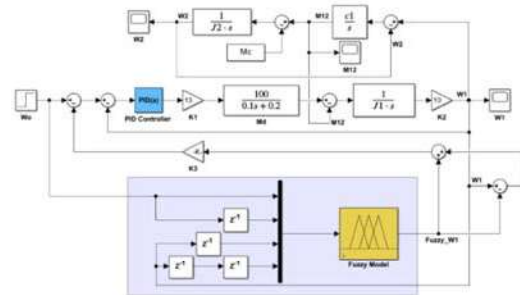


Fig. 10. Adaptive control model for two-mass electric drive systems

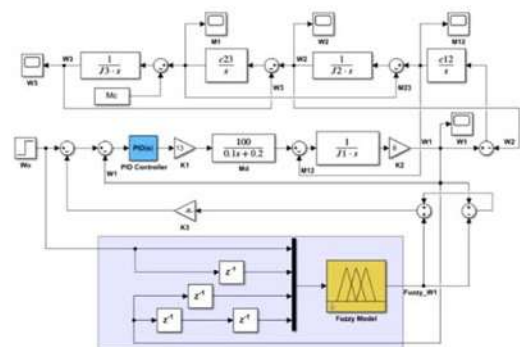


Fig. 11. Adaptive control model for three-mass electric drive systems

The input sequences of the fuzzy system are formed by the current and delayed signals of the angular velocity of the electric motor (Fig. 12). The output signal is generated by taking into account the degree of delay. The number of input signals for the considered mechanical part of the electric drive system is set to 12. Figures 13 and 14 show the membership functions of the input signals after training. From the sequence of input and output signals of the neuro-fuzzy regulator, 16 fuzzy rules are formulated for control. Below there are some rules:

- If  $w_o(k)$  is mf12 and  $w_o(k-1)$  is mf12 and  $w_z(k-1)$  is mf1 and  $w_z(k-2)$  is mf1 then  $w_1(k)$  is 24;
- If  $w_o(k)$  is mf12 and  $w_o(k-1)$  is mf12 and  $w_z(k-1)$  is mf1 and  $w_z(k-2)$  is mf2 then  $w_1(k)$  is 25.5;
- If  $w_o(k)$  is mf12 and  $w_o(k-1)$  is mf11 and  $w_z(k-1)$  is mf1 and  $w_z(k-2)$  is mf1 then  $w_1(k)$  is 14;
- If  $w_o(k)$  is mf12 and  $w_o(k-1)$  is mf11 and  $w_z(k-1)$  is mf2 and  $w_z(k-2)$  is mf1 then  $w_1(k)$  is 7;
- If  $w_o(k)$  is mf11 and  $w_o(k-1)$  is mf12 and  $w_z(k-1)$  is mf1 and  $w_z(k-2)$  is mf1 then  $w_1(k)$  is 32.

Training samples are generated by using four input and output signals of the fuzzy model. This data is loaded to train the neural network. In this case, during the training process, it is set that the network should be trained for 300 cycles. However, after the 40 Epoch, the error no longer decreases, which means that the network is already trained. It turns out that for the model formed according to the fuzzy rule 16, the root-mean-square error is 0.0013.

By using the Neuro-fuzzy Designer interface, the system has been trained, tested and checked. About 2000 data have been collected at the input and output of the system. The collected data have been divided into three separate datasets, 50% of which have been used for network training, 25% for testing, and 25% for re-checking. The training error has been 0.015, and the testing error has been 0.024 (Figs. 15). In Figs. 15, the test and training data are marked with blue dots, and the corresponding to them output values of fuzzy logic are marked with red asterisks. The testing data are used to evaluate the effectiveness of the trained network. The checking data are used to prevent the retraining of the model. After training, the structure of the ANFIS neural network, which is shown in Fig. 16, can be evaluated.

