Simulation of Dynamic Characteristics of a Trigenerative Climate Control System Based On Peltier Thermoelectric Modules

Vasilyev G. S., Kuzichkin O. R., Surzhik D. I.

[1]*Vladimir State University named after Alexander Grigoryevich and Nikolai Grigorievich Stoletovs,*
Vladimir, 600000, Russia

Abstract
The application of the principle of trigeneration allows to simultaneously provide electricity to power electronic devices, as well as heat and cold to create the necessary microclimate of the premises and increase efficiency compared to separate cooling and heating systems. The use of Peltier thermoelectric modules (TEM) as part of trigenerative systems allows for smooth and precise control of the temperature regime, high manufacturability and reliability due to the absence of moving parts, resistance to shock and vibration, and small weight and size parameters of the system. One of the promising areas of improvement of trigenerative systems is their modeling and optimization based on the automatic control theory. A block diagram and functional model of an energy-saving trigenerative climate control system based on Peltier modules are developed, and the transfer functions of an open and closed system are obtained. The simulation of the transient characteristics of the system with varying parameters of the components is performed. The directions for improving the quality of transients in the climate control system are determined, as well as the prospects of the proposed methodology for modeling and analyzing control systems operating in substantially nonlinear modes.

***Keywords**:*
energy trigeneration, thermoelectrics, Peltier effect, thermoelectric modules, transfer function, dynamic characteristic.

1. Introduction

The application of the trigeneration principle [1] allows to simultaneously obtain electricity to power electronic devices, as well as heat and cold to create the necessary microclimate of the premises. Studies have shown that the combined cooling and heating mode of a trigeneration system can be significantly more efficient than an independent cooling and heating system, which justifies the complexity of the design [2]. A separate direction is the integration of TE cooling systems in facilities based on solar energy (refrigeration systems, as well as air conditioning systems in a wide temperature range) [3].

The use of thermoelectric modules (TEM) as part of trigenerative systems allows for smooth and precise control of the temperature regime, high manufacturability and reliability due to the absence of moving parts, resistance to shock and vibration, and small weight and size parameters of the system [4-9]. Aboelmaaref et al. [10] identified the best standards for the use of solar energy with technological cooling and air conditioning systems, such as thermoelectric and thermoelectronic, for large-scale applications, since its productivity has reached at least 30%, which is very promising.

The efficiency of thermoelectric and thermoemission characteristics can be improved by optimizing heat exchange and improving the configuration of products in thermoelectric and thermoemission systems, which facilitates the use of thermoelectric and thermoemission systems for use in refrigeration and air conditioning in remote areas [11-18]. Another promising direction for improvement of trigenerative systems is their modeling and optimization based on the automatic control theory [19-21].

The aim of the work is to develop and apply a methodology for modeling the dynamic characteristics of a trigenerative climate control system based on Peltier thermoelectric modules.

1.1. Block diagram of an energy-saving trigenerative climate control system based on TEM

The operation principle of a trigeneration energy-saving climate control system for agricultural enterprises using thermoelectric batteries operating in direct (TEM1) and inverse modes (TEM2) is shown in Figure 1. In this case, the operation of the system and the main power supply of the main consumers of electricity (E1) is carried out from a thermal power plant (TEM) running on gas engine fuel (GEF).

Manuscript received June 5, 2021
Manuscript revised June 20, 2021
https://doi.org/10.22937/IJCSNS.2021.21.6.33

