ANALYSIS OF MODELING METHODS OF LINEAR AND NONLINEAR AUTOMATIC CONTROL SYSTEMS

S.M. Kerimova[1], S.J. Alimamedova[2]

•

Azerbaijan State Oil and Industry University, Baku, Azerbaijan
[1] saida.karimova@asoiu.edu.az; [2] alimammadova.sara@asoiu.edu.az

Abstract

The article discusses the stability of automatic control systems (ACS). The stability of the automatic control system is the main characteristic of the automatic return of the system to its initial state of equilibrium after exposure to certain influencing factors on this system. In other words, it is the property of the system to maintain its resistance to external influences and its efficiency. The issue of reliability is aimed at preventing unforeseen and dangerous consequences of system instability, especially in such diverse fields as aviation, energy, and industry. A stable system ensures more accurate performance of the specified functions and is less prone to probable failure, and they can work for a long time without human intervention. An important place in the issue of determining the stability of ACS is occupied by the identification of errors that occur mainly during transients occurring in systems. The detected error is determined by the difference between the input signal (setpoint) and the input signal. In addition, the error that occurs in the system depends on different types of input signals, so these inputs can be stepwise, linear, etc. they can be typical. It should be noted that bias error analysis is useful only for stable systems. That is, before investigating an error in the system, it is necessary to determine the stability of this system. The article also considered the issue of calculating the error in the system with negative feedback. Using the Matlab/Simulink program, algorithms related to the detection of an error in the ACS are compiled. When studying the issues of ACS stability, the issue of regulating the gain coefficients of various types through a PID (Proportional-Integral-Derivative) regulator is being investigated.

Keywords: automatic control system, stability, excitation effect, transfer function, gain factor, controller

I. Introduction

The stability of an automatic control system is one of the fundamental characteristics that determine its overall effectiveness, operational quality, and long-term safety. In engineering terms, stability refers to the system's inherent ability to automatically return to its initial equilibrium state after it has been subjected to external disturbances, internal fluctuations, or other influencing factors. This means that even if the system experiences shocks, sudden changes in input, or unexpected environmental conditions, a stable system will naturally correct itself and resume its intended behavior without continuous external intervention.

In simpler terms, stability is the essential property that allows the system to resist external impacts and continue performing its intended functions reliably and predictably. Without this capability, even the most advanced automatic control systems could fail under real-world conditions, compromising not only performance but also safety and operational integrity.

But why is stability such an essential requirement for any control system? To answer this question, several key considerations must be highlighted [1-4]:

1. Safety concerns – System instability can lead to unpredictable and potentially hazardous consequences, particularly in critical industries such as aviation, energy production, chemical processing, and manufacturing. In these sectors, even minor instabilities can escalate into major accidents.

2. Accuracy and performance – A stable system is capable of executing assigned tasks with higher precision, ensuring that operational goals are met without excessive deviations or oscillations.

3. Reliability and durability – Stability is directly tied to the system's long-term dependability. A system that maintains stability is less prone to unexpected breakdowns, requires fewer emergency interventions, and can function for extended periods with minimal maintenance. This not only reduces operational costs but also ensures smoother workflows and greater confidence in the system's performance. Unstable systems, by contrast, can wear out components faster due to erratic operation, leading to downtime, increased maintenance, and reduced service life.

By mastering the fundamental principles of control system stability, engineers can design solutions that are not only more reliable and efficient but also inherently safer. Stability knowledge enables them to predict system behavior under various conditions, adjust design parameters appropriately, and prevent potential problems before they occur.

Furthermore, the study of stability is far from a purely theoretical exercise—it plays a critical role in a wide range of practical applications, including industrial automation, robotics, aerospace engineering, power systems, transportation technologies, and many other fields. As technology advances, these applications increasingly demand higher precision, faster response times, and greater resilience, all of which depend on robust system stability.

The topic of stability also opens a broad spectrum for exploration. Numerous aspects can be examined, such as different methods for analyzing system stability, the influence of nonlinear effects that complicate traditional stability assessments, and the practical application of stability theories across diverse industries. These areas not only expand academic knowledge but also provide a strong incentive for further research, technological innovation, and the creation of more advanced and resilient control systems.

Purpose. Relevance of the problem and related studies. Modern automatic information and control systems (ACS) are highly complex structures, incorporating numerous interconnected subsystems and components. This growing complexity introduces significant challenges in system modeling and analysis. With the rapid evolution of technology, the integration of advanced tools such as artificial intelligence, adaptive algorithms, and sophisticated software platforms further raises the need for improved approaches to ensure and evaluate stability [5-8].