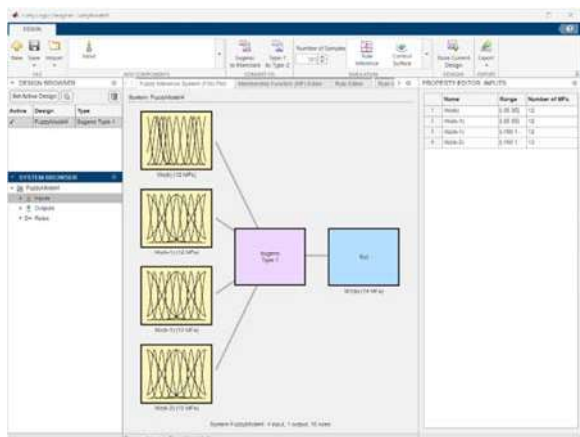
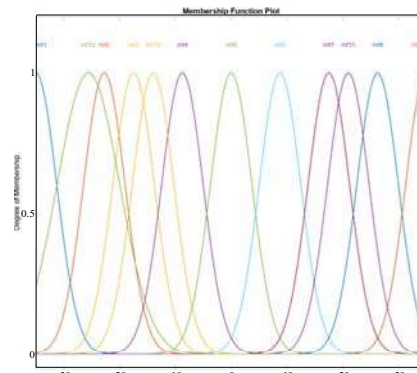
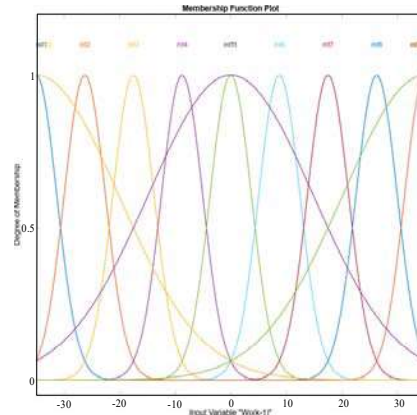


Fig. 12. The block diagram of a fuzzy controller

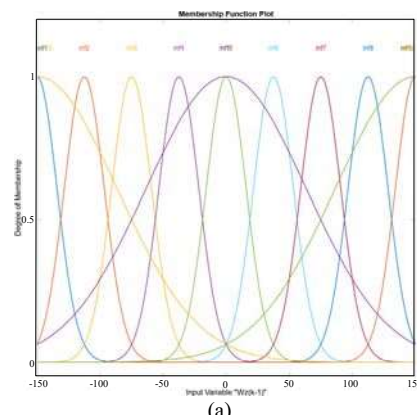


(a)

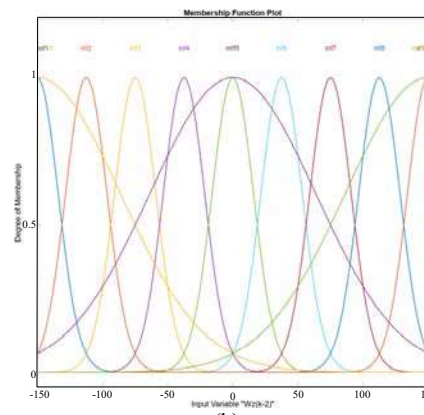


(b)

Figs. 13. Membership function for (a)  $W_o(k)$  and (b)  $W_o(k-1)$

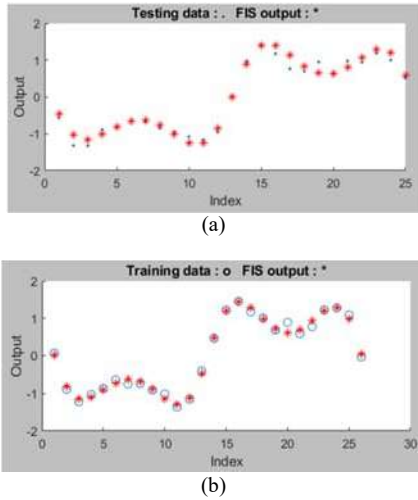


(a)



(b)

Figs. 14. Membership function for (a)  $W_z(k-1)$  and (b)  $W_z(k-2)$



Figs. 15. (a) Testing and (b) training data

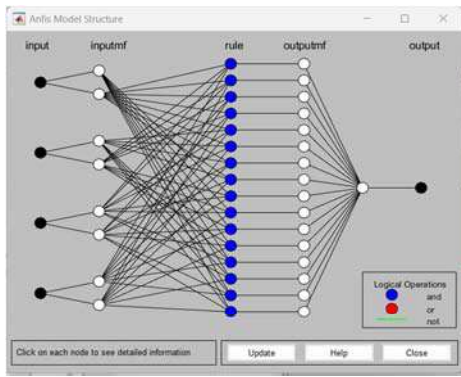


Fig. 16. ANFIS architecture with input–output membership functions

The ANFIS architecture consists of five levels. The values entered in the first layer are converted to their fuzzy interpretation. In the second layer, the values of the membership functions for each input variable on each fuzzy ensemble are calculated. The Gauss function is used.

