UDC 621.331:621.314.632
DOI: 10.15587/1729-4061.2021.229827

SYNTHESIS OF THE TRANSFER FUNCTION OF THE VOLTAGE CONTROLLER IN AN ACTIVE FILTER-STABILIZER CONVERTER

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It has been established that in order to ensure effective filtration and stabilization of the voltage of DC traction substations, it is advisable to use active filters-stabilizers. The dynamic characteristics of an active filter-stabilizer have been analyzed taking into consideration its discrete properties. It has been shown that the voltage converter in an active filter-stabilizer with bilateral pulse-width modulation for small values of control signal increment is an amplitude-pulse modulator of the second kind.

In order to improve the efficiency of using an active filter-stabilizer, which is part of the DC traction substation converter, the task was set to synthesize the transfer function of its converter's voltage controller. When analyzing a closed automatic control system, it was established that the transfer function of the voltage controller, which ensures the implementation of processes of finite duration in the closed automatic control system, includes a proportional part, an integral part, and a differential part. To determine the time constants for the transfer function of the PID-controller, as well as its damping coefficient, a closed automatic control system of the active filter-stabilizer voltage converter was investigated using an apparatus of Z-transformation. The result of synthesizing the transfer function of the voltage controller has established the parameters for the controller's transfer function, which ensure that the process of finite duration is executed in a closed system of automatic control over the converter's output voltage. The transition process in the system with a stepwise input effect of the processes of finite duration has been calculated, which confirmed that the transition process in the system ends after three clock intervals of discreteness. Establishing a transition process that ends over the finite number of discrete intervals, which is determined by the order of the characteristic equation, means that the process has been optimized for performance

Keywords: transfer function, voltage controller, converter, transition process, control system

Received date 03.02.2021
Accepted date 20.04.2021
Published date 30.04.2021

How to Cite: *Shcherbak, Y., Semenenko, Y., Semenenko, O., Karpenko, N., Suprun, O., Plakhtii, O., Nerubatskyi, V. (2021). Synthesis of the transfer function of the voltage controller in an active filter-stabilizer converter. Eastern-European Journal of Enterprise Technologies, 2 (2 (110)), 71–77. doi: https://doi.org/10.15587/1729-4061.2021.229827*

1. Introduction

Increasing the intensity of transportation and the introduction of high-speed traffic along the sections of DC traction networks lead to a decrease in the quality of electricity supply to the electric rolling stock [1]. The growth in the electromagnetic influence of traction networks significantly disrupts the regular operation of railroad automation, signaling tools, autoblocks and communication lines, which can lead to negative consequences. The possibilities of applying conventional measures to strengthen the DC traction power supply system are exhausted [2]; they no longer guarantee its effective and reliable functioning. In order to improve the energy quality for traction consumers, it is necessary to stabilize the output voltage of the traction substation, that is, to keep it constant regardless of external influences. Such impact factors are the change in the supply voltage to a converter and the growth of current loads. Voltage stabilization is also necessary to prevent additional energy losses arising from currents of flow in the traction network between substations with a two-way power supply to sections. Given the global trends in improving the efficiency of energy facilities, it is a relevant task to study the systems of output voltage filtration and stabilization at DC traction substations.

2. Literature review and problem statement

In order to ensure a high-quality power supply to rolling stock and improve electromagnetic compatibility of the DC traction power supply system with adjacent electrical units, it is advisable to use the active filtration and stabilization of voltage at the substation output [3, 4]. Work [5] considers measures to increase the efficiency of active filtration in DC power systems but such systems do not provide for the stabilization of the output voltage. A converter that enables the filtering and stabilization of DC voltage is proposed in paper [6]; however, such a scheme is intended exclusively for low voltage sources, for example, solar panels. Work [7] shows that the stabilization and normalization of the harmonic composition of voltage can be achieved by using volt-additional converters based on the three-phase voltage rectifiers with pulse-width modulation (PWM) at traction substations. Such rectifiers include six or twelve double-quadrant keys on high-voltage *IGBT* [8], which complicate their technical execution and significantly increase their cost.

There are known active filters-stabilizers (AFS) of alternating voltage [9], designed to stabilize the voltage on the buses of nonlinear consumers and to filter currents of higher harmonics. The principle of AFS operation is based on the use of energy stocked in jet drives [10]. At the same time, AFS often acts as a compensator for higher harmonics, turned on sequentially with the main power source [11]. Based on the analysis of known technical solutions, paper [12] suggested the structure of AFS of constant voltage, which employs a similar principle of active filtration and stabilization of rectified voltage. AFS has a simpler power scheme that reduces energy losses, and its cost is less than that in a system with a volt-additional voltage rectifier, while the quality of energy at the substation output has better indicators.

Work [13] analyzes the AFS dynamic characteristics, taking into consideration discrete properties. It has been shown that the AFS voltage converter with bilateral pulse-width modulation for small values of control signal gain is an amplitude-pulse modulator of the second kind.

In order to improve the effectiveness of AFS application, further research is needed, and the first thing to do is to synthesize the transfer function of the AFS voltage controller.