In contemporary engineering, the stability of both linear and nonlinear systems remains a key area of study. Traditional analytical methods are constantly being refined, while new techniques are being developed to address the unique challenges posed by increasingly dynamic and intelligent control systems. The aim of the present article is to investigate the fundamental issues related to the stability of control systems. Specifically, the focus is on:

- identifying and discussing the main parameters that define the stability of various types of systems;
- analyzing typical scenarios and equivalent system models that are used to simplify stability studies;
- emphasizing the importance of mathematical tools and calculations in evaluating system stability and predicting system behavior under different conditions.

By addressing these aspects, this study contributes to a broader understanding of how stability principles can be applied to modern control systems, ensuring that they meet the demands of safety, precision, and reliability in a rapidly changing technological landscape [9-11].

II. Materials and methods

In determining the stability of ACS, the determination of errors arising during the transition processes occurring in the systems plays an important role. The determined error is determined by the difference between the input signal (given value) and the input signal. In addition, the error arising in the system depends on different types of input signals, since these input signals can be step, linear, etc. types. It should be noted that the analysis of the determined error is useful only for stable systems. That is, before examining the error in the system, the stability of that system must be determined. Based on the value of the output signal, we can calculate the error using the transfer function of an open or closed loop with the following expressions:

$$e(\infty) = \lim_{s\to 0} sE(s) = \lim_{s\to 0} \frac{sR(s)}{1+G(s)} \tag{1}$$

$$e(\infty) = \lim_{s\to 0} sE(s) = \lim_{s\to 0} sR(a)(1-T(s)) \tag{2}$$

Using the Laplace transform, we obtain the following expressions for different input signals, for example [4]:

- When the "Step" input signal R(s)=1/s:

$$e(\infty) = \frac{1}{1+\lim\limits_{s\to 0} G(s)} = \frac{1}{1+k_s} \Rightarrow k_s \lim_{s\to 0} G(s) \tag{3}$$

- When the "Ramp" input signal R(s)=1/s²:

$$e(\infty) = \frac{1}{\lim\limits_{s\to 0} sG(s)} = \frac{1}{k_v} \Rightarrow k_v = \lim_{s\to 0} sG(s) \tag{4}$$

- Parabolic input signal R(s) = 1/s³:

$$e(\infty) = \frac{1}{\lim\limits_{s\to 0} sG(s)} = \frac{1}{k_v} \Rightarrow k_v = \lim_{s\to 0} sG(s) \tag{5}$$

Usually, when investigating the stability of systems, the distortions occurring in these systems should also be taken into account. Let us assume that we need to compensate for the distortion in any control system, in other words, the system has been introduced with unusable signals (Fig. 1).

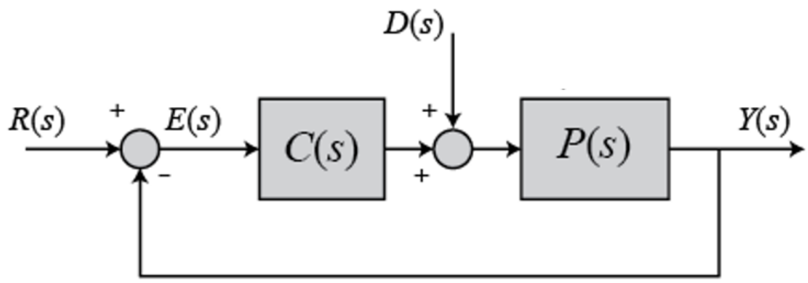

Figure 1: *Negative feedback circuit diagram*

In order to determine the error caused by the excitation signal D(s) shown in Fig. 1 in the system, we can use the following expression:

$$e(\infty) = \lim_{s\to 0} sE(s) = \frac{1}{\lim\limits_{s\to 0} \frac{1}{P(s)} + \lim\limits_{s\to 0} G(s)} \tag{6}$$

It should be noted that the signal entering the G(s) controller is not actually considered the fixed error E(s). By error, we mean only the difference between the given value and the current value: E(s) = R(s) - Y(s) [12-16].

In the feedback loop depicted in Fig. 2, in the presence of a transfer function H(s), the signal R(s) is distorted by the effect of that transfer function.