The parameters of the membership functions are selected by using the error backpropagation algorithm. At the third level, the degree of activation of each rule is determined.

At the fourth level, the final output value of each rule is calculated. In the fifth layer, a defuzzification operation is performed, i.e. the fuzzy signal is converted into a crisp one. The developed adaptive control system has been tested for two-mass and three-mass electric drive control systems in accordance with the data given in Table I. Studies have been conducted for the resistance torque, varying according to the characteristic shown in Fig. 17.

The results obtained are compared with a system with a PID controller with the same data. The values obtained for the coefficients of the transfer function of the PID controller in the developed adaptive system are shown in Table II. All the studies shown in Figures 18–22 are carried out for different values of the connection stiffness. This is because during operation, changes in elastic connections occur in the links of the mechanical part for various reasons.

TABLE I  
CALCULATED DATA

Type of electric drive system	Parameter	Value
Two-mass system	$J_1$	2500 kg m <sup>2</sup>
	$J_2$	3170 kg m <sup>2</sup>
	$c$	186667 N m/rad
		560000 N m/rad
Three-mass system	$J_1$	1680000 N m/rad
	$J_2$	2500 kg m <sup>2</sup>
	$J_3$	600 kg m <sup>2</sup>
		3170 kg m <sup>2</sup>
	$c_{12}$	186667 N m/rad
		560000 N m/rad
	$c_{23}$	140000 N m/rad
	420000 N m/rad	
		1260000 N m/rad

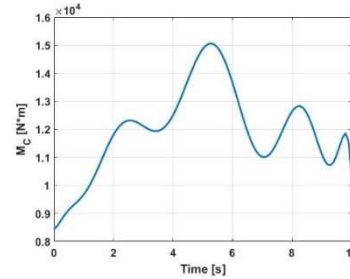


Fig. 17. The characteristic of the change in torque resistance

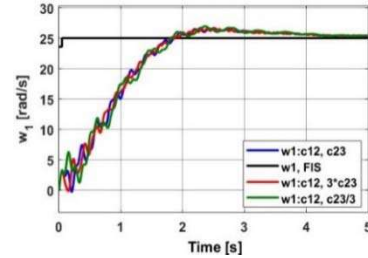
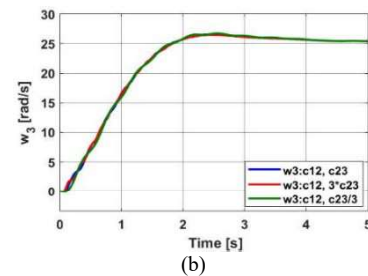
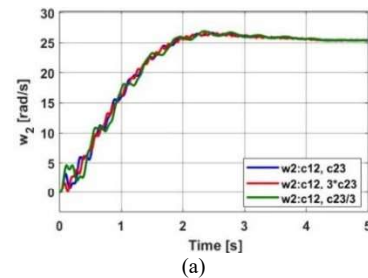


Fig. 18. For different values of connection stiffness, a change in the angular velocity of rotation of the motor rotor of a three-mass system with a PID controller and for fuzzy controllers



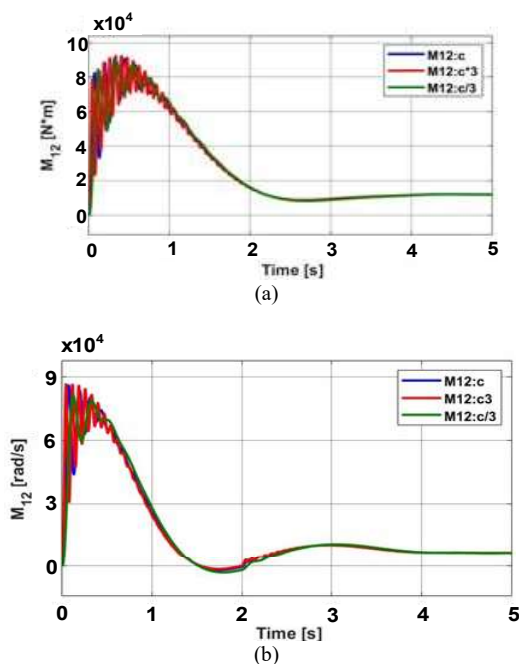
Figs. 19. For different values of connection stiffness, changes in the velocities of (a) the second and (b) the third masses with adaptive control of a three-mass system

