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E.M. Vereshchago, V.I. Kostiuchenko, S.M. Novogretskyi

Analysis of a DC converter working on a plasma arc

Introduction. *The article is devoted to the analysis of a stabilized direct current converter operating on a plasma arc. Electroplasma technologies of the new generation cause the need to design workable systems that provide control of technological processes and their dynamic optimization in real time. The improvement of any electroplasma technology begins with the improvement of the operating parameters of the main element of plasma installations - the power source.* ***Goal*** *is to build and study a continuous model of a pulsed source of secondary power supply, which works on an electric welding and plasma arc.* ***Methodology.*** *In the work, a mathematical description of the converter was performed. The continuous model of the system is substantiated, taking into account its features, namely, the load (gas-discharge gap) is a source of voltage and dynamic resistance. The parameters of the constant part during circuit synthesis are determined: the components of the gain of the constant part, the relative signal coefficient of the current sensor and the PWM gain. Studies of the open system «power source - arc» have been carried out.* ***Results.*** *MATLAB objects were created - continuous mathematical models of the object in the form of transfer functions. The obtained transient characteristics for different options: «arc current - control signal» and « inductor current - control signal» showed that open systems are unstable. It was found that in the case of instability, the filling frequency of self-oscillations occurring in the linear mode is close to the frequency of natural oscillations of the circuit. The dependence of the module and the argument of the input resistance of the power part of the pulsed power supply with parallel capacitance to the electric arc and without it, which have matching frequency characteristics, is established. The circuit considered with the initial data adopted in this article has a frequency transfer coefficient of the same type as the first-order non-minimum-phase (phase-shifting) link. Frequency response graphs for the output impedance of the power unit show that this power unit is a broadband frequency-selective system with a bandwidth of $B_{0.707}$ = 100 kHz.* ***Originality.*** *Expressions for the frequency transfer function, input and output resistance of the pulse voltage converter operating on an arc load were obtained by the method of averaging and linearization. The frequency amplitude and phase characteristics for the pulse voltage converter with an LC filter and the output according to the arc current and the choke current were studied. The transfer functions of the continuous model in terms of arc current and choke current at the specified parameters are the same, which must be taken into account when designing regulators.* ***Practical significance.*** *The frequency characteristics of the input and output resistances and transfer functions can be used when forming a technical task for designing a power source to assess the stability of the «pulse converter - arc» system and rational calculation of input filters.* References 22, tables 1, figures 7.

Key words: **input and output resistance, filter, impedance, stabilization system, stability, complex load.**

В роботі проведено аналіз стабілізованого перетворювача постійного струму, що працює на плазмову дугу. Обґрунтовано безперервну модель системи з урахуванням її особливостей. Визначені параметри незмінної частини під час аналізу схеми заміщення замкнутої структури системи електроживлення для дугового навантаження із від'ємним диференціальним опором. Проведені дослідження розімкнутої системи «джерело живлення - дуга». Встановлено, що розглянута схема з вихідними даними, прийнятими в даній статті, має частотний коефіцієнт передачі такого ж виду, що і немінімально-фазова ланка першого порядку. Отримано частотні характеристики вхідного та вихідного опорів перетворювача, навантаженого на дугу. Бібл. 22, табл. 1, рис. 7.

Ключові слова: **вхідний та вихідний опір, фільтр, імпеданс, система стабілізації, стійкість, комплексне навантаження.**

Introduction. In today's advanced fields of science, technology and industry, electroplasma and welding technologies are widely used, which use low-temperature plasma (devices with negative differential resistance). A large class of such devices is DC plasmatrons. Plasmatrons are most often used for cutting materials, heating gas, as plasma ignition systems in the combustion chambers of gas turbine engines for various purposes, etc. [1-3]. Here we should also mention plasma melting, strengthening of metals, plasma chemistry, special metallurgy, solving environmental problems, obtaining new clean materials, applying films and coatings by the vacuum-plasma method, etc.

The improvement of any electroplasma technology must begin with the improvement of the operating parameters of the main element of plasma installations – the power source, which is achieved by designing and constructing its main nodes. Thus, the study of a DC converter operating on a plasma arc is not only of practical, but also theoretical interest, as well as an important and relevant scientific and applied problem.