3. The aim and objectives of the study

The aim of this study is to synthesize the transfer function of the AFS voltage converter controller, which is necessary to improve the efficiency of using AFS as part of the DC substation converter.

To accomplish the aim, the following tasks have been set:

– to build a transfer function of the voltage controller in an AFS converter, which would meet the requirements for the existence of a process of finite duration and the astatism of the first order in a closed automatic control system;

– to define the conditions for a process of finite duration, which could make it possible to select the parameters for the AFS output voltage controller;

– to check the adequacy of results from synthesizing the transfer function of the voltage controller of the AFS converter.

4. The study materials and methods

Fig. 1 shows the functional diagram of the converter with AFS, in which the stabilization of the output voltage is carried out by a closed automatic control system. The functional diagram includes MR – the main rectifier; VC – voltage converter; CR – charge rectifier; PWM – pulse-wide modulator; VCC – voltage controller; OVS – output voltage sensor.

Work [13] shows that the dynamic processes that occur in a closed control system of the converter at a traction substation are determined exclusively by the properties of a volt-additional converter based on the rectifier with PWM. A volt-additional converter, as well as an AFS converter, ensures the stabilization and suppression of voltage pulsations by forming the voltage that compensates for deviations of the constant component and pulsations of the output voltage in a converter at a traction substation. Given this, we can conclude that the electromagnetic processes of the main MR do not affect the dynamic processes in the automatic control system of the AFS converter.

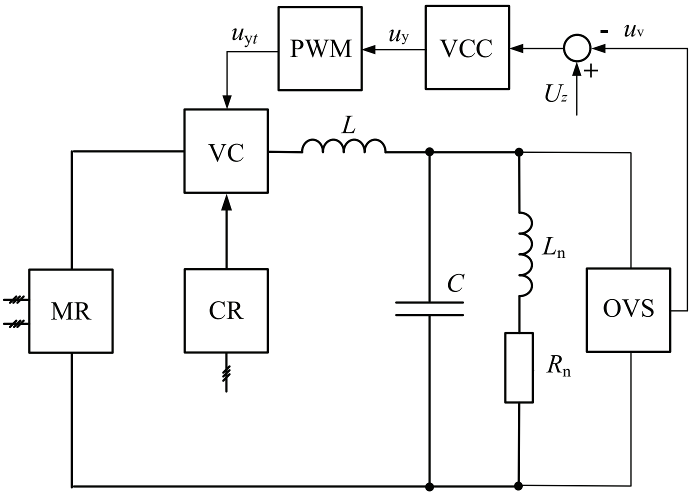


Fig. 1. Automatic control system over the output voltage of the converter with an active filter-stabilizer

Fig. 2 shows a functional diagram of the system of automatic control over an active filter-stabilizer. We studied the AFS-related dynamic processes under the following assumptions: the elements of the *LC*-filter and the power keys of the AFS voltage converter are ideal.

The structural diagram of the closed system of automatic control over the output voltage of the AFS converter is compiled using the pulse model of a converter from [13]; it is shown in Fig. 3.

The AFS voltage converter with bilateral PWM at low deviations from the established state is represented in the form of two ideal pulse elements with a quantization period equal to the PWM period T_{sh}. The static transfer coefficients K_{pin}, K_{pik} and the dynamic transfer coefficients F_{in}, F_{ik} take into consideration the effect of the variable component of the output voltage along the feedback circuit on the control system.

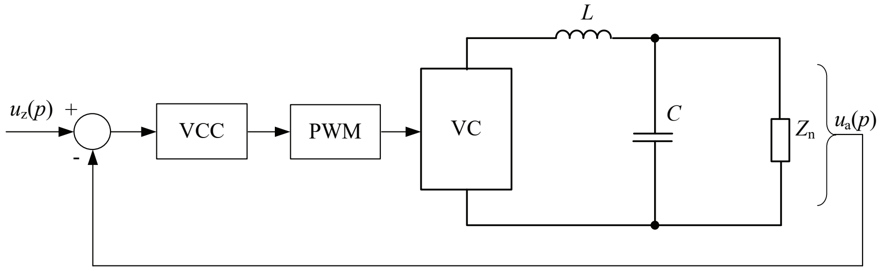


Fig. 2. Functional diagram of the automatic control system of an active filter-stabilizer

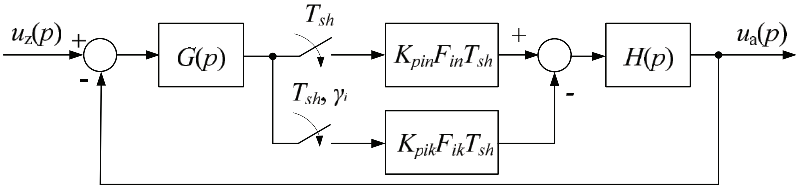


Fig. 3. Structural diagram of the closed system of automatic control over a voltage converter of the active filter-stabilizer

The transfer function of the output link of the AFS voltage converter (Fig. 2) takes the following form:

$$H(p)=\frac{1}{T_f^2 p^2+2\xi T_f p+1}, \tag{1}$$

where $T_f=\sqrt{LC}$ is the time constant of the passive filter; $\xi=\frac{1}{2Z_n(p)}\cdot\sqrt{\frac{L}{C}}$ is the passive filter damping coefficient.