TABLE II  
COEFFICIENTS OF PID CONTROLLERS OF THE ADAPTIVE SYSTEM OF THE MECHANICAL PART OF TWO-MASS AND THREE-MASS ELECTRIC DRIVE SYSTEMS

Type of electric drive system	Proportional amplification factor	Integral amplification factor	Differential amplification factor
Two-mass	0.936	0.126	164.41
Three-mass	0.900	0.120	100.0

This especially appears in systems that are in operation for a long period. The change in connection stiffness is considered for a two-mass system for the cases  $c$ ,  $3c$ ,  $c/3$  shown in Table I, and for a three-mass mechanism for various combinations of  $c_{12}$ ,  $3c_{12}$ ,  $c_{12}/3$  and  $c_{23}$ ,  $3c_{23}$ ,  $c_{23}/3$ .

The use of the fuzzy logical controller as a reference model makes it possible to smooth out the frequency and the amplitude of oscillations of changes in the rotation speed of the first, second and third masses in the transient processes (Figs. 18, 19). This is especially important because the wear rate of the drive links slows down. From a comparative analysis of elastic torques between different masses in transients, it can be seen that the developed adaptive control system leads to suppression of elastic vibrations of the mechanical part and a reduction in the time of transition to a stable mode (Figures 20-22). Studies of the influence of the moment of inertia of the mechanical part on the change in the rotation speed of the load also gives good results. The adaptive control system provides stabilization of the rotation speed of the mechanism in the shortest possible time, which cannot be said about a system with a traditional regulator (Fig. 23). Only the characteristic parameters of the adaptive control systems with a PID controller and with the neuro-fuzzy reference model are compared (Table II) for combinations of different connection stiffness values.



Figs. 20. In the two-mass drive system, the change in elastic torque  $M_{12}$  for different values of connection stiffness (a) only with the help of a PID controller, (b) adaptive control

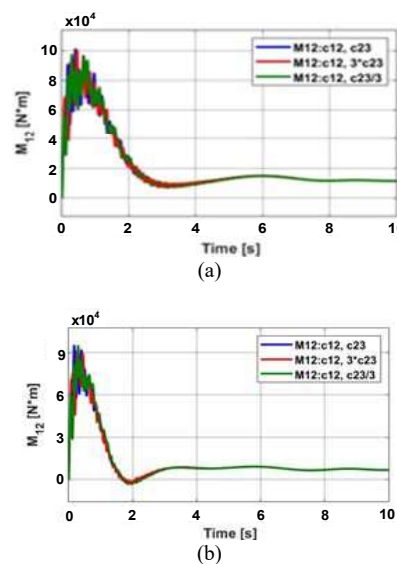
The results obtained show that the developed adaptive model makes it possible to increase the efficiency of control by reducing the rise time, overregulation and regulation time (Table III).

#### IV. Discussion

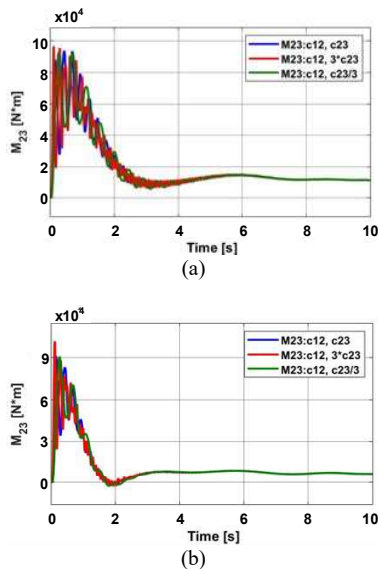
The analysis shows that an effective control of mechanisms operating with uncertain changes can be achieved through the development of a reliable, adaptive, high-speed and high-precision control system for the mechanical part of the electric drive system.

TABLE III  
PARAMETERS CHARACTERIZING THE MODES OF OPERATION OF ADAPTIVE CONTROL SYSTEMS WITH ONLY A PID CONTROLLER AND THE NEURO-FUZZY MODEL