Two classes of models are used for the analysis of processes in pulse power converters – key (simulation) and continuous [4-7]. Continuous (averaged) ones became the most widespread during the analysis of the stability of closed stabilization systems taking into account pulse energy converters and the synthesis of regulators of these systems [4-7].

Note that the differential resistance of the arc R_{diff0} depending on the location of the operating point on one or another section of the arc volt-ampere characteristic can take on zero, positive, and negative values. It is in the case of finding the operating point on the falling section of the arc volt-ampere characteristic that the converter, taking into account the behavior of the object, forms a system with negative resistance. The behavior of such systems is significantly different from the systems described in the literature under constant load. Instabilities and self-oscillating modes may occur in a system with negative resistance [8]. Self-oscillations, as a rule, have negative consequences: deterioration of the quality of the technological process, reduction of productivity, etc.

The study of systems with negative R_{diff0} is of not only practical, but also theoretical interest [8]. It is appropriate to study the peculiarities of the dynamics of open systems. This makes sense not only because of their wide application in practice, but also because, on simple examples, we can learn the used analysis method and show the influence of certain external feedbacks on the dynamic properties of a closed system compared to an open one.

The complexity of the nonlinear discrete model of the pulse converter (its exact mathematical model), which works on a non-linear load, makes the analysis of the latter in an automatic current stabilization system (closed control system) extremely difficult [5]. At the same time, works [1, 5, 6] show that when the commutation period T ($T \to 0$) decreases, nonlinear pulse systems approach linear continuous systems in terms of properties [1, 5]. Considering the high switching frequency of modern converters for electrical technologies, the task of building their limit continuous models turns out to be very promising. Averaged models are the most convenient for practice, as they allow applying well-developed methods of analysis and synthesis of linear continuous systems to nonlinear discrete systems.

When designing key power sources, continuous linear models of pulse converters are widely used [1, 5]. Their averaged models are substantiated and widely used in various works.

In [9], for example, continuous linearized models of basic converters are given. The method of their construction is based on the assumption that the choke has no active resistance. In addition, the used approach does not allow taking into account the output resistance of the power source, the filter at the input of the converter, etc.

In works [4, 5], the need to take into account the active resistance of the choke circuit during the analysis and synthesis of pulse converter control systems is indicated.

Structural dynamic models of DC pulse converters operating on a complex load with and without taking into account the choke resistance are substantiated, for example, in works [4-7].

In [8], the general issues of power supply and interaction of an electric arc from a current-controlled voltage source and a voltage-controlled current source are considered.

In [10], a power source with a current characteristic, which is made according to the following block diagram, was investigated: an AC source – a transformer – a rectifier – an inductance connected in series with an arc resistance.

Since the pulse converter working on an arc load is not sufficiently studied in the literature, the task of this article is to build a continuous model of the converter and to study the peculiarities of its operation.

Next, an attempt is made to perform an analysis using a simple continuous model of the converter, which takes into account the active resistance of the keys, the choke and the output resistance of the power source and operating on an arc load. It is assumed that the adjustment of the output parameter is carried out using PWM-2.

The goal of the article is to build and study a continuous model of a pulse source of secondary power supply, which works on an electric welding and plasma arc.

Mathematical description of the converter. Replacing circuit of the power supply system for an electric arc load, which includes a loaded *LC* filter, a correction device (*CD*), a modulator (*M*) implementing PWM-2, a pulse converter (*PC*), which forms pulses with the amplitude of the supply voltage nU_{in} at the input of the filter and duration, which is determined by the switching function k_F of the modulator, and sensors of voltage *VS* and current *CS* with k_V and R_{CS} coefficients, respectively, is shown in Fig. 1, where, for commonality, the resistance R connected in parallel with the capacitor C of the output filter is shown.

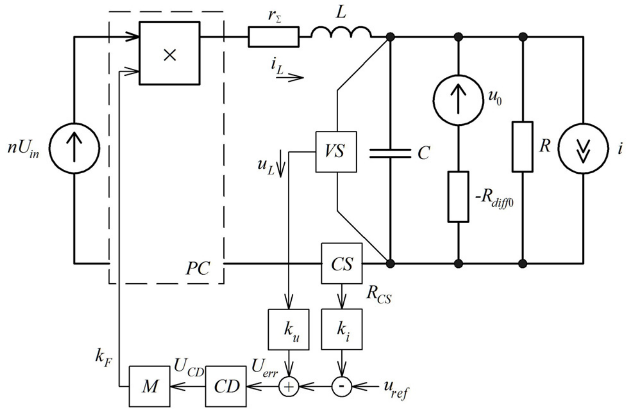

Fig. 1. Replacing circuit of the closed structure of the power supply system for arc load with negative differential resistance