If one uses the p_1 and p_2 poles of the characteristic polynomial from equation (1), then the transfer function of the output link of the AFS converter takes the following form

$$H(p)=\frac{1}{T_f^2(p-p_1)\cdot(p-p_2)}. \tag{2}$$

The existence of a process of finite duration and the physical implementation of its conditions impose restrictions on the transfer function of the continuous part of the closed automatic control system. This limitation is that the process of finite duration is executed in a system in which the difference in the order of denominator polynomials and the numerator of the transfer function of the continuous part is equal to unity. In such systems of automatic control, the reaction of the continuous part has gaps of the first kind.

If the transfer function of the output link of the AFS converter $H(p)$ is represented as a serial connection of elementary links

$$H(p)=\frac{\prod_{j=1}^{n}T_j(p-p_j)}{\prod_{i=1}^{m}T_i(p-p_i)}, \tag{3}$$

then the transfer function of the reduced continuous part of the automatic control system, which meets the requirements for the existence of a process of finite duration and the first-order astatism, takes the form given in [14]:

$$H'(p)=\frac{\prod_{j=1}^{n}T_j(p-p_j)\cdot\prod_{q=1}^{m-n}T_q(p-p_q)}{\prod_{i=1}^{m}T_i(p-p_i)}. \tag{4}$$

The transfer function of the voltage controller, which needs to supplement the represented continuous part of the system to obtain a process of finite duration, based on expressions (3) and (4), takes the following form:

$$G(p)=\frac{H'(p)}{H(p)}=$$

$$=\frac{\prod_{q=1}^{m-n}T_q(p-p_q)}{T_1 p}. \tag{5}$$

The integral part in the equation of the transfer function of the voltage controller $G(p)$ ensures the elimination of a static adjustment error under a constant operational mode of the automatic control system. The differential part ensures the difference in the order of polynomials in the denominator and numerator, which should be equal to unity. Based on equations (2) and (5), we synthesize the transfer function of the represented continuous part, which ensures obtaining a process of finite duration in the system of automatic control over the output voltage of the AFS converter:

$$H(p)=\frac{T_2^2(p-p_3)\cdot(p-p_4)}{T_1T_f^2 p(p-p_1)\cdot(p-p_2)}, \tag{6}$$

where p_3 and p_4 are zeros of the transfer function, which have a functional connection to the poles p_1, p_2.

Then, taking into consideration equation (6), the transfer function of the controller, in accordance with equation (5), takes the following form:

$$G(p)=\frac{T_2^2(p-p_3)\cdot(p-p_4)}{T_1 p}, \tag{7}$$

alternatively, according to [14], is written as follows:

$$G(p)=\frac{T_2^2 p^2+2\mu T_2 p+1}{T_1 p}, \tag{8}$$

where T_1, T_2 are the time constants of the transfer function of the controller; μ is the damping coefficient.

To determine the time constants of the transfer function of controller (8), as well as the damping coefficient, we continue to analyze the closed automatic voltage control system of the AFS converter using the apparatus of Z-transformation. The structural diagram of the system of automatic control over the output voltage of the AFS converter is shown in Fig. 4.

Fig. 4 shows the following designations:

- $G(p)=\frac{T_2^2 p^2+2\mu T_2 p+1}{T_1 p}$ is the transfer function of the voltage converter;
- $H(p)=\frac{1}{T_f^2 p^2+2\xi T_f p+1}$ is the transfer function of the aperiodic LC-filter;
- K_0 is the static transfer coefficient;
- K_1 is the coefficient of transfer of the feedback circuit;
- F_1, F_2 are the pulsation factors.

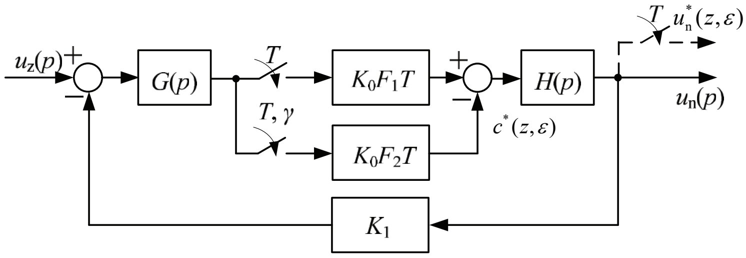


Fig. 4. Structural diagram of the system of automatic control over the output voltage of an active filter-stabilizer converter