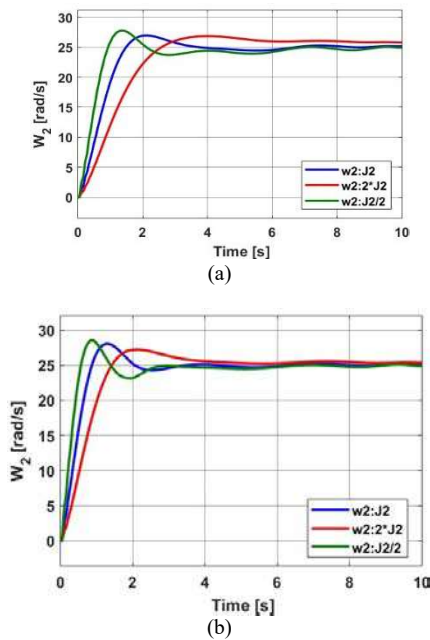
Connection stiffness values, N m/rad	Type of control system	Rise time, s	Over-regulation, %	Tuning time, s
I				
$c_{12} = 560000$	PID only	1.4	6.8	6
$c_{23} = 420000$				
II				
$c_{12} = 560000$	with PID and the neuro-fuzzy model	0.9	6.2	2.4
$c_{23} = 1260000$				
III				
$c_{12} = 560000$	PID only	1.5	7	6.1
$c_{23} = 420000$				
II				
$c_{12} = 186667$	with PID and the neuro-fuzzy model	0.93	6.4	2.5
$c_{23} = 1260000$				
III				
$c_{12} = 186600$	with PID and the neuro-fuzzy model	0.93	6.4	2.5
$c_{23} = 140000$				



Figs. 21. The change in the elastic torque  $M_{12}$  at different values of  $c$  in a three-mass electric drive system (a) only using a PID controller, (b) adaptive control



Figs. 22. Change in the elastic torque  $M_{23}$  in the electric drive system for different values of  $c$  (a) only using a PID controller, (b) adaptive control



Figs. 23. Changing the motor rotation speed in a two-mass electric drive system at different values of the moment of inertia (a) only using a PID controller, (b) adaptive control

The combined use of neuro-fuzzy and PID controllers allows avoiding the disadvantages inherent in classical control systems and achieve new results thanks to the advantages inherent in these controllers. A comparative analysis of changes in the elastic torque at different values of connection stiffness confirms that the adaptive control system developed in contrast to the known methods:

- Reduces the transition time to stable mode;
- Suppresses elastic vibrations of the mechanical part;
- Reduces fluctuations in the angular velocities of rotation of the masses included in the system in transients.

The developed system has excellent characteristics. In particular, compared to the classical tuning, it provides a reduction in rise time by 33%, debugging time by 60% and overregulation by 8.8%. By taking into account the results obtained, in a further research, the authors will implement the developed adaptive control system into a general automated control system and evaluate the effectiveness of its coordinated work with other systems. A new hypothesis on the development of an adaptive control model for the mechanical part of the electric drive system proposed by the authors can also be successfully applied to improve the efficiency of control of systems operating with a shock load. By considering that in this case the torque of resistance created by the mechanism is a time-dependent function that changes sharply by indefinite values, the new requirements that follow from this should be considered.

## V. Conclusion

The challenges arising from the development of industry pose new challenges to the control of electric drive systems of technological mechanisms. The key to solve these problems is the development of a highly efficient control system by using new approaches. This paper presents an adaptive control system for the mechanical part of the electric drive of mechanisms operating under uncertain conditions, in which the application capabilities of neuro-fuzzy and PID controllers are integrated. As a result of the study of the developed adaptive control model, the following conclusions are made:

1. The vibrations of the elastic torque of the mechanical part are reduced, and the duration of the transition process is shortened due to the applied reference model;
2. The study of transients at different values of connection stiffness have shown that, although a decrease in connection stiffness leads to an increase in the amplitude and intensity of vibrations of the elastic torque, due to the high adaptability of the control system, the levels of their elastic torque are aligned in the steady state mode;
3. The system demonstrates high efficiency when changing the moment of inertia of the mechanism load. This is fixed as a result of comparing the changes in the rotational speeds of the mechanisms of the classical and adaptive control systems developed by us;
4. The adaptive control system provides high speed and accuracy due to the high learning ability provided by the neural network. The network has been trained for 40 Epoch. Under the conditions of the formed rules, RMSE is 0.0013.

The conclusions drawn allow stating that the developed control model can be successfully applied to improve the efficiency and the reliability of the electric drive systems of technological mechanisms operated in various fuzzy conditions. Unlike the well-known adaptive control systems, which are mainly applicable to a specific

mechanism, the model developed in this paper can show the best results in control systems of the mechanisms operating under uncertain conditions and changing according to various laws. The analysis of the results obtained shows that the proposed system has many opportunities for development due to the expansion of the base of rules and their effective learning ability. This allows for integrated work with various control systems.