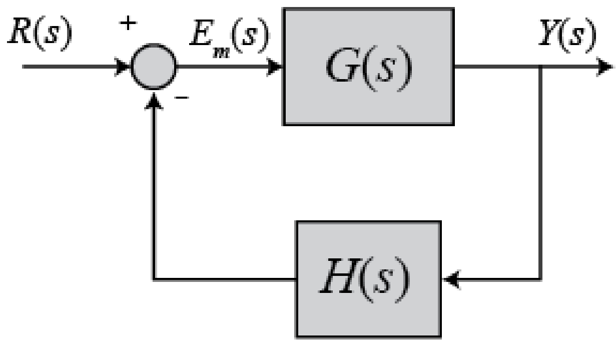

Figure 2: *Scheme of ACS in the presence of transfer function H(s)*

In this case, the structural diagram of the control system under study should be drawn as shown in Fig. 3.

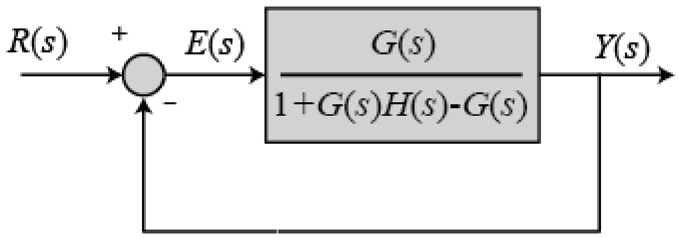

Figure 3: *The equivalent circuit of the ACS depicted in Fig. 2*

To illustrate the process more clearly, let's look at the issue of investigating the stability of an ACS using the MATLAB program. Let's assume that the transfer function of the controller is calculated by the following expression:

$$G(s) = \frac{k(s+3.5)(s+5.3)}{s(s+8)(s+9)} \tag{7}$$

As can be seen from Fig. 3, the transfer function of the feedback loop is unity. In this case, there will be no continuous error when a step signal is input to the system, but if a parabolic signal is input, this will cause an infinite error [17-21]. That is, the error in the system will be eliminated only by the influence of the step signal. First, we assume the amplification factor k=1 in expression (7) and write the corresponding algorithm from the MATLAB command window.

```
s = tf('s');
G = ((s+3.5)*(s+5.3))/(s*(s+8)*(s+9));
T = feedback(G,1);
t = 0:0.1:25;
u = t;
[y,t,x] = lsim(T,u,t);
plot(t,y,'r',t,u,'g')
xlabel('Time (sec)')
ylabel('Amplitude')
title('Input-red, Output-gree')
```

Then we get the input-output characteristic shown in Fig. 4. As can be seen from this figure, we can see that the output signal is about 16 times the input signal during a period of 20 seconds (the decision error is about 4), that is, the decision error of this system is quite large. In this case, we can adjust the gain coefficients that bring the system to a stable state by using a PID (Proportional-Integrator-Derivative) controller. For this purpose, the model shown in Fig. 5 is designed [22-25].

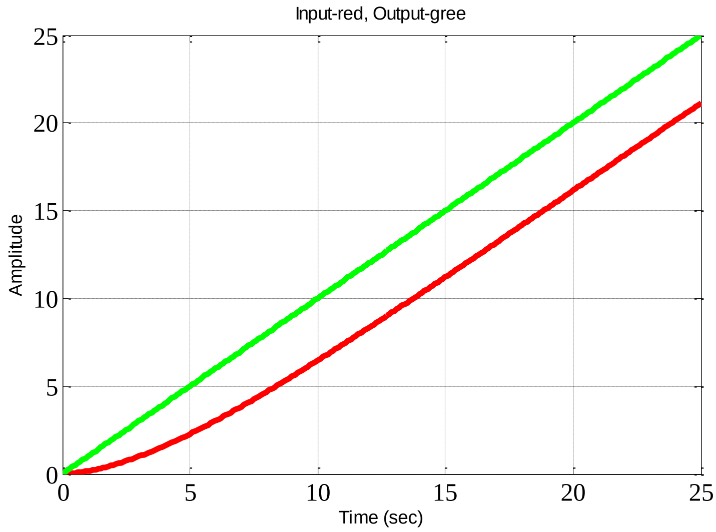

Figure 4: *Time characteristics of ACS input-output signals*

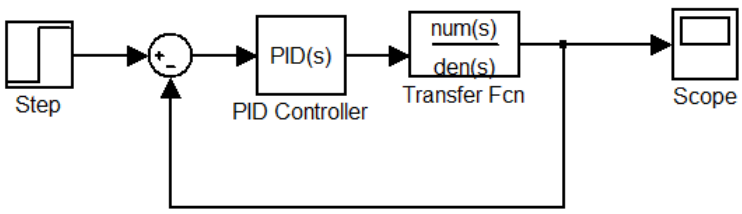

Figure 5: *Simulink model of ACS*

The description of the parameters window of the PID controller included in the Simulink model of the ACS is shown in Fig. 6.

