

The dependence of the deviation of the output stabilized current of the resonant power supply during frequency control in the systems of materials pulse processing

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Dmytro Vinnychenko

Department of Pulse Electrotechnical Systems
Institute of Pulse Processes and Technologies
of NAS of Ukraine
Mykolaiv, Ukraine
vdvvs@gmail.com

Natalia Nazarova

Department of Pulse Electrotechnical Systems
Institute of Pulse Processes and Technologies
of NAS of Ukraine
Mykolaiv, Ukraine
nazarovanataly2000@gmail.com

Iryna Vinnychenko

Department of Computerized Control Systems
Admiral Makarov National University of Shipbuilding
Mykolaiv, Ukraine
i.l.vinnychenko@gmail.com

Abstract — The calculated dependences for determining the deviation of the output current of the resonant power supply of the materials pulsed processing system from a given stabilized value are obtained. The inversely proportional dependence of the output current on the frequency at the input of the series resonant circuit is obtained. These dependencies can be applied for the frequency control of the inverter's switches commutation which stabilizes the RMS value of the output current. At the close to short circuit modes, the deviation of the output current from the stabilized value does not exceed 2%, and therefore it can be ignored.

Keywords — stabilized RMS current; resonant power supply; frequency control.

I. INTRODUCTION

Power supplies with stabilized output current are most common for arc load [1]. In modern industrial power supplies, pulse-width current regulation with hard switching are quite popular. For soft switching, resonant inverters with switching in zero current and voltage are used [2-5]. The Q-factor of such resonant circuits is not big enough and causes the high voltage in the resonant circuit being the negative factor.

However, in the electro-discharge processing of dielectric and semiconducting environment, the power supplies that provide high voltages up to 50 kV are usually required. In such cases, the pulse current generators [6] with accumulative capacitors [7] are used, which form discharge pulses with long currentless pauses [8].

The production of metal-carbon composite nanomaterials by the electro-discharge method is known as well [9]. It should be noted that the use of the pulse

current generators, the discharge current cannot be stabilized. Traditionally, to control the generator of impulse currents, not the characteristics themselves (discharge current or voltage) are used, but their functionals, for example, the maximum value of the discharge current, the voltage at which the formation of the discharge channel ends, and others [10, 11].

Thus, many technical applications, in addition to stabilizing the output current, require the high voltage at the output of the power supply (step-up secondary power supply systems), such as the method of electric-discharge synthesis of carbon nanomaterials from carbon-containing gases [12], in which the closure of the gas discharge channel at the frequency of up to 20 kHz requires the high voltage up to 30 kV, or charging the capacitive storage of the pulse current generator with direct current [15], where up to 50 kV are needed. For these applications, the resonant power supply with the series resonant circuit may be optimal, since it provides an almost constant RMS current in the wide range of the load voltage variation [1].

The provision of the given stabilized current is usually carried out using parametric control, which does not react to the current state of the load characteristics [14]. However, for some technical applications, for example, the optimal mode of obtaining nanocarbon from gas [15], it is necessary to maintain the specified value of the stabilized current, depending on the real time load characteristics. Fixed sinusoidal current systems are widely used in industry [1], where it is known that the output alternating current is determined by the inductive resistance of the resonant circuit, which can be changed by controlling the frequency. But the task of controlling the value of the output current of the

inverter with the series resonant circuit is complicated by the need to maintain either the resonant mode or the mode of stabilization of the output current. However, the current is stabilized at the resonant frequency. When the source frequency deviates from the resonant frequency, the output current value deviates from the preset stabilized value. For technical applications, it is necessary to consider this deviation, therefore, the studying of the deviation of the resonant power supply output stabilized current caused by the frequency deviating from the resonant one is an urgent task.

Thus, **the research goal** is to determine the quantitative characteristics of the deviation of the resonant power supply for the materials pulsed processing output current from the given stabilized value with the frequency control of the inverter switches commutation, by which the given effective value of the output current is obtained.