In Fig. 1: i is the current source considered as a disturbance (change) in the load current. The resistance r_Σ includes both the output resistances of the converter and the rectifier, as well as the ohmic losses of the filter choke. Here, the losses resistance may depend on the frequency [11-15]. The load (gas discharge gap) is the series-connected voltage source U_0 and dynamic resistance R_{diff0}.

The converter on the circuit is presented in the form of a power four-pole with an information controlled input (Fig. 1) [5, 16], where $n = w_{21} / w_1 = w_{22} / w_1$. The transmission coefficient of the modulator *PC*, which in our case is defined as $k_F(t)$, if the error signal does not depend on time, is determined by the relationship:

$$k_{PWM} = T / U_m ,$$

where U_m is the amplitude (range) of the fractional function (sawtooth voltage), T is the sweep period.

Usually $R >> r_\Sigma$ (in particular R is missing, i.e. $R \to \infty$).

Denoting by $Z_n(s)$ the operator resistance of the parallel connection of C and R_{diff0}:

$$Z_n(s) = -R_{diff\,0} / \left(1 - sR_{diff\,0}C\right) = -R_{diff\,0} / \left(-\tau s + 1\right),\ \tau > 0 ,$$

we obtain the following expression of the transfer function (TF) of the output *LC* filter in terms of voltage:

$$K(s) = \frac{Z_n(s)}{Z_{in}(s)} = \frac{Z_n(s)}{r_\Sigma + sL + Z_n(s)} =$$

$$= k_f \left(s^2 k_f LC + s(L/(r_\Sigma - R_{diff\,0}) + R_{eq}C) + 1\right)^{-1} =$$

$$= \frac{k_f}{T_f{}^2 s^2 + 2\xi_f T_f s + 1} = \frac{k_f}{T_f{}^2[(s + \alpha_f)^2 + \omega_f{}^2]},$$

where $\tau = R_{diff0}C > 0$ is the time constant of the circuit of the output capacitor; $R_{eq} = r_\Sigma \parallel (-R_{diff0})$; $k_f = -R_{diff0}/(-R_{diff0} + r_\Sigma) > 0$ is the transmission coefficient of the DC filter; $Z_{in}(s)$ is the input operator resistance of the regulator at $R = \infty$ in the continuous current mode; T_f and ξ_f are the time constant and damping coefficient of the filter, defined as

$$T_f = \sqrt{k_f LC}\ ;\ \xi_f = \frac{1}{2}\sqrt{k_f}\left(r_\Sigma \sqrt{C/L} + \frac{1}{R_{diff0}}\sqrt{L/C} \right) =$$

$$= \frac{1}{2}\sqrt{k_f}\left(1/Q + d_s\right) = \frac{1}{2}\sqrt{k_f}(d_r + d_s)\ ;\quad \alpha_f = \xi_f / T_f\ ;$$

$$\omega_f = \sqrt{1/T_f^2 - \alpha_f^2} = \sqrt{\omega_0^2 - \alpha_f^2}\ ;\quad \omega_0^2 = 1/(k_f LC)\ ,$$

where $Q = \frac{1}{r_\Sigma}\sqrt{L/C} = \rho / r_\Sigma$ is the Q factor of the LC filter without taking into account the attenuation introduced by the resistance R and regeneration; $d_s = -S_{diff}\sqrt{L/C}$ is the regeneration introduced into the circuit by a load (electric arc); $d_r = r_\Sigma\sqrt{C/L}$ is the damping introduced into the circuit by resistance; $\rho = \sqrt{L/C}$ is the characteristics of the circuit forming the filter; $d = d_r + d_s$ is the complete fading (regeneration) of the circuit; $S_{diff} = 1 / R_{diff0}$ is the differential steepness of the arc volt-ampere characteristic.