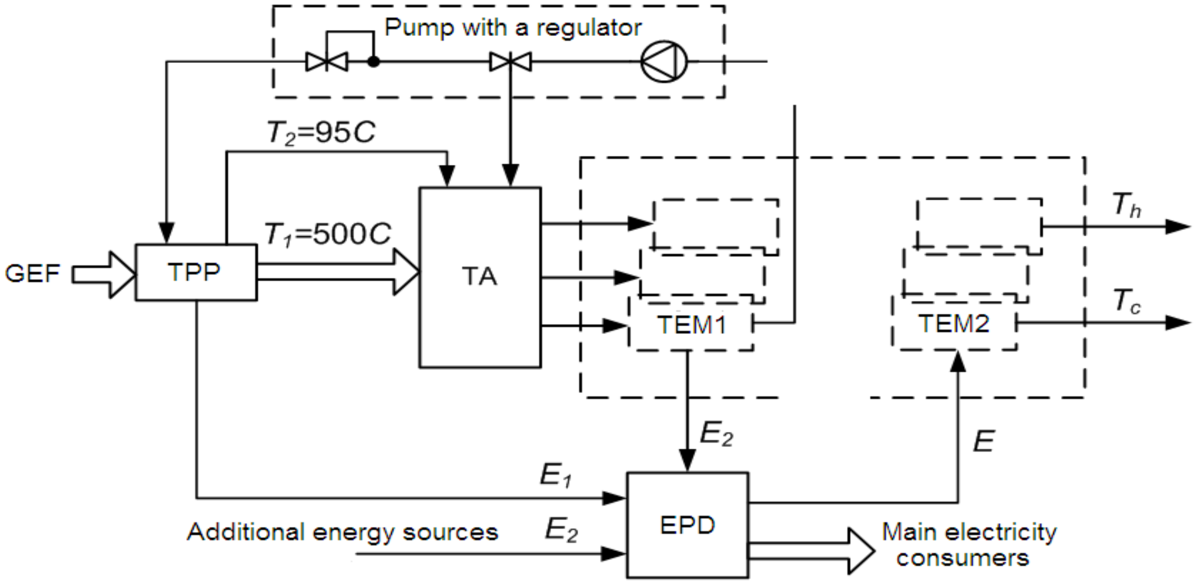


Fig. 1. Structure of the trigeneration energy-saving climate control system for agricultural enterprises

In this case, the heat generated by the thermal power plant (TPP) is utilized at the expense of a two-circuit thermal accumulator of the distributor (TA) with terminals to the TEM1, built on Peltier modules and generating electricity E2. Providing local places with required climatic conditions (temperatures of a hot and cold side Th and Tc) is carried out at the expense of TEM2, which also uses Peltier modules and is supplied from a electric power distributor (EPD).

A block diagram of an energy-saving trigeneration system for a single control object (n=1) is shown in Figure 2. If there are several control objects, a power supply source is common to all of them. The diagram shows: CCS1 – climate control system, TEM$_1$ – system of thermoelectric modules, VS$_1$ – ventilation system, PS$_{1i}$ – point source of cold or heat, D$_{1i}$ – climate detector, I$_{CONTR1I}$ – control influences for thermoelectric modules, T$_{PS1i}$ – temperature of a point source of heat or cold, T$_{D1j}$ – temperature recorded by a climate detector. The differentiation operator $p=d/dt$ allows to take into account the dynamic properties of each object of the system in its transfer function.

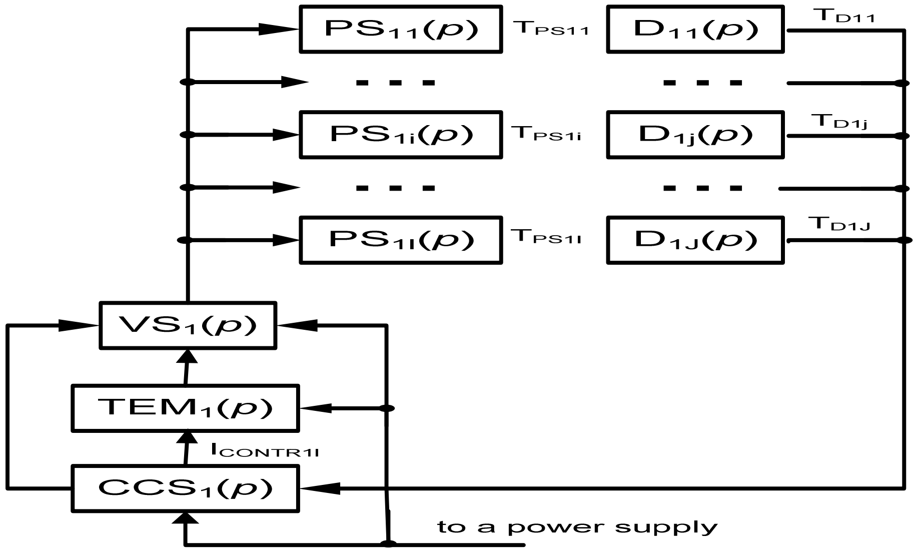


Fig. 2. Block diagram of an energy-saving trigeneration system for monitoring a single TEM