The presented comments allow stating that the results obtained have wide opportunities for development and can be successfully applied to the development of control systems that provide high reliability, speed and adaptability of various technological mechanisms.

## Acknowledgements

This work was supported by the Higher Education and Science Committee of MESCS RA, in the frames of the research project № 21T-2B195.

## References

- [1] L. Wang, H. Li, J. Huang, J. Zeng, L. Tang, W. Wu, Y. Luo, Research on and Design of an Electric Drive Automatic Control System for Mine Belt Conveyors, *Processes*, vol. 11, n. 6, 2023, pp. 1-18.
- [2] A. Merabet, Advanced Control for Electric Drives: Current Challenges and Future Perspectives, *Electronics*, vol. 9 n. 11, 2020, pp. 1-4.
- [3] W. Cai, X. Wu, M. Zhou, Y. Liang, Y. Wang, Review and Development of Electric Motor Systems and Electric Powertrains for New Energy Vehicles, *Automotive Innovation*. vol. 4, 2021, pp. 3-22.
- [4] N. Nalibayev, B. Kozhageldi, Z. Omarov, A. Zhanpeiissova, M. Tashimbetov, Analysis of Problems and Prospects for Improving Automatic Control Systems of Interconnected Electric Drives, *Journal of Robotics and Control (JRC)*, vol. 5, n.2, 2024, pp. 378-387.
- [5] J. Zhang, B. Wang, W. Bai, S. Yang, A Study on the Mechanism of Dynamic Pressure during the Combinatorial Key Strata Rock Column Instability in Shallow Multi-coal Seams, *Advances in Civil Engineering*, 2021, pp. 1-11.
- [6] Q. Wen, L. He, F. Gao, Stochastic Models and Control of Anchoring Mechanisms for Grasping in Microgravity, *Appl. Sci.*, vol. 12, n.6, 2022, pp.1-18.
- [7] M. Baghdasaryan, V. Hovhannisyan, Stability Assessment of an Ore Mill Electric Drive Using Machine Learning, *HighTech and Innovation Journal*, Vol. 15, n.2, 2024, pp. 213-230.
- [8] Baghdasaryan, M., Davtyan, D., Energy Saving in the Ore Beneficiation Technological Process by the Optimization of Reactive Power Produced by the Synchronous Motors, (2021) *International Review of Electrical Engineering (IREE)*, 16 (4), pp. 377-384.  
doi: <https://doi.org/10.15866/iree.v16i4.20119>
- [9] X. Chen, H. Wei, T. Deng, et al., Investigation of electromechanical coupling torsional vibration and stability in a high-speed permanent magnet synchronous motor driven system. *Appl. Math. Modell.* vol. 64, 2018, pp. 235–248.
- [10] W.Y. Bai, D.T. Qing, Y.W. Wang, et al., Dynamic characteristic of electromechanical coupling effects in motor-gear system, *J. Sound Vib*, vol. 423, 2018, pp.50–64.
- [11] M. Baghdasaryan, *Methods of Research and Optimization of the Mineral Raw Material Grinding Process*, NOVA Science Publishers, 2019.
- [12] S. Jiang, W. Li, Y. Wang, et al., Study on electromechanical coupling torsional resonance characteristics of gear system driven by PMSM: a case on shearer semi-direct drive cutting transmission system, *Nonlinear Dynamics*, vol. n.2, 2021, pp. 1205-1225.
- [13] S. Wang, Y. Zuo, H. Wang, X. Ge, An coupling vibration suppression method based SDDC for PMSM traction drive system, *The 2022 IEEE 5th International Electrical and Energy Conference (CIEEC)*, 27-29 May, Nanjing, China.
- [14] B. Damayanti, H. Syawaludin, A. Gunawan, Design of PI and PID Control System for Induction Motor Control on Gamma Irradiator Characterization Prototype Using a Modified Ziegler-Nichols Method, *Journal of Electrical Technology UMY (JET-UMY)*, vol. 6, n.2, 2022, pp. 94-102.
- [15] M. Shamsuzzoha, *PID Control for Industrial Processes*. Norway, 2018. 218p.
- [16] S.M. Alghamdi, M.N. Ajou, N.H. Abu-Hamdeh, A. Karimipour, Introducing a new PID controller to control the addition of PCM to the building with ventilation heat recovery installation to reduce the energy demand of the cooling system, *Journal of Building Engineering*, vol. 56, n.2, 2022, 104766.
- [17] K. Ang, G. Chong, PID Control System Analysis, Design, and Technology, *IEEE transactions on control systems technology*, vol. 13, n. 4, 2005, pp. 559-576.
- [18] S. I. Khather, M. A. Ibrahim, M. H. Ibrahi, PID Controller for A Bearing Angle Control in Self-Driving Vehicles, *Journal of Robotics and Control*, vol. 5 n.3, 2024, pp. 647-654.
- [19] G. Huang, X. Yuan, K. Shi, X. Wu, A BP-PID controller-based multi-model control system for lateral stability of distributed drive electric vehicle, *Journal of the Franklin Institute*, vol. 356, n.13, 2019, pp. 7290-7311.
- [20] A. Jassim, E.Karam, M. M. Ali, Design of Optimal PID Controller for Electric Vehicle Based on Particle Swarm and Multi-Verse Optimization algorithms, *Engineering and Technology Journal*, vol. 41, n2, 2023, pp. 1-10.
- [21] A. Aboelhasan, M. Abdelgeliel, E. Zakzouk, M. Galea, Design and Implementation of Model Predictive Control Based PID Controller for Industrial Applications. *Energies*, vol. 13, n. 24, 2020, pp.1-22.
- [22] Baghdasaryan, M., Ulikeyan, A., Study of the Operating State of a Synchronous Motor Electric Drive by Means of Changes Estimation of the Stator Current Behavior, (2022) *International Review of Electrical Engineering (IREE)*, 17 (2), pp. 177-184.  
doi: <https://doi.org/10.15866/iree.v17i2.21738>
- [23] Baghdasaryan, M., Avetisyan, A., Study of Stability Conditions of the “Electric Drive Motor - Technological Mechanism” System, (2023) *International Review of Electrical Engineering (IREE)*, 18 (2), pp. 111-118.  
doi: <https://doi.org/10.15866/iree.v18i2.22925>
- [24] M. Kaminski, T. Tarczewski, Neural Network Applications in Electrical Drives—Trends in Control, Estimation, Diagnostics, and Construction. *Energies*. vol. 16, n. 11, 2023, pp.1-26.
- [25] D.V. Chernyshev, Neural Network Control of an Electromechanical System, *2020 International Multi-Conference on Industrial Engineering and Modern Technologies (FarEastCon)*, 6-9 October 2020, Vladivostok, Russia.
- [26] G. Banda, S.G. Kolli, An Intelligent Adaptive Neural Network Controller for a Direct Torque Controlled eCAR Propulsion System, *World Electr. Veh. J.* vol. 12, n.1, 2021. pp. 1-17.
- [27] W. Santos, *Fuzzy Control Systems: Design, Analysis and Performance Evaluation*, NOVA science publishers, USA, 2017, 252 p.
- [28] P. Derugo, K. Szabat, T. Pajchrowski, K. Zawirski, Fuzzy Adaptive Type II Controller for Two-Mass System, *Energies*, vol. 15, n.2, 2022, pp.1-24.
- [29] A. Lozynsky, L. Demkiv, Synthesis of Multicriteria Controller by Means of Fuzzy Logic Approach. *Advances in fuzzy systems*, Nov., 2014, pp. 1-5.
- [30] R. Moezzi, T.M. Vu, M. Tamre, Fuzzy Logic Control for a Ball and Beam System, *International Journal of Innovative Technology and Interdisciplinary Sciences*, vol. 1, n.1, 2018, pp. 39-48.
- [31] Khouili, D., Labbadi, M., Ramzi, M., Lahlouh, I., Design of a Robust Nonlinear PID Controller: Simulation and Experimental Validation for a Computer Aided Aerothermic System, (2022) *International Review of Automatic Control (IREACO)*, 15 (1), pp. 12-19.  
doi:<https://doi.org/10.15866/ireaco.v15i1.21696>
- [32] Romphochai, S., A Novel Adaptive Virtual Inertia Control-Based Adaptive Neuro-Fuzzy to Enhance Frequency Stability of a