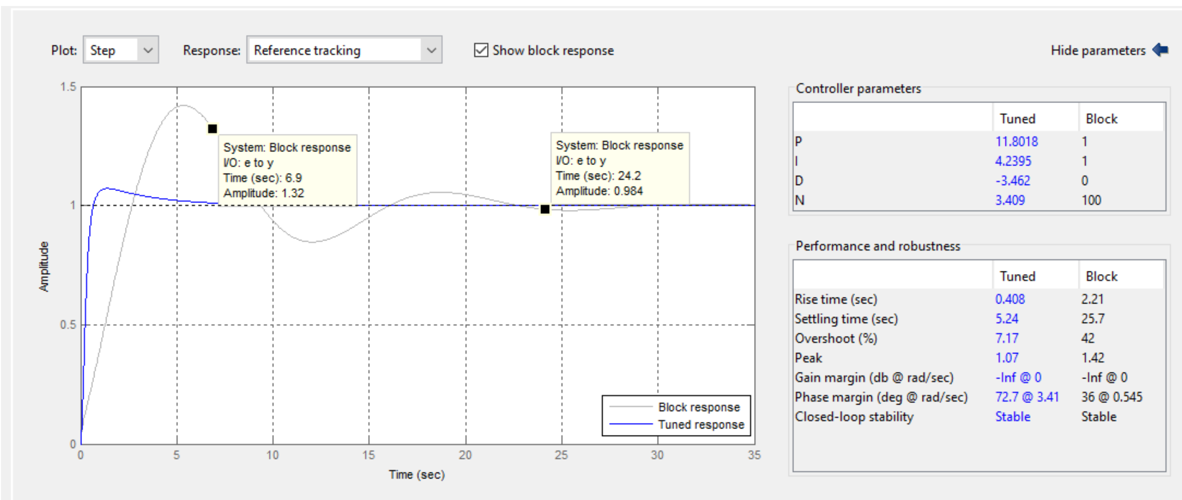

Figure 6: *Description of the PID controller parameters window*

In Fig. 6, "Block response" is the system response, and "Tuned response" is the system response corresponding to the value of the gain coefficients proposed by the PID controller. In Fig. 7, the values of the gain coefficients set for the stable system of the PID controller are given [26-28].

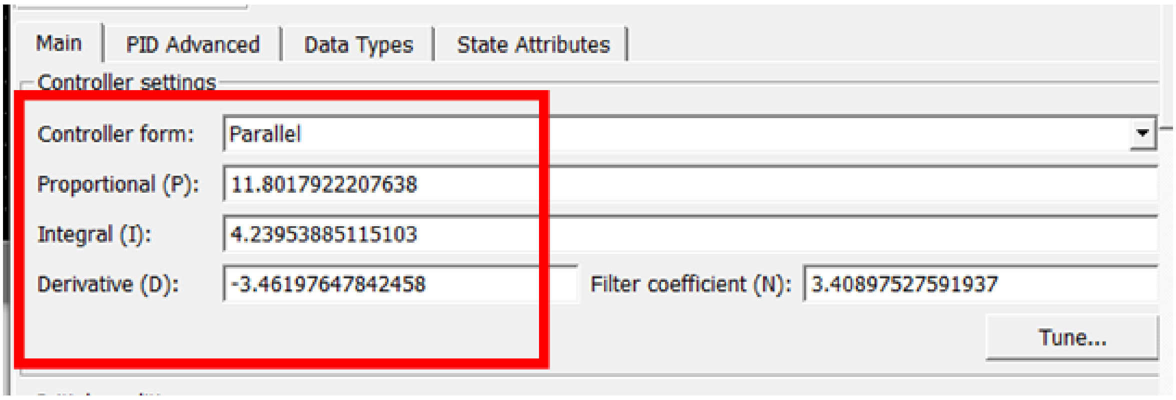

Figure 7: *Values of the PID controller's adjustable gain coefficients for a stable system*

III. Conclusions

First and foremost, the study highlighted that the determination of system stability must precede any error analysis. This approach is essential because instability can distort system behavior to such an extent that meaningful error calculations become impossible or irrelevant.