The microclimate is controlled by the climate control system, which controls the TEM by current $I_{CONTRnl}$ which depends on the desireable temperatures T_{DESnl} and the measurement results of the climate detectors T_{Dnj}

$$I_{CONTRnl} = f(T_{DESnl}, T_{Dnj}).$$

The inertia of the climate detector is approximately described by a first-order differential equation

$$T_{Dnj} + \tau_{nij} \frac{dT_{Dnj}}{dt} = k_{nij} T_{PSni}$$

where τ_{nij} is the time constant of the detector, or by the equivalent transfer function of the aperiodic link

$$H_{nij}(p) = \frac{T_{Dnj}}{T_{PSni}} = \frac{k_{nij}}{1 + \tau_{nij} p}. \tag{1}$$

1.2. Functional model of the TEM-based climate control system

An example of a functional model of a trigenerative system based on TEM is shown in Fig. 3. The transfer functions of the blocks of the model **H**(p) are given by vectors, the number of the vector element determines the channel number. The following designations are accepted: $\mathbf{T}_{DES}$ – desired temperature (input influence), $\mathbf{T}_{noise}$ – noise or interference, $\mathbf{T}_{PS}$ – the temperature of a point source of heat or cold, $\mathbf{T}_{D}$ – the temperature recorded by a climate detector.

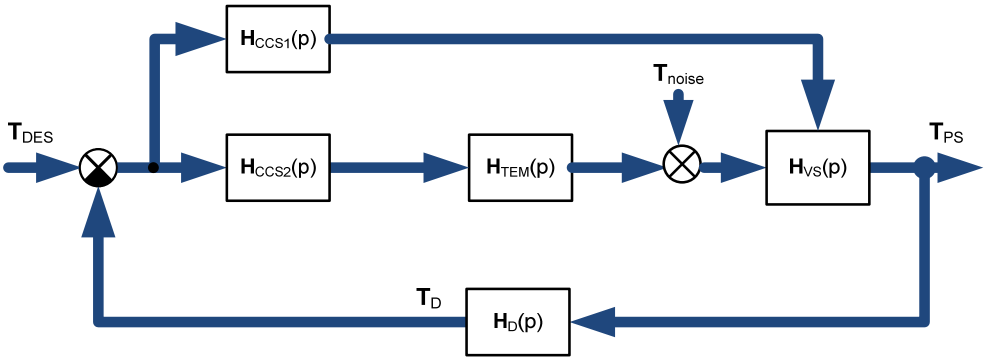


Fig. 3. Functional model of an energy-saving trigenerative climate control system based on TEM

The transfer function of one control channel of the system (Fig. 3) for the influence T_{DES} has the form

$$H(p) = \frac{T_{PS}(p)}{T_{DES}(p)} = \frac{H_{open}(p)}{1 + H_{open}(p) H_D(p)}, \tag{2}$$

$$H_{open}(p) = H_{CCS1}(p) + H_{CCS2}(p) H_{TEM}(p) H_{VS}(p)$$

where is the transfer function of the open system. The transfer function of the proportional-integral (PI) controller used as the controller of the climate control system has the form

$$T_{CCS}(p) = k_p + \frac{k_i}{p}. \tag{3}$$

The transfer functions of the TEM and the climate control detector are approximately described by models of first-order inertial links

$$T_{TEM}(p) = \frac{k_{TEM}}{1 + T_{TEM} p}, \quad T_d(p) = \frac{k_d}{1 + T_d p}, \tag{4}$$

where k is the link transfer coefficient, and T is the link time constant. In the analysis, it may be necessary to take into account nonlinearities of the TEM (for example, dependence of the junction temperatures on the value of the control current) or other blocks [22-24]. For this purpose, an approach based on piecewise linear approximation of the TEM amplitude characteristic and crosslinking of partial solutions on separate linear sections can be used [25-26]. The approach will allow us to apply linear theory and analytically investigate the dynamic modes of control systems with substantially nonlinear TEM [27].

The transfer function of the ventilation system without taking into account its inertia has the form

$$T_{VS}(p) = k_v. \tag{5}$$

Taking into account the expressions (3)-(5), the transfer function of the open system takes the form

---

Manuscript received June 5, 2021
Manuscript revised June 20, 2021
https://doi.org/10.22937/IJCSNS.2021.21.6.33

$$H_{open}(p) = k_{p1} + \frac{k_{i1}}{p} + \frac{k_v k_{TEM} \cdot \left(k_{p2} + \frac{k_{i2}}{p} \right)}{1 + k_{TEM}\, p},$$

(6)

and the transmission coefficient of the system as a whole (2) in the absence of the first climate control channel CCS1 (k_{i1}=k_{p1}=0) is written as