For the circuit in Fig. 1 equation that determines the current in the filter choke $\tilde{i}_L$ will be as follows:

$$Z(s)\tilde{i}_L = nD\tilde{u}_{in} + nU_{in}\tilde{d} + Z_n(s)\tilde{i} - (Z_n(s)/R_{diff0})\tilde{u}_0\ ,$$

where

$$Z(s) = \frac{Z_n(s)}{K(s)} = \frac{R_{diff0}[s^2 k_f LC + s\left(\frac{L}{r_\Sigma - R_{diff0}} + R_{eq}C\right) + 1]}{k_f(-\tau s + 1)}\ ;$$

the symbol «~» shows an infinitesimally small change of the variable with respect to the value in the periodic mode; $d = 2t_p / T$ is the filling factor; D is the value of the filling factor in the steady state (periodic) mode [17-20].

At $C = 0$, the last equation will take the form

$$\tilde{i}_L = k_f \frac{\tilde{i} - \tilde{u}_0 / R_{diff0} + (nD/R_{diff0})\tilde{u}_{in} + (nU_{in}/R_{diff0})\tilde{d}}{s[L/(r_\Sigma - R_{diff0})] + 1}\ .$$

Having chosen as the output variable the arc current $i_{arc} = i_n$, which does not coincide with the state variable, we obtain the transfer functions for the control influence «arc current – control signal»:

$$\frac{\tilde{I}_{arc}(s)}{\tilde{d}(s)} = nU_{in}\frac{Z_n(s)}{Z_1(s) + Z_n(s)}S_{diff} = nU_{in}K(s)S_{diff}\ ,$$

and by disturbing influences – the sensitivity of the arc current to a change in the input voltage u_{in} and to the disturbing current i and voltage u_0:

$$\frac{\tilde{I}_{arc}(s)}{\tilde{U}_{in}(s)} = nDK(s)S_{diff}\ ;\quad \frac{\tilde{I}_{arc}(s)}{\tilde{I}(s)} = -Z_1(s)K(s)S_{diff}\ ;$$

$$\frac{\tilde{I}_{arc}(s)}{\tilde{U}_0(s)} = -(s^2 LC + sr_\Sigma C + 1)K(s)S_{diff}\ ,$$

where $Z_1(s) = Ls + r_\Sigma$ is the operator resistance of the choke circuit.

Determination of the parameters of the constant part of the circuit. Let's find the components of the gain factor of the constant part. Having chosen the steepness of the current sensor R_{CS} = 0.75 mΩ, we determine the CS relative signal coefficient k_i = 82 and the PWM gain

$$k_{PWM}/T = F(T/U_m)(1/T) = F/U_m = 1/2{,}5 = 0{,}4\ \text{B}^{-1}\ ,$$

where the ripple factor F is taken equal to 1; U_m = 2.5 V is the amplitude (span) of sawtooth voltage.

The amplification factor of the constant part at k_f = 1 and F = 1

$$k_0 = k_i k_{PWM} nU_{in}(R_{CS}/-R_{diff0})/T =$$

$$= -82 \cdot 250 \cdot 0{,}4 \cdot 75 \cdot 10^{-5} / 0{,}49 = -12{,}55.$$

The switching frequency is taken as 26 kHz, the choke inductance of the output LC filter is L = 300 μH, and the capacity of the output capacitor, which depends on the requirements, is C = 3 μF, r_Σ = 0.01 Ω, R_{diff0} = –0.49 Ω [21].

Study of the open system «power source – arc». Let's create MATLAB objects – continuous mathematical models of our object in the form of transfer functions (*transfer function form*). The answer will be the following result in the command window (Table 1).

Table 1

Transfer functions of the object

No.	Transfer function*
1	$\frac{416.4}{9\cdot 10^{-10}\cdot s^2 - 0.000612\cdot s + 1}$
2	$\frac{208.2}{9\cdot 10^{-10}\cdot s^2 - 0.000612\cdot s + 1}$
3	$\frac{-0.000612\cdot s + 416.4}{9\cdot 10^{-10}\cdot s^2 - 0.000612\cdot s + 1}$
4	$\frac{-0.000306\cdot s + 208.2}{9\cdot 10^{-10}\cdot s^2 - 0.000612\cdot s + 1}$

*options 1, 2 – TF «arc current – control signal» with k_{CR} = 33.18 and k_{CR} = 16.59; options 3, 4 – TF «choke current – control signal» with k_{CR} = 33.18 and k_{CR} = 16.59.