A relation between the input and output signals of the closed automatic control system, recorded in the form of *Z*-transformation [13], is determined as follows:

$$\begin{cases} u_n^*(z,\varepsilon) = c^*(z,\varepsilon)\cdot H^*(z,\varepsilon); \\ c^*(z,\varepsilon) = \\ = \dfrac{\left[u_zG^*(z,\varepsilon)F_1 - z^{-1}u_zG^*(z,1+\varepsilon-\gamma)F_2\right]K_0T}{1+\left[-HG^*(z,\varepsilon)F_1 + z^{-1}HG^*(z,1+\varepsilon-\gamma)F_2\right]K_0K_1T}. \end{cases} \quad (9)$$

The system of equations (9) produces an expression for the output signal of a closed automatic control system

$$u_n^*(z,\varepsilon) = \\ = \frac{\left[u_zG^*(z,\varepsilon)F_1 - z^{-1}u_zG^*(z,1+\varepsilon-\gamma)F_2\right]K_0TH^*(z,\varepsilon)}{1+\left[-HG^*(z,\varepsilon)F_1 + z^{-1}HG^*(z,1+\varepsilon-\gamma)F_2\right]K_0K_1T}, \quad (10)$$

where $0 \le \varepsilon \le \gamma$;

$$u_zG^*(z,\varepsilon) = Z_\varepsilon\left\{u_z(p)G(p)\right\};$$

$$HG^*(z,\varepsilon) = Z_\varepsilon\left\{H(p)G(p)\right\}.$$

The synthesis of conditions for a process of finite duration is to be performed by investigating the characteristic equation obtained from (10)

$$1+\begin{bmatrix} -HG^*(z,\varepsilon)F_1 + z^{-1}\times \\ \times HG^*(z,1+\varepsilon-\gamma)F_2 \end{bmatrix}K_0K_1T = 0. \quad (11)$$

According to [15], the modified *Z*-transformation of the transfer function of the represented continuous part of the automatic voltage control system of the AFS converter is determined as follows:

$$HG^*(z)\Big|_{m=0} = \frac{z}{\alpha^2+\beta^2}\times \\ \times\begin{Bmatrix} \dfrac{a_0}{z-1} + \left(\alpha^2+\beta^2-a_0\right)\times \\ \times\dfrac{z-e^{-\alpha T}\left[\cos\beta T + tg\varphi\cdot\sin\beta T\right]}{z^2-2ze^{-\alpha T}\cos\beta T + e^{-2\alpha T}} \end{Bmatrix}, \quad (12)$$

$$HG^*(z,1-\gamma) = \frac{z}{\alpha^2+\beta^2}\times \\ \times\begin{Bmatrix} \dfrac{a_0}{z-1} + \left(\alpha^2+\beta^2-a_0\right)e^{-\alpha(1-\gamma)T}\times \\ \times\dfrac{z\left[\cos(1-\gamma)\beta T - \mathrm{tg}\varphi\cdot\sin(1-\gamma)\beta T\right] - e^{-\alpha T}\left(\cos\gamma\beta T + \mathrm{tg}\varphi\cdot\sin\gamma\beta T\right)}{z^2-2z\cdot e^{-\alpha T}\cos\beta T + e^{-2\alpha T}} \end{Bmatrix}. \quad (13)$$

The following designations are accepted in expressions (12) and (13):

$$\alpha = \frac{\xi}{T_f};\ \ \alpha^2+\beta^2 = \frac{1}{T_f^2};$$

$$\beta = \frac{\sqrt{1-\xi^2}}{T_f};\ \ a = \sqrt{1-\xi^2};$$

$$a_0 = \frac{1}{T_2^2};\ \ \mathrm{tg}\varphi = \frac{1}{a}\left[\frac{\xi\left(T_2^2+T_f^2\right)-2\mu T_2T_f}{T_2^2-T_f^2}\right].$$

One of the criteria for the analysis and synthesis of the pulsed systems of automatic control is to obtain a transition process ending over the finite number of discrete intervals, which is determined by the order of the characteristic equation.

5. Results of investigating the transfer function of a voltage controller

5. 1. Results of the transfer function synthesis

If expression (8) is represented as the sum of individual components, then we obtain the following equation as a result of the synthesis of the transfer function of the voltage controller:

$$G(p) = \frac{2\mu T_2}{T_1} + \frac{1}{T_1p} + \frac{T_2^2}{T_1}p. \quad (14)$$

The components of equation (14) represent the proportional, integral, and differential parts of the transfer function of a PID controller.

5. 2. Determining conditions for a process of finite duration

Taking into consideration (12) and (13), characteristic equation (11) takes the following form:

$$1-\frac{T_2^2}{T_1T_f^2}K_0K_1TF_1\frac{z}{\alpha^2+\beta^2}\times \\ \times\left\{\frac{a_0}{z-1} + \left(\alpha^2+\beta^2-a_0\right)\frac{z-e^{-\alpha T}\left(\cos\beta T + tg\varphi\cdot\sin\beta T\right)}{z^2-2ze^{-\alpha T}\cos\beta T + e^{-2\alpha T}}\right\} + \\ +\frac{T_2^2}{T_1T_f^2}K_0K_1TF_2\frac{z}{\alpha^2+\beta^2}\times \\ \times\begin{Bmatrix} \dfrac{a_0}{z-1} + (\alpha^2+\beta^2-a_0)e^{-\alpha(1-\gamma)T}\times \\ \times\dfrac{z\left[\cos(1-\gamma)\beta T - tg\varphi\cdot\sin(1-\gamma)\beta T\right] - e^{-\alpha T}\left(\cos\gamma\beta T + tg\varphi\cdot\sin\gamma\beta T\right)}{z^2-2ze^{-\alpha T}\cos\beta T + e^{-2\alpha T}} \end{Bmatrix} = 0. \quad (15)$$