A key focus was placed on the relationship between input signals and system errors. It was established that the error — defined as the difference between the desired (given) input value and the actual system output — is significantly influenced by the type of input signal. Since input signals can vary, the resulting transient errors also exhibit different characteristics. This means that system designers and engineers must take into account not only the magnitude of the error but also its dynamic behavior under diverse operational conditions.

The study further explored the calculation and detection of system errors using advanced modeling and simulation tools. By leveraging MATLAB/Simulink, a set of algorithms was developed to accurately identify and quantify errors that arise in ACS during transient processes. These algorithms provide a practical framework for engineers to simulate various operating scenarios, analyze system responses, and refine designs before real-world implementation.

Additionally, the research examined the role of PID controllers in enhancing system stability and minimizing errors. The process involved the adjustment of different types of amplification coefficients (proportional, integral, and derivative gains) to optimize system response. The findings reaffirmed that proper tuning of these parameters can significantly improve both stability and overall system performance, effectively reducing steady-state and transient errors.

In summary, the study not only confirmed the central role of stability in ACS analysis but also demonstrated practical methods for evaluating and improving system performance. By combining theoretical stability considerations with simulation-based error detection and control strategies, a comprehensive approach was established. This integrated perspective is invaluable for the future development of ACS, ensuring they remain reliable, precise, and adaptable in increasingly complex technological environments.

References

[1] S.A. Khanahmedova, "Methods of modeling linear and nonlinear systems of automatic control", PROCEEDINGS OF AZERBAIJAN HIGH TECHNICAL EDUCATIONAL INSTITUTIONS, Vol. 37 (05) issue 02, 2024, pp. 223-241

[2] Z.A. Hasanov, S.A. Khanahmedova, "Management Theory", Textbook, ASOIU publication, Baku-2022, p. 166

[3] S.A. Khanahmedova, S.Y. Shikhaliyeva, S.J. Alimamedova, S.M. Kerimova, "Some issues of designing a hybrid electric machine", International Journal on "Technical and Physical Problems of Engineering", (IJTPE), Vol. 15, No3, pp.45-52, September 2023

[4] Rao V.Dukkipati, "Analysis and design of Control systems", New age international publish., New Dehli, 2006, pp.269

[5] Khanahmedova S.A., "Investigation of some electrical circuits using simulation in MATLAB/Simulink", Vestnik nauki journal, № 2 (59) Issue 1, 2023, pp. 125-129

[6] Aminzare Z., Sontag E.D., "Synchronization of Diffusively-Connected Nonlinear Systems: Results Based on Contractions with Respect to General Norms", IEEE Trans. Netw. Sci. Eng., 2014, 1, pp. 91–106

[7] S.A. Khanahmadova, A.I. Mamedov, "Mathematical analysis of regulated dc motor of hybrid system". International Journal on "Technical and Physical Problems of Engineering" (IJTPE), Vol. 15, No4, pp.19-24, December 2023

[8] Knights V., Petrovska O., Prchkovska M., "Enhancing Smart Parking Management through Machine Learning and AI Integration in IoT Environments", In Navigating the Internet of Things in the 22nd Century—Concepts, Applications, and Innovations [Working Title], IntechOpen: London, UK, 2024

[9] S.A. Khanakhmedova, S.M. Kerimova S.J. Alimamedova, "Mathematical modeling of the operation of a three-phase power transformer at low voltage quality", International Journal on "Technical and Physical Problems of engineering" (IJTPE), Vol.14, No 4, pp.225-232, December 2022

[10] Mammadov N. S., Mukhtarova K. M., "METHODOLOGY FOR ASSESSING THE RELIABILITY OF AGS BASED ON RENEWABLE ENERGY SOURCES", Reliability: Theory & Applications, Volume 19, No 4 (80), pp.648-653, 2024

[11] Sultanov Rafig, Elbrus Ahmedov and Nadir Aliyev, "Implementation of the maximum permissible overload capacity of a DC motor", Reliability: Theory & Applications 20.1 (82), 2025, pp. 728-733