For the TF of object 3-4, the indicators are equal: the order and the instability index are equal to two $n = s_n = 2$, the degree $r_C = n - m = 2 - 1 = 1$, the indexes of aperiodic and oscillatory neutrality are equal to zero $s_a = s_v = 0$, the index of non-minimum phase $s_{nf} = 1$, the amplification factor $k = k_0 k_{CR}$. The assignment of these indicators and the amplification factor k reflects the essential features of the TF $W(s)$ and they can be used to characterize certain properties of the system determined by this TF [22].

Transient characteristics (TC) for options 1, 3 are shown in Fig. 2. Open systems are unstable s_n = 2>0. Nyquist diagrams for the considered options are shown in Fig. 3. As shown in Fig. 3, the frequency response never covers the point –1, j0, so closed systems are also unstable.

The input resistance of the power part (PP) according to the diagram in Fig. 1 in operator form

$$Z_{i0}(s) = -(R_{diff0} - r_\Sigma)\frac{s^2 k_f LC + s\left(-L/(R_{diff0} - r_\Sigma) - R_{eq}C\right) + 1}{-\tau_C s + 1}\ ,$$

where $\tau_C = R_{diff0}C > 0$ is the time constant of the circuit of the output capacitor; $R_{eq} = r_\Sigma \parallel (-R_{diff0})$; $k_f = R_{diff0} / (R_{diff0} - r_\Sigma)$ is the transmission coefficient of the DC filter.

It is easy to show that its output resistance is determined by the expression

$$Z_{00}(s) = k_f \frac{sL + r_\Sigma}{s^2 k_f LC + s\left(-L/(R_{diff0} - r_\Sigma) + R_{eq}C\right) + 1}\ .$$

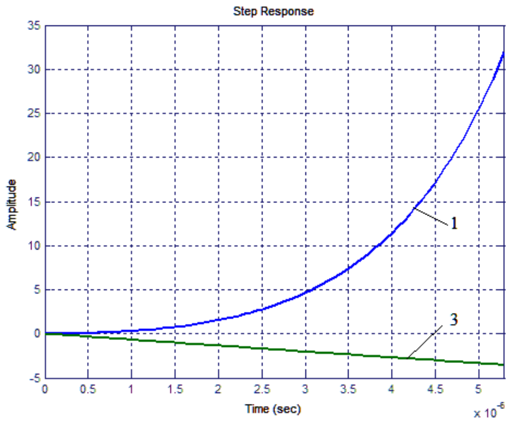

Fig. 2. TC graphs of unstable systems: option 1 (1), option 3 (3)

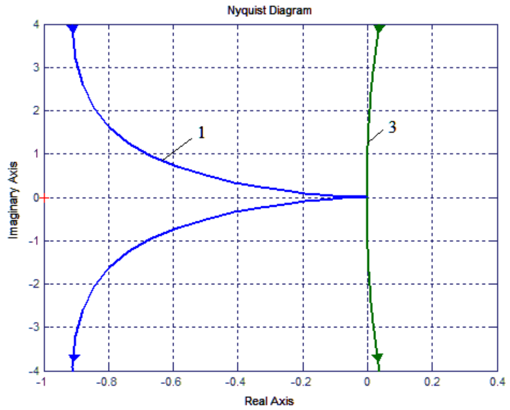

Fig. 3. Nyquist diagrams for unstable systems: option 1 (1), option 3 (3)

Since the losses resistance is quite small, then

$$Z_{00}(s)=\frac{s/C}{s^2-s/(R_{diff0}C)+1/(LC)}. \qquad (1)$$

Noting that, in the general case, $1/\sqrt{LC}=\omega_0$ is the frequency of natural oscillations of the circuit without losses and $\alpha=-0{,}5S_{diff}/C=-0{,}5\omega_0 Q$ is the damping coefficient of the circuit, we rewrite the expression as follows (here, the main conditions were chosen so that instabilities could occur)

$$Z_{00}(s)=\frac{s/C}{s^2-2\alpha s+\omega_0^2} \quad (\alpha>0).$$

In this case $\omega_0=1/\sqrt{LC}=$ $=(\sqrt{300\cdot10^{-6}\cdot3\cdot10^{-6}})^{-1}$ $=33.33\cdot10^3$ s^{-1} or f_0 = 5.307 kHz.

Therefore, in the case of instability, the filling frequency of self-oscillations occurring in the linear mode is close to the frequency of natural oscillations of the circuit f_0.