The process of finite duration implies that the free component, predetermined by the poles of the transfer function of the automatic control system, fades over the finite number of clock intervals of the pulse element. The nature of the fading of the free component is determined from the characteristic equation of system (15), which has the number of roots equal to the order of the reduced continuous part of the automatic control system [16]. The process of finite duration is implemented by combining the roots of the characteristic equation with the coordinate origin of the *z*-plane, which is equivalent to reducing characteristic equation (15) to the following form: $z^n=0$. If we write the characteristic equation in the canonical form $A_1z^n+A_2z^{n-1}+...+A_n=0$, the conditions for a finite duration are expressed as a system of equations made up of coefficients corresponding to the following system of equations:

$$\begin{cases} A_1=0, \\ A_2=0, \\ \dots\dots\dots, \\ A_n=0. \end{cases} \tag{16}$$

By substituting those coefficients A_i in the system of equations (16) that were obtained from characteristic equation (15), and by performing simple but rather cumbersome transformations, we obtain the following conditions for a process of finite duration:

$$T_1=K_0K_1TF_1; \tag{17}$$

$$T_2^2=T_f^2\left(1+K_0K_1F_2\frac{T}{T_1}\right); \tag{18}$$

$$\begin{gathered}\mu=a\left(T_2^2-T_f^2\right)T_f\times \\ \times\frac{\dfrac{F_1}{F_2}-1+e^{\alpha\gamma T}\left(\dfrac{T_2^2}{T_f^2}+1\right)\left[\cos\gamma\beta T+\dfrac{\xi}{a}\cdot\dfrac{T_2^2+T_f^2}{T_2^2-T_f^2}\sin\gamma\beta T\right]}{2T_2\left(T_2^2+T_f^2\right)\cdot\sin\gamma\beta T}\times \\ \times\left(1+K_0K_1F_2\frac{T}{T_1}\right).\end{gathered} \tag{19}$$

Equations (17) to (19) make it possible to determine the time constants and a damping coefficient in the transfer function of a PID-controller (14).

5. 3. Checking the results of synthesizing a transfer function of the voltage controller in an active filter-stabilizer

For verification, we shall calculate and construct a transition process in a closed automatic control system under a stepped input influence u_z.

The conditions established for a process of finite duration in (17) to (19) make it possible to choose the parameters for a PID-controller $G(p)$ of the output voltage in an active filter-stabilizer. The dynamic properties of the automatic control system when adjusting for a process of finite duration are to be considered by analyzing its reaction to the stepped input influence $u_z(t)=1(t)$.

In accordance with (10), the polynomial of the output signal expression's numerator $U_n^*(z)$ takes the following form:

$$\begin{gathered}N_n^*(z)=zK_0\frac{T}{aT_f}e^{-\xi\frac{T}{T_1}}\cdot\sin\frac{T}{T_f}\times \\ \times\left\{\begin{aligned}&\left[\frac{T_2^2}{T_1T}+2\mu\frac{2}{T_1}\cdot\frac{z}{z-1}+\frac{T}{T_1}\cdot\frac{z}{(z-1)^2}\right]\cdot F_1- \\ &-\left[\begin{aligned}&z^{-1}\frac{T_2^2}{T_1T}+2\mu\frac{2}{T_1}\cdot\frac{1}{z-1}+ \\ &+\frac{T(1-\gamma)}{T_1(z-1)}+\frac{T}{T_1(z-1)^2}\end{aligned}\right]\cdot F_2\end{aligned}\right\}.\end{gathered} \tag{20}$$

Consider the output signal U_n^* at $\gamma=0.5$. In this case, $F_1=F_2=F_\gamma$.

Hence:

$$\begin{gathered}N_n^*(z)= \\ =\frac{z^2\dfrac{T_2}{T_1}\left(\dfrac{T_2}{T}+2\mu\right)+z\left[\dfrac{T}{2T_1}-2\dfrac{T_2}{T_1}\left(\dfrac{T_2}{T}+\mu\right)\right]+\dfrac{T_2^2}{T\cdot T_1}}{z(z-1)}.\end{gathered} \tag{21}$$

The output signal of the control system is:

$$U_n^*(z)=\frac{K_0}{K_1}\cdot\frac{a\dfrac{T}{T_f}\cdot e^{-\xi T/T_f}\sin a\dfrac{T}{T_f}\left(z^2C_1-zC_2+C_3\right)}{z^2(z-1)}, \tag{22}$$

where

$$C_1=\frac{T_2}{T_1}\left(\frac{T_2}{T}+2\mu\right);\ C_2=\frac{T}{2T_1}-\frac{2T_2}{T_1}\left(\frac{T_2}{T}+\mu\right);\ C_3=\frac{T_2^2}{T\cdot T_1}.$$