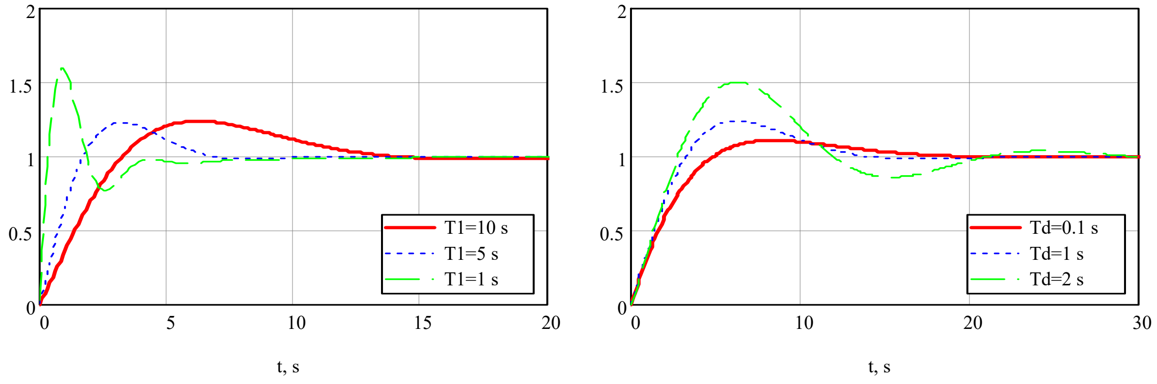
$$H(p) = \frac{k_v k_{TEM} \cdot (1 + T_d p)(k_{i2} + k_{p2} p)}{k_d k_{i2} k_v k_{TEM} + (1 + k_d k_{p2} k_v k_{TEM})p + (k_{TEM} + T_d)p^2 + k_{TEM} T_d p^3}$$

. (7)

1.3. Simulation of dynamic modes of the TEM-based climate control system

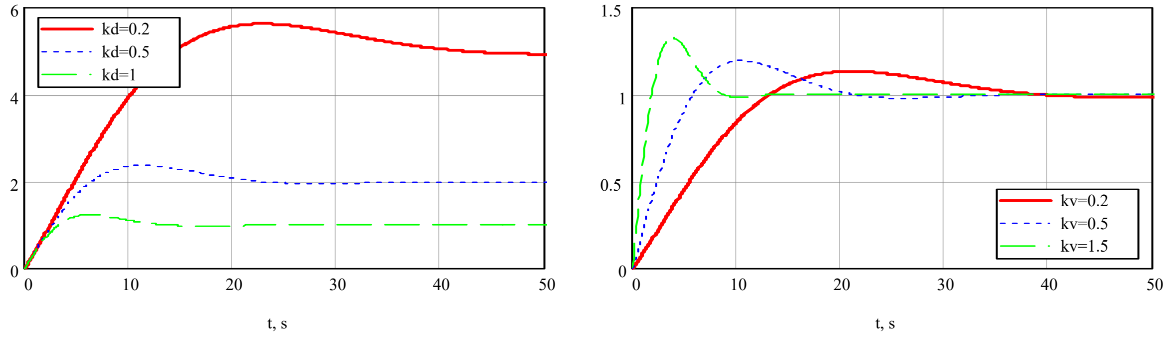
Based on the proposed approach, the transient characteristics of the TEM-based climate control system are modeled. The Heaviside function $T_{DES}(t) = 1(t)$, its operator image $T_{DES}(p) = 1/p$ is taken as an input influence. The following values of the system parameters are accepted: the transmission coefficients of the controller CCS1 k_{i1}=k_{p1}=0 (the first channel is missing), the coefficients of CCS2 k_{i2}=1 and k_{p2}=4, the transmission coefficient of TEM k_{TEM}=1, the transmission coefficient of the ventilation system k_v=0.9, the transmission coefficient of the climate detector k_d=1, the time constant of TEM T_{TEM} =10 s, the time constant of the climate detector T_d=1 c.

The simulation results are shown in Fig. 4-6. The analysis of the obtained dependences shows that with an increase in T_{TEM} (Fig. 4a) and an increase in k_v (Fig. 5b), the control time decreases, but the damping factor of the transient process increases. With an increase in T_d (Fig. 4b), k_{i2} (Fig. 6a) and k_{p2} (Fig. 6b), the quality of the transition process deteriorates in both parameters: an increase of the control time and an increase of the damping factor. The increase in k_d (Fig. 5a) causes an increase of the control time, damping factor, and steady-state value.