If C = 0, then

$$Z_{00}(s)=sL(-\tau_{load}s+1)^{-1}, \qquad (2)$$

where $\tau_{load}=L/R_{diff0}>0$ is the load circuit time constant.

Options (Fig. 4) of the dependencies of the module and the argument of the input resistance of the PP of the pulse power supply with and without parallel capacitance to the electric arc have frequency characteristics (FC) that coincide.

The closeness of FC indicates similarity and small differences in transient processes according to the main quality indicators. Thus, the circuit under consideration with the initial data adopted in this article has a frequency transfer coefficient of the same type as a first-order non-minimum phase (phase-shifting) link

$$Z(j\omega)=k(\tau j\omega-1),$$

where $k=R_{diff0}$, $\tau=L/R_{diff0}>0$.

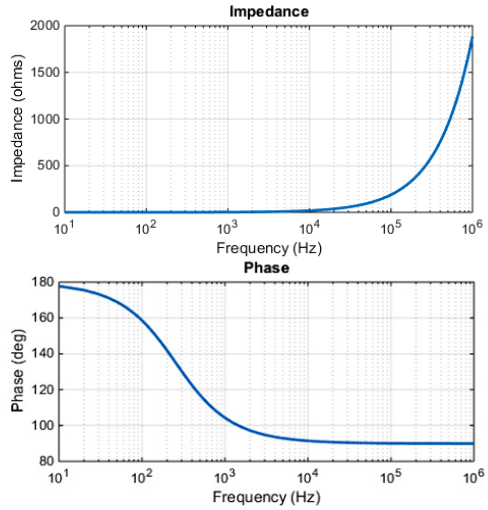

Fig. 4. Frequency characteristics of the input impedance of the PP of the power source loaded on an electric arc, for C = 0 and C = 3 μF

Frequency response graphs for the output impedance of the PP, constructed according to expressions (1), (2), are shown in Fig. 5. Note that for $C\neq0$, this PP is a broadband frequency-selective system ($B_{0.707}/f_0$ >> 1) with bandwidth $B_{0.707}$ = 100 kHz.

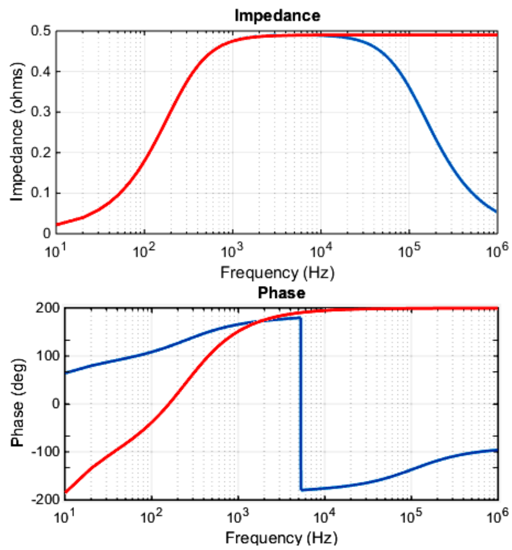

Fig. 5. Graphs of frequency response (above) and phase response (below) of the output circuit impedance

Logarithmic characteristics of the module and phase of the input conductance of the PP of the *PC* for the case of the absence of capacitance at the output of the pulse current stabilizer – unstable with negative self-alignment of the aperiodic link

$$Y_{i0}(s)=1/Z_{i0}(s)=k(-1+\tau s)^{-1} \qquad (3)$$

have been constructed in Fig. 6,*a*; the Nyquist diagram is shown in Fig. 6,*b*. According to (3), the asymptotic characteristic has a break at the point $\omega_1 = 1 / \tau$. Bandwidth is 0 – 465 Hz.

Figure 7 shows the frequency response and phase response of the «power source – arc» system in the open state.