Parameters for the aperiodic anti-aliasing filter are selected according to equation (1): $T_f=1\cdot10^{-3}$ s, $\xi=0.5$. Parameters for the controller are determined from equations (17) to (19): $T_1=1\cdot10^{-3}$ s, $T_2=1.095\cdot10^{-3}$ s. The period of discreteness is $T=0.2\cdot10^{-3}$ s. Substituting the above parameters for the passive filter and a PID controller in the formula for the output signal of the system (22), and performing its decomposition into a Laurent power series, we obtain the following expression for a transient process:

$$\begin{gathered}u_n(t)=0.23\cdot z^{-1}+0.68\cdot z^{-2}+ \\ +0.88\cdot z^{-3}+0.88\cdot z^{-4}+...+0.88\cdot z^{-n}.\end{gathered} \tag{23}$$

Fig. 5 shows the $u_n(t)$ dependence of the transition process, built on the basis of equation (23).

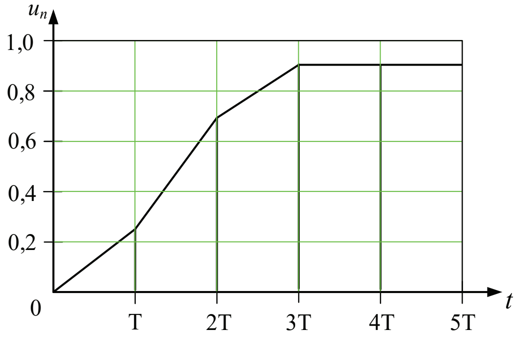


Fig. 5. Transition process in a closed structure

The AFS simulation model, which is shown in Fig. 6, helped us verify the results of the synthesis of the transfer function of an AFS converter's voltage controller. The model includes a basic twelve-pulsation rectifier and a six-pulsation rectifier for the charge of capacitive energy storage. The control system (*Subsystem*1 unit) produces signals through which the AFS voltage converter forms a compensating voltage to stabilize the average value and suppress the variable component of the output voltage of the substation converter. A stepped task signal is fed into the control system, as a result of which there is a transition process in the AFS output voltage control system, the course of which is shown by the time charts in Fig. 7.