[12] Meindl M., Lehmann D., Seel T., "Bridging Reinforcement Learning and Iterative Learning Control: Autonomous Motion Learning for Unknown", Nonlinear Dynamics. Front. Robot. AI 2022, 9, 793512

[13] Nijat Mammadov, Ilkin Marufov, Saadat Shikhaliyeva, Gulnara Aliyeva, Saida Kerimova, "Research of methods power control of wind turbines", Przeglad Elektrotechniczny, No 5, 2024, pp. 236-239, DOI: 10.15199/48.2024.05.44

[14] S.A. Khanahmadova, A.I. Mamedov, "Structural design and theoretical studies of operation of a drive Hybrid Electric Machine", International Journal on "Technical and Physical Problems of Engineering (IJTPE), Vol. 16, No1, pp.1-6, March 2024

[15] Elshad Safiyev, Ilham Rahimli, Nijat Mammadov, "Method of qualitative impregnation of electric motor windings", Przegląd Elektrotechniczny, No 8, 2024, pp.238 -240, DOI: 10.15199/48.2024.08.48

[16] Rzayeva S.V., Ganiyeva N.A., Piriyeva N.M., "Modern approaches to electrical equipment diagnostics", International Journal on technical and Physical Problems of Engineering (IJTPE), Issue 58, Vol. 16, No 1, pp. 182-189, 2024

[17] Khanna A., Kaur S., "Internet of Things (IoT), Applications and Challenges: A Comprehensive Review", Wirel. Pers. Commun., 2020, 114, pp. 1687–1762

[18] Ilkin Marufov, Najiba Piriyeva, Nijat Mammadov, Shukufa Ismayilova, "Calculation of induction levitation vertical axis wind generator-turbine system parameters, levitation and influence loop" Przegląd Elektrotechniczny, 2024 , No.2, pp.135-139, DOI: 10.15199/48.2024.02.27

[19] N.M.Piriyeva, G.S. Kerimzade, "Mathematical model for the calculation of electrical devices based on induction levitators", International Journal on technical and Physical Problems of Engineering (IJTPE), Issue 55, Vol.15, No.2, pp.274-280, June 2023

[20] Nadir Aliyev, Elbrus Ahmedov, Samira Khanahmedova, Sona Rzayeva, "Synthesis of the Exact Parameters of the Electromagnetic Brake of a Wind Electric Installation", Przeglad Elektrotechniczny journal, № 10, Poland, 2023, pp. 120-124, DOI: 10.15199/48.2023.10.123

[21] I.N.Rahimli, N.S. Mammadov, R.K. Karimova, "Analysis of wind turbine control algorithms as part of a wind power plant", International Journal on technical and Physical Problems of Engineering (IJTPE), Issue 62, Vol.17, No.1, pp.81-90, March 2025

[22] Yilmaz N., Wu J.Y., Kazanzides P., Tumerdem U., "Neural Network-Based Inverse Dynamics

Identification and External Force Estimation on the da Vinci Research Kit", In Proceedings of the 2020 IEEE International Conference on Robotics and Automation (ICRA), Paris, France, 31 May–31 August 2020

[23] A.I. Abdulkadyrov, S.C. Osmanov, N.A. Aliyev, G.A. Aliyeva, "Features of Calculating the Parameters of Special Electric Machines", News of Azerbaijan Higher Technical Schools, No. 5, Issue 87, pp. 55-61, Baku, Azerbaijan, 2013

[24] Z.A. Hasanov, S.A. Khanahmedova, "Regulation Technique", Textbook, ASOIU publication, Baku-2016, p. 130.

[25] Linder A., Kennel R., "Model predictive control for electrical drives", 2005 IEEE 36th Power Electronics Specialists Conference, IEEE, 2005, pp. 1793-1799

[26] Frey G., Hussain T, "Modeling techniques for distributed control systems based on the IEC 61499 standard-current approaches and open problems", In Proceedings of the 2006 8th International Workshop on Discrete Event Systems, Ann Arbor, MI, USA, 10–12 July 2006, pp. 176–181

[27] Simonazzi M., Delmonte N., Cova P., Menozzi R., "Models for MATLAB Simulation of a University Campus Micro-Grid", Energies 2023, 16, 5884

[28] S.A. Khanahmedova, S.M. Kerimova, S.J. Alimamedova, Z.Sh. Huseynova, "Some issues related to modeling electrical circuits on the MATLAB platform", Problems of Energy, No 2, Baku 2022, pp. 166-170