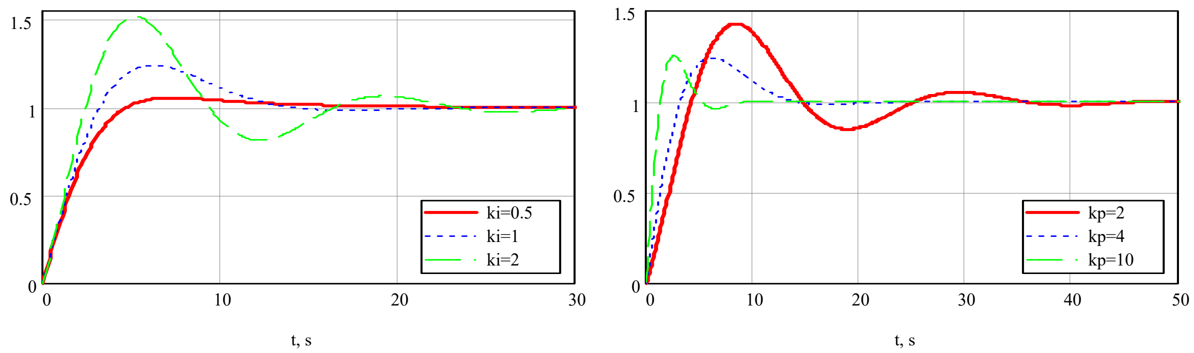
a) b)

Fig. 4. Transient characteristics of the TEM-based climate control system: a) with different time constant of TEM (T1); b) with different time constant of the climate detector (Td)



a) b)

Fig. 5 . Transient characteristics of the TEM-based climate control system: a) with different gain of the climate detector (kd); b) with different gain of the ventilation system (kv)



a) b)

Fig. 6. Transient characteristics of the TEM-based climate control system: a) with different inertia coefficient of CCS2 (ki); b) with different proportionality coefficient of CCS2 (kp)

2. Conclusion

A new approach to modeling the dynamic characteristics of climate control systems based on Peltier thermoelectric modules is developed. It is a fairly simple and convenient tool for studying characteristics of such systems, their quality indicators, and can also be used to solve optimization and synthesis problems, both for single- and multi-channel systems. A block diagram and functional model of an energy-saving trigenerative climate control system based on Peltier modules are presented, and the transfer functions of an open and closed system are obtained. The transient characteristics of the system are modeled while varying the parameters of the component links: the transmission coefficients of the controller, the Peltier module, the ventilation system kv=0.9, the climate detector, as well as the time constants of the Peltier module and the climate detector. The simulation showed directions for improving the dynamic properties of the system, namely, reducing the control time and damping factor, as well as selecting the steady-state value of the transition process.

With a significant nonlinearity of the control object (Peltier module) or other circuit blocks, piecewise linear approximation of the amplitude characteristics of nonlinear blocks and crosslinking of particular solutions on separate linear sections can be used, which allows to apply linear theory and analytically study the dynamic modes of control systems with significantly nonlinear modules for required temporal changes of the desired temperature.

Acknowledgements

The article was prepared as part of the state task "Research and development of complex energy-saving and thermoelectric regenerative systems" application number 2019-1497, subject number FZWG-2020-0034.

References

[1] Galimova L. V., Slavin R. B. Analysis of the efficiency of an energy-saving trigeneration system / Refrigeration equipment - No. 3. - p. 16-19. (2012).

[2] Wang, J.; Wu, J.; Zheng, C. Analysis of trigeneration system in combined cooling and heating mode. Energy and Buildings, 72, pp. 353–360. (2014).

[3] Wang RZ, Dai YJ. Solar thermoelectric refrigerator. Patent No. 01239142, 5, China. (2001).

[4] Wei He, Jinzhi Zhou, Jingxin Hou, Chi Chen, Jie Ji, Theoretical and experimental investigation on a thermoelectric cooling and heating system driven by solar, Applied Energy 107 - 89-97. (2013).

[5] Hongxia Xia, Lingai Luob, Gilles Fraisseb11, Development and applications of solar-based thermoelectric technologies, Renewable and Sustainable Energy Reviews, 923-936; (2007).

[6] Dai YJ, Wang RZ, NiL, Experimental investigation on a thermoelectric refrigerator driven by solar cells, Renewable Energy 28:949–59. (2003).

[7] Hongxia Xia, Lingai Luob, Gilles Fraisseb, Development and applications of solar-based thermoelectric technologies, Renewable and Sustainable Energy Reviews, 11 923-936. (2007).