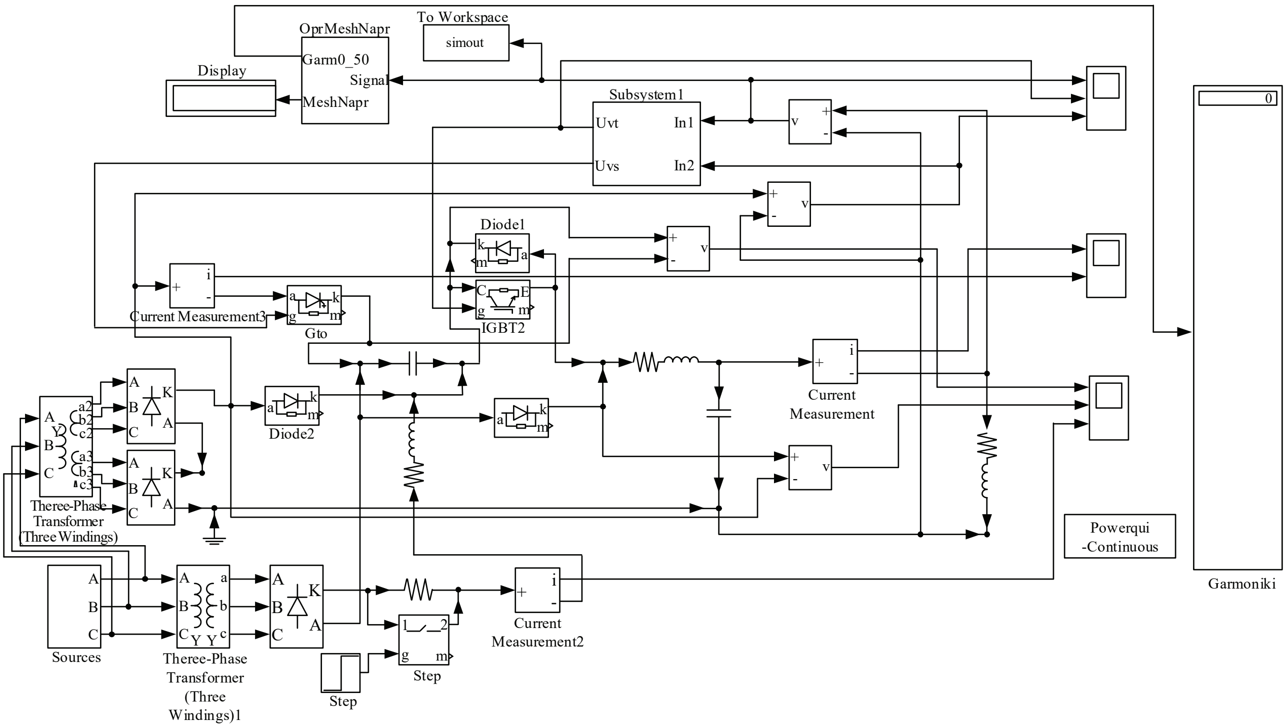
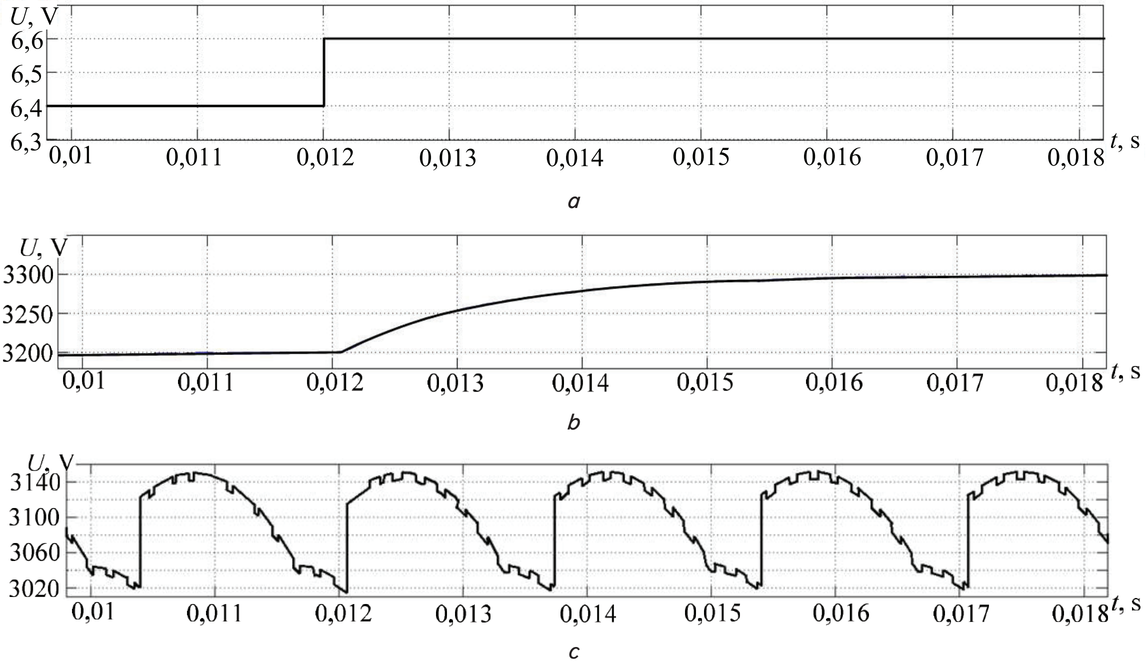


Fig. 6. Simulation model of the serial-type active filter-stabilizer



a

b

c

Fig. 7. Voltage oscillograms of the converter with an active filter-stabilizer during the transition process: *a* – formed stepped task signal; *b* – output voltage of the converter; *c* – voltage at the output of the rectifier

Our tests have confirmed that the transition process in the examined system ends in three clock intervals of discreteness.

6. Discussion of results of studying a transfer function of the voltage controller in an active filter-stabilizer

The result of our study is the synthesized equation (9), which represents the proportional, integral, and differential parts of the transfer function of the AFS output voltage controller. The established conditions for a process of finite duration (17) to (19) make it possible to choose the parameters for a PID controller, namely the time constants of the transfer function of the controller and a damping coefficient. The special feature of this study is the use of the modified *Z*-transformation of the transfer function of the reduced continuous part of an automatic system that controls the output voltage of the AFS converter.

It follows from expression (23) and Fig. 5 that the transition process in the studied system ends in three clock intervals of discreteness, which corresponds to the order of the characteristic equation. To confirm these results, simulation modeling was carried out with the results shown in Fig. 7. That is, we have obtained a process of finite duration under a stepped input influence in a closed system of automatic control over the output voltage of AFS converter, or, in other words, a transition process has been optimized for performance. Given this, we have achieved an increase in the stability of the power supply system under the transient and emergency modes, thereby improving the quality of load power supply and reducing energy losses in traction networks.

This study did not address the issue of determining the pulsation factors in a closed system of automatic control over the output voltage of the AFS converter. In the future, it is planned to conduct appropriate studies of pulsation factors in a closed AFS automatic control system whose output voltage constant component is adjusted by bilateral pulse-wide modulation.

7. Conclusions

1. A transfer function of the voltage controller of the AFS converter has been synthesized, which ensures the implementation of processes of finite duration in a closed automatic control system and the first-order astatism. It was established that the synthesized transfer function of the voltage controller includes the proportional, integral, and differential parts.

2. The conditions for the process of finite duration have been obtained, which make it possible to select the parameters for a PID-controller of the AFS output voltage. The use of these parameters ensures optimization of transient processes in terms of performance speed in the system of automatic control over the output voltage of the converter at a traction substation.