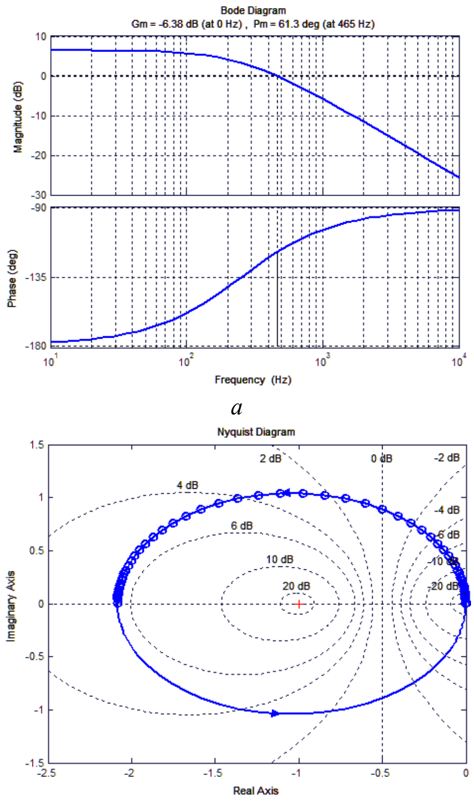

Fig. 6. Modulus and argument of the input admittance of the PP (a); Nyquist hodograph for this case (b)

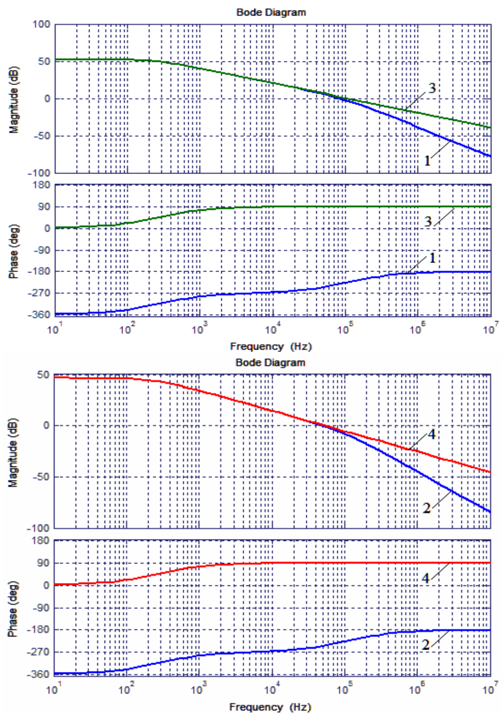

Fig. 7. Frequency response and phase response of the open circuit of the pulse current stabilizer when controlled by the output current i_{arc} (1-2) and the choke current i_L (3-4)

From graphs shown in Fig. 7 it can be seen that the closed system for the considered options will be unstable ($L(\omega) > 0$, $\varphi_{\text{margin}}(\omega) < 0$; $L \to \infty$, $\varphi_{\text{margin}} = -51.9° \div 90.2°$), which introduces additional complications in the construction of the converter control circuit [21].

From the nature of $\varphi(\omega)$ and $A(\omega)$ (Fig. 7), it follows that the construction of closed current stabilization systems of the considered converter causes difficulties, since it is very difficult to ensure a sufficient margin of stability at a high amplification factor in a closed circuit due to a very rapid increase in the phase shift (the angle $|\varphi|$ exceeds 180°) with an almost unchanged frequency response of the converter.

Thus, the considered continuous models can be used in the process of designing devices based on pulse voltage converters for loads with negative differential resistance: sources of secondary power supply, etc., to conduct research on the main properties of these converters.

Conclusions.

1. Expressions for the frequency transfer function, input and output resistances of a pulse voltage converter operating on an arc load with negative differential resistance were obtained by the method of averaging and linearization.

2. The transfer functions of the converter with output by arc current and choke current are not minimally in phase. This explains the nature of the phase characteristics of the converter and the complexity of the synthesis of current regulators for it.

3. The frequency response and phase response for the pulse voltage converter by arc current and choke current were studied.

4. The transfer functions of the continuous model by arc current and choke current at the given parameters are the same, which must be taken into account when designing regulators.

Conflict of interest. The authors of the article declare that there is no conflict of interest.

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E.M. Vereshchago[1]*, PhD, Assistant Professor,*
V.I. Kostiuchenko[1]*, PhD, Assistant Professor,*
S.M. Novogretskyi[1]*, PhD, Assistant Professor,*
[1] Admiral Makarov National University of Shipbuilding,
9, Heroyiv Ukraine Ave, Mykolaiv, 54025, Ukraine,
e-mail: venmkua@gmail.com;
vitalii.kostiuchenko@nuos.edu.ua (Corresponding Author);
sergii.novogretskyi@nuos.edu.ua

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