[8] van Sark WGJHM. Feasibility of photovoltaic - thermoelectric hybrid modules. Appl Energy;88:2785–90. (2011).

[9] Hara T, Azum H. Cooling performance of solar cell driven, thermoelectric cooling prototype headgear. Appl Therm Eng 1998;18:1159–69.

[10] M.Aboelmaaref, Moustafa & Askalany, Ahmed & Harbi, Khalid. Solar thermoelectric cooling technology. (2017).

[11] Gorobets N.V., Ohrem V.G. Peltier thermoelectric cooler with additional conductive element / Applied physics. - № 4. - Pp. 124-127. (2007).

[12] Zone A.P. Determining the conditions for obtaining the maximum energy efficiency of the Peltier element / News of Southwestern state University. –№3(20). -Pp. 153-158. (2016).

[13] Anatychuk L.I.Thermoelements and thermoelectric devices. - Kiev– 768p. (1979).

[14] Evdulov O.V. Development of devices and systems for cooling based on high-current thermoelectric energy converters, Dissertation for the degree of Doctor of Technical Sciences, Makhachkala. - 330 p. (2019).

[15] Gnusin P.I. Study of the Peltier element efficiency in various operating modes / Video science. - №1(1).–Pp. 20-27. (2016).

[16] Ohrem V.G. Thermoelectric cooling using the Peltier effect / Applied physics. - № 5. - Pp. 123-126. (2011).

[17] Ohrem V.G. New Peltier thermoelectric coolers for deep cooling / Applied physics. - № 4. - Pp. 121-127. (2006).

[18] Orlov M. E. Theoretical foundations of heat engineering. Heat exchange / Ulyanovsk State Technical University. - Ulyanovsk : UlSTU, - 204 p. (2013).

[19] Grinkevich V. A. Synthesis of a temperature controller for Peltier element // Collection of scientific works NSTU. – No 1 (94). – P. 7-31. – DOI: 10.17212/2307-6879-2019-1-7-31. (2019).

[20] Grinkevich V. A. Synthesis of the current controller for Peltier element // Collection of scientific works NSTU. – No 3-4 (93). – P. 16-39. – DOI: 10.17212/2307-6879-2018-3-4-16-39. (2018).

[21] Mirabbasi, D. A Comparison of Several Approaches to Load Frequency Control of Multi Area Hydro-Thermal System. Journal of Research in Science, Engineering and Technology, 3(04), 24-30, (2015).

[22] Vasilyev, G.S., Kuzichkin, O.R., Surzhik, D.I. Method for modeling dynamic modes of nonlinear control systems for thermoelectric modulesAdvances in, Dynamical Systems and Applications, 15 (2), pp. 187-197. DOI: 10.37622/ADSA/15.2.2020.187-197. (2021).

[23] Surzhik, D.I., Kuzichkin, O.R., Vasilyev, G.S. An integrated approach to the construction of energy-saving trigeneration systems for objects of the agro-industrial complex, International Journal of Engineering Research and Technology, 13 (12), pp. 4622-4626. (2021)

[24] Surzhik, D.I., Vasilyev, G.S., Kuzichkin, O.R., Konstantinov, I.S. Construction of energy-saving cooling and thermoelectric regenerative systems based on peltier modules (2020) International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management, SGEM, August (4.1), pp. 37-44. (2020).

[25] Jozdaemi, E., & Golchin, A. The Effects of Iron Fertilization and sulfuric acid Application in Irrigation water on Root Growth and Chemical composition of Bean cultivars in a Calcareous soil. International Journal of Forest, Soil and Erosion (IJFSE), 7(1), 11-16. (2017).

[26] Vasilyev, G.S. Analysis of dynamic characteristics of the nonlinear amplitude-phase converter at complex input influence / G.S. Vasilyev, I.A. Kurilov, S.M. Kharchuk, D.I. Surzhik // International Siberian Conference on Control and Communications, SIBCON 2013. – Catalog Number: CFP13794-CDR. SCOPUS, IEEEXplore, ISBN: 978-1-4799-1062-5/13/2013 IEEE. – p. 6693641. DOI: 10.1109/SIBCON.2013.6693641. (2013).

[27] Chapnevis, A., Güvenç, I., & Bulut, E. Traffic Shifting based Resource Optimization in Aggregated IoT Communication. In 2020 IEEE 45th Conference on Local Computer Networks (LCN) (pp. 233-243). IEEE.(2020)