- Microgrid with Seamless Transition, (2021) *International Review of Electrical Engineering (IREE)*, 16 (1), pp. 78-94.  
doi: <https://doi.org/10.15866/iree.v16i1.18168>
- [33] B. Alagoz, A. Tepljakov, E. Petlenkov, G. Yeroglu, Multi-loop Model Reference Adaptive Control of Fractional-order PID Control Systems, *The 2017 40th International Conference on Telecommunications and Signal Processing (TSP)*, 05-07 July 2017, Barcelona, Spain.
- [34] Ignatyev, V., Kovalev, A., Spiridonov, O., Kureychik, V., Soloviev, V., Ignatyeva, A., A Method of Optimizing the Rule Base in the Sugeno Fuzzy Inference System Using Fuzzy Cluster Analysis, (2020) *International Review of Electrical Engineering (IREE)*, 15 (4), pp. 316-327.  
doi: <https://doi.org/10.15866/iree.v15i4.16545>
- [35] A. Jamnia, *Design of Electromechanical Products: A Systems Approach*. 1st Edition. Published by CRC Press, 2016, 416 p.
- [36] M. Baghdasaryan, *Methods of Research and Optimization of the Mineral Raw Material Grinding Process*, NOVA science publishers, USA, 2019, 306 p.
- [37] G.G. Tiruneh, A.R. Fayek, V. Sumati, Neuro-fuzzy systems in construction engineering and management research, *Automation in Construction*, vol. 119, 2020, pp. 1-23.
- [38] L. Wang, S.-R. Lu, J. Wen, Recent Advances on Neuromorphic Systems Using Phase-Change Materials, *Nano Review*, vol. 12, 2017, pp. 1-22.
- [39] K. Cpalka, L. Rutkowski, Flexible Takagi-Sugeno Neuro-Fuzzy Structures, *The 5th WSEAS Int. Conf. on Simulation, Modeling and Optimization*, August 17-19, 2005, Corfu, Greece.
- [40] A. Chatterjee, K. Watanabe, An optimized Takagi-Sugeno type neuro-fuzzy system for modeling robot manipulators, *Neural Computing & Applications*, vol. 15, 2006, pp. 55-61.
- [41] Z. Kovacic, S. Bogdan, *Fuzzy Controller Design: Theory and Applications*. 1st Edition, CRC Press, 2005, 416 p.
- [42] D. S. Hooda, V. Raich, *Fuzzy Logic Models and Fuzzy Control*, Alpha Science International Ltd. Oxford, U.K., 2017, 408 p.