II. DEPENDENCES OF THE OUTPUT CURRENT OF THE RESONANT POWER SUPPLY ON THE LOAD RESISTANCE AND THE FREQUENCY DEVIATION FROM THE RESONANT ONE

The resonant power supply consists of a connected voltage inverter, a series resonant LC circuit and an active load connected in parallel with the capacitor C (Fig. 1, a). To obtain the electrical load characteristics, it is sufficient to analyze the simplified scheme (Fig. 1, b).

The paper proposes to use the principle of frequency dependence of reactive resistance of inductive elements, or the control of the frequency-dependent parameters change of the flow-forming circuit on the basis of the resonant tank. The advantage of this approach is the implementation of the principle of the parametric current stabilization, which is the simplest and the most reliable in the construction of the power devices.

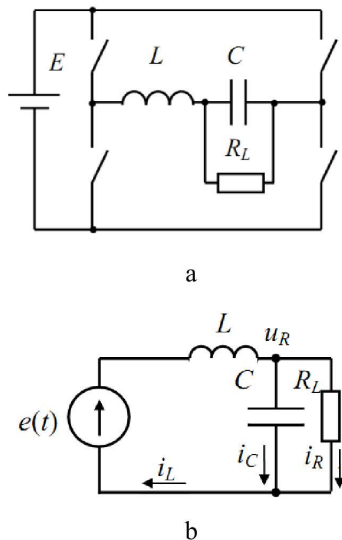


Figure 1. The resonant power supply

The total resistance of the circuit in fig. 1,b for the harmonic case:

$$\mathbf{Z}_{RLC} = j\omega_0 L + \frac{R}{1 + Rj\omega_0 C} = \frac{j\omega_0 L(1 + Rj\omega_0 C) + R}{1 + Rj\omega_0 C}, \quad (1)$$

where $\omega_0 = \frac{1}{\sqrt{LC}}$ is the resonant frequency.

The current of the inverter switches for the harmonic case is symbolically equal to $\mathbf{I}_L = \frac{\mathbf{E}}{\mathbf{Z}_{RLC}}$, where \mathbf{I}_L and \mathbf{E} are the current and sinusoidal voltage complexes $e(t)$.

The load R_L voltage is

$$\mathbf{U}_R = \mathbf{I}_L \cdot \frac{R}{1 + Rj\omega_0 C} = \frac{\mathbf{E} \cdot (1 + Rj\omega_0 C)}{j\omega_0 L(1 + Rj\omega_0 C) + R} \cdot \frac{R}{1 + Rj\omega_0 C},$$

$$\mathbf{U}_R = \frac{\mathbf{E} \cdot R}{j\omega_0 L(1 + Rj\omega_0 C) + R}. \quad (2)$$

The load current is

$$\mathbf{I}_R = \frac{\mathbf{E}}{j\omega_0 L(1 + Rj\omega_0 C) + R}, \quad (3)$$

$$\mathbf{I}_R = \frac{\mathbf{E}}{j\omega_0 L + R(j\omega_0 C j\omega_0 L + 1)}. \quad (4)$$

After algebraic transformations and considering the resonance condition

$$j\omega_0 L = \frac{1}{j\omega_0 C} \quad (5)$$

one can get the well-known dependence [Volkov], which determines the independence of the load current from the load resistance.

$$\mathbf{I}_R = \frac{\mathbf{E}}{j\omega_0 L + Rj\omega_0 C(\omega_0 L - \frac{1}{\omega_0 C})} = \frac{\mathbf{E}}{j\omega_0 L}. \quad (6)$$

We introduce the relative deviation of the frequency of the inverter from the resonant one

$$q = \frac{\omega_1}{\omega_0}. \quad (7)$$

Denote the harmonic number n . For n harmonics of frequency $q\omega_0$ from (4) taking into account (5) we obtain

$$\mathbf{I}_{Rn} = \frac{\mathbf{E}_n}{jnq\omega_0 L + R(j\omega_0 C j\omega_0 L \cdot (nq)^2 + 1)} =$$

$$= \frac{\mathbf{E}_n}{jnq\omega_0 L + R(1 - (nq)^2)}. \quad (8)$$

Enter the value of the reduced dimensionless load resistance $k = \frac{R}{nq\omega_0 L}$, and substitute it to (8)

$$\mathbf{I}_{Rn} = \frac{\mathbf{E}_n}{jq\omega_0 L \cdot n \cdot (1 + jk((nq)^2 - 1))}. \quad (9)$$

Summarize the obtained results in the case of the rectangular input voltage.