3. The adequacy of the results from synthesizing the transfer function of an AFS voltage controller has been verified by calculating and modeling the transition process in the system under the stepped input influence of processes of finite duration. It has been confirmed that the transition process in the studied system ends in three clock intervals of discreteness, which corresponds to the order of the characteristic equation.

References

1. Panasenko, M. V., Honcharov, Yu. P., Sychenko, V. H. (2009). Problemy elektromahnitnoi sumisnosti pidsystem elektrychnoi tiahy postiynoho strumu i vykorystannia zasobiv sylovoi elektroniky dlia yikh vyrishennia. Elektrotekhnika ta elektroenerhetyka, 2, 22–28.
2. Maksimchuk, V. F. (2013). Strategic objectives and priorities of economic development electrification and power supply. Elektryfikatsiya transportu, 5, 99–105.
3. Samsonkin, V. M., Panasenko, N. V., Bozhko, V. V., Goncharov, Yu. P., Eres'ko, A. V., Zamaruev, V. V. et. al. (2008). Energoeffektivnyy preobrazovatel'nyy agregat s funktsiyami fil'tratsii garmonik vyhodnogo napryazheniya tyagovoy podstantsii sistemy elektrosnabzheniya postoyannogo toka napryazheniem 3 kV. Visnyk Dnipropetrovskoho natsionalnoho universytetu zaliznychnoho transportu imeni akademika V. Lazariana, 20, 66–72.
4. Goncharov, Yu. P., Panasenko, M. V., Bozhko, V. V. (2008). Tyagoviy vipryamlyach z reversivnim vol'tododatkom na dvohoperatsiynih napivprovidnikovih priladah. Tekhnichna elektrodynamika, 2, 16–21.
5. Goswami, R., Wang, S. (2017). Investigation of multiple feedback active filter configurations for differential mode(DM) electromagnetic interference(EMI) noise in AC/DC converter applications. IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics Society. doi: https://doi.org/10.1109/iecon.2017.8217227
6. Ribisi, E. T., Freere, P. (2017). Stabilizing photovoltaic DC rail voltage using an active filter. 2017 IEEE AFRICON. doi: https://doi.org/10.1109/afrcon.2017.8095687
7. Ivakina, K. Y. (2013). Analysis of electromagnetic processes rectifier with pulse-width modulation. Visnyk of Vinnytsia Polytechnical Institute, 6, 65–67.
8. Goncharov, Yu. P., Zamaruev, V. V., Ivahno, V. V., Lyubich, R. I., Panasenko, N. V. (2009). Minimizatsiya fil'trovogo oborudovaniya tyagovyh podstantsiy s pomosch'yu vol'todobavochnogo preobrazovatelya. Visnyk DNUZT im. V. Lazariana, 27, 56–60.
9. Urazbahtina, N. G., Kuz'mich, V. N., Styskin, A. V. (2010). Pat. No. 99909 RF. Aktivnyy fil'tr-stabilizator peremennogo napryazheniya. No. 2010119136/07; declareted: 12.05.2010; published: 27.11.2010, Bul. No. 33.
10. Gazijahani, F. S., Abadi, A. A., Safari, A. (2017). Robust Bi-level Model for Optimal Allocation and Design of Power System Stabilizer in MultiMachine Power Systems. International Journal of Control and Automation, 10 (9), 67–86. doi: https://doi.org/10.14257/ijca.2017.10.9.07
11. Safari, A., Shayeghi, H., Shayanfar, H. A. (2016). Coordinated control of pulse width modulation based AC link series compensator and power system stabilizers. International Journal of Electrical Power & Energy Systems, 83, 117–123. doi: https://doi.org/10.1016/j.ijepes.2016.03.042
12. Semenenko, O. I., Semenenko, Y. O. (2016). Active filterstabilizer rectifier unit for traction substation. Information and control systems at railway transport, 4, 29–33. doi: https://doi.org/10.18664/ikszt.v0i4.79392
13. Shcherbak, Y., Semenenko, Y., Semenenko, A. (2017). Analysis of dynamic characteristics of the active filter-stabilizer. Eastern-European Journal of Enterprise Technologies, 2 (8 (86)), 10–15. doi: https://doi.org/10.15587/1729-4061.2017.95995
14. Scherbak, Ya. V. (1999). Parametricheskoe formirovanie protsessa konechnoy dlitel'nosti v sistemah s poluprovodnikovymi preobrazovatelyami. Vestnik HGPU, 69, 15–21.
15. Dzhuri, E.; Tsypkin, Ya. Z. (Ed.) (1963). Impul'snye sistemy avtomaticheskogo regulirovaniya. Moscow: Fizmatizdat, 455.
16. Shipillo, V. P. (1975). Opredelenie ustanovivsheysya reaktsii lineynoy sistemy na periodicheskoe vozdeystvie metodom z-preobrazovaniya. Izv. VUZov. Elektromehanika, 5, 538–543.