## Authors' information

<sup>1</sup>Institute of Energetics and Electrical Engineering, National Polytechnic University of Armenia.

<sup>2</sup>Institute of Information and Telecommunication Technologies and Electronics, National Polytechnic University of Armenia.



**Marinka Baghdasaryan** is a Professor, Doctor of Technical Sciences, Pro-rector and the Head of the "Electrical Machines and Apparatus" Chair of National Polytechnic University of Armenia, the Head of the scientific-research laboratory of Electromechanics and Electrical Radio materials. She has graduated from Yerevan Polytechnic Institute (at present – National Polytechnic University of Armenia, NPUA) qualified as an electrical engineer. In 1992, she received her Ph.D. degree and in 2003 - the Doctor of Science degree in Electrical Engineering. At present, her investigations are devoted to the modeling and design of measuring devices, as well as the control, diagnostics, and optimization of the Electromechanical Systems. She is an Academician of the Engineering Academy of Armenia, and the Editor-in-chief of the NPUA Proceedings – Series "Electrical Engineering and Energetics".

E- mail: [m.baghdasaryan@seua.am](mailto:m.baghdasaryan@seua.am)



**Azatuhi Ulikyan** received an Engineering degree in the field of "Technical Systems Control and Automation" at State Engineering University of Armenia, in 1993. In 2013 she was awarded the Ph.D. in Engineering by the resolution of the RA Supreme Certifying Committee in Automation Systems and Electronics. In 2016, the Academic Council of National Polytechnic University of Armenia awarded Azatuhi Ulikyan the title of Associate Professor in "Informatics, Computer Technology and Automation". Azatuhi Ulikyan has participated as a researcher in many grants conducted by the SCS. She specializes in SISO and MIMO linear, nonlinear control systems modelling and design.

E-mail: [azatuhi.ulikyan@polytechnic.am](mailto:azatuhi.ulikyan@polytechnic.am)



**Vardan Hovhannisyan** received Bachelor's and Master's degrees in Electrical Engineering from the National Polytechnic University of Armenia in 2021 and 2023, respectively. He is currently a postgraduate student at the Chair of Electrical Machines and Apparatuses of the same University. His interests include control, optimization and diagnostics of the electromechanical systems. In this field he conducts research and experiments in the basic laboratory of "Electromechanics and Electrical Radio materials" of the National Polytechnic University of Armenia.

E-mail: [vardan@aragatsltd.am](mailto:vardan@aragatsltd.am)