The shape of the output voltage of the full-bridge voltage inverter is rectangular with the amplitude U_m and the period $T=2\pi/\omega$, the Fourier series distribution is as follows:

$$e(t) = \frac{4 \cdot U_m}{\pi} \cdot \sum_{n=1}^{\infty} \frac{\sin(n\omega t)}{n}, n=1,3,5... \quad (10)$$

where n is the voltage harmonic number.

Whence the complex EMF for each harmonic can be represented as follows

$$\mathbf{E}_n = \frac{4 \cdot U_m}{\pi} \cdot \frac{e^{j0}}{n}, \quad (11)$$

The modulus of the amplitude of the load current for n harmonics is obtained from (9) taking into account (11)

$$I_{mn} = \frac{E_n}{nq\omega_0 L \sqrt{1+k^2((nq)^2-1)^2}},$$

$$I_{mn} = \frac{4 \cdot U_m}{\pi n^2 q \omega_0 L \sqrt{1+k^2((nq)^2-1)^2}}. \quad (12)$$

The load current RMS value is determined by the amplitude of each harmonic as follows

$$I_R = \sqrt{\frac{I_{m1}^2}{2} + \frac{I_{m3}^2}{2} + \frac{I_{m5}^2}{2} + \dots + \frac{I_{mn}^2}{2}}. \quad (13)$$

Substituting (12) into (13) obtain

$$I_R = \frac{2\sqrt{2} \cdot U_m}{\pi q \omega_0 L} \cdot \sqrt{\sum_{n=1}^{\infty} \left(\frac{1}{n^2 \sqrt{1+k^2((nq)^2-1)^2}} \right)^2}. \quad (14)$$

For the rectangular voltage of the inverter, the sum of the series (14) at $k=0$, $q=1$ is equal to

$$I_R = \frac{U_m}{4\sqrt{3} f_0 L}, \quad (15)$$

where $f_0 = \omega_0 / 2\pi$.

Using (14) allows to set the output current I_R , changing the switching frequency of the power switches of the inverter according to the law

$$q = \frac{2\sqrt{2} \cdot U_m}{\pi \omega_0 L I_R} \cdot \sqrt{\sum_{n=1}^{\infty} \left(\frac{1}{n^2 \sqrt{1+k^2((nq)^2-1)^2}} \right)^2}. \quad (16)$$

For the harmonic case, the effective value of the load current is obtained from (9), using $n=1$, and instead of E_n we use the effective value of the sinusoidal EMF $e(t)$.

$$I_R = \frac{E}{q \omega_0 L \sqrt{1+k^2(q^2-1)^2}}. \quad (17)$$

Using (16) allows to set the output current I_R , changing the inverter switching according to the law

$$q = \frac{E}{I_R \omega_0 L \sqrt{1+k^2(q^2-1)^2}}. \quad (18)$$

III. MATHEMATICAL MODELING OF THE OUTPUT CURRENT AT THE CLOSE TO RESONANT FREQUENCY

The control of the output current by means of the switching frequency of the power switches (17) leads to the deviation from the resonant mode, which may disrupt the stabilization of the output current RMS value. Therefore, the mathematical modeling of the output current at the close to resonant frequency is performed.

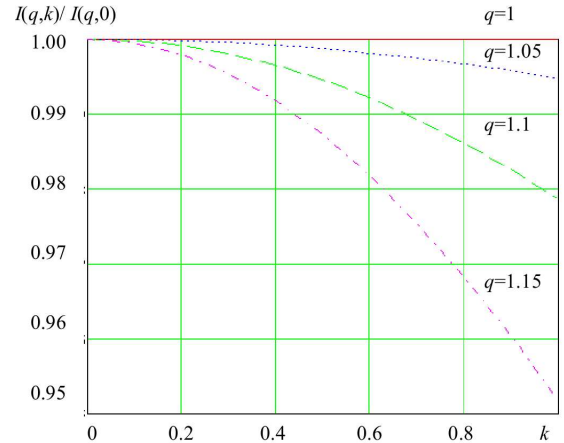
Set the value of the relative switching frequency of the power switches $q = \omega/\omega_0$ and by means of MathCad calculate the deviation of the output current for different q from its calculated value during the change of the load factor k .

First, the calculation is performed according to the formula for the first harmonic, which gives high accuracy in the resonant mode and is characterized by the simplified notation. The current value is calculated for each q and k :

$$I(q, k) = \sqrt{\frac{2\pi}{q\omega_0} \int_0^{q\omega_0} \left(\frac{U_m}{q\omega_0 L} \cdot \frac{\cos(q\omega_0 t)}{\sqrt{1+k^2(q^2-1)^2}} \right)^2 dt}. \quad (19)$$

Deviations of the relative output current at the given deviation of the relative frequency q from the resonant one, reduced to the short-circuit current $I(q,k)/I(q,0)$, shown in Fig. 2. In fig. 2, a there are the results of the calculation for the first harmonic according to (19), and in Fig. 2, b there are the results of the calculation for 10 harmonics. For the convenience of the current analysis, they circuit currents reduced to their value at $k=0$ (which corresponds to the short-circuit mode of the load).

The results of the calculation in Fig. 2, b, shows the deviation of the relative output current at the given deviation of the relative frequency q from the resonant one and with the load k , given to the short-circuit current $I(q,k)/I(q,0)$.



a

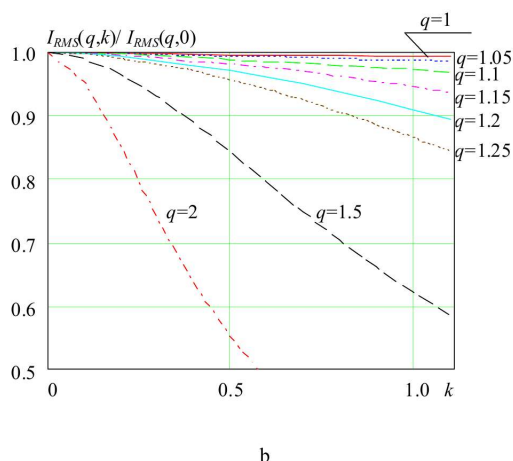


Figure 2. Deviations of the relative output current

Fig. 3, a shows the same dependences constructed by formula (17). Analysis of the simulation results showed that the use of (17) and (19) gives identical results and coincides with the experimentally obtained dependences. When $k=0,2$, the deviation of the current from its short-circuit value is less than 0.3%. The deviation of the load current from the short-circuit current can be calculated by (17) or (19).

Fig. 3, b, shows the deviation of the relative output current at the given deviation of the relative frequency q from the resonant, given to the short-circuit current at $q=1$: $I(q,k)/I(1,0)$, calculated by (17). The obtained dependences show that the load current can be adjusted by changing the inverter switching frequency.

The calculation of the RMS current for the inverter rectangular voltage will be carried out according to the equation for the sum of ten harmonics, which gives high accuracy in all conditions

$$I(q,k) = \sqrt{\frac{2U_m}{\pi^2 L} \int_0^{2\pi} \sum_{n=1}^{10} \left(\frac{\cos(qn\omega_0 t)}{n^2 \sqrt{1+k^2(n^2 q^2 - 1)^2}} \right)^2 dt}. \quad (20)$$

The results of the calculation according to (14) are shown in Fig. 4, which shows the deviation of the relative output current at the given deviation of the relative frequency q from the resonant one and at the load resistance of k , given to the short-circuit current at $I(q,k)/I(q,0)$ (Fig. 4, a), and given to the short-circuit current at $q=1$: $I(q,k)/I(1,0)$ (Fig. 4, b).

Analysis of the simulation results showed that the use of (14) for the sum of ten harmonics coincides with the calculation according to (20), and allows to calculate the load current, which coincides with the experimentally obtained dependences.

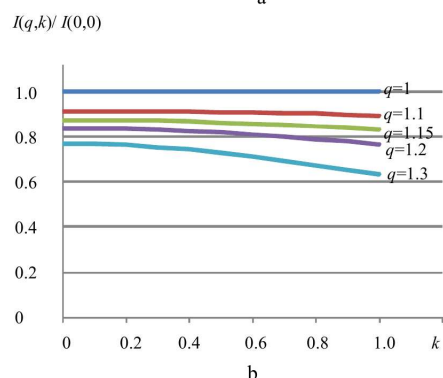
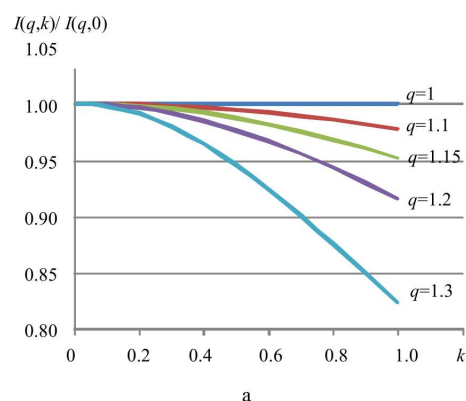
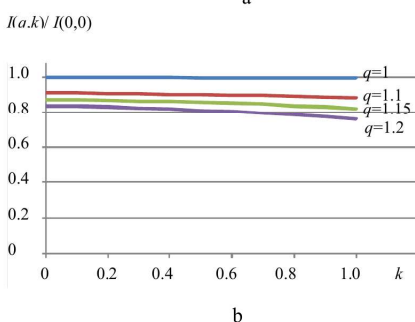
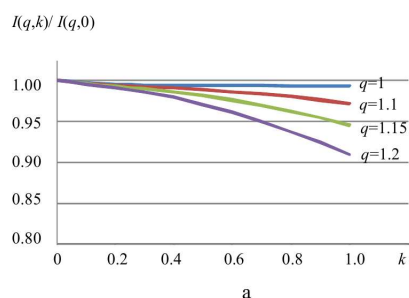


Figure 3. Deviation of the relative output current at the given deviation of the relative frequency

A comparison of the dependences in Fig. 3 and Fig. 4 shows that the deviation of the relative output load current at the rectangular voltage on the inverter is up to 1% greater than the deviation for the case when the resonant circuit is powered by the sinusoidal voltage source. This simplifies the real time calculations when controlling the load current, using the equation for the first harmonic (18), which requires less resource consumption of the computing system of the controller.


 Figure 4. Deviation of the relative output current at the given deviation of the relative frequency q from the resonant one and at the load

The results of the calculations shown in Fig. 2–Fig. 4 are well coordinated with the experimentally obtained results shown in table. 1.

TABLE I. THE RESULTS OF THE CALCULATIONS

k	q		
	1	1,1	1,2
0	1	1	1
0,4	0,99	0,99	0,98
0,6	0,99	0,99	0,96
0,8	0,99	0,98	0,94
1	0,99	0,97	0,91

An important feature of the considered resonant power supply is the deviation of the output current due to the load from its stabilized value (6) at the non-zero value of the load resistance k . This deviation is greater the greater the deviation of the frequency from the resonant one is. But increasing the frequency allows to smoothly adjust the output load current. The control law of the output RMS current by changing the switching frequency of the inverter power switches (16), (18), allows for smooth regulation of the output current to ensure its optimal value. During the construction of the control system that provides the given current value, it is necessary to consider the deviation of the output current from its stabilized value. For example, in the process of the capacitors charging using such a power supply, the equivalent load resistance increases and may exceed $k=1$ [13]. In this case, the current deviation must be considered. The expected deviation of the current value during the use of the inverter with the resonant circuit input rectangular voltage can be calculated using the equation for the sinusoidal voltage with the frequency of the first harmonic (16) not for the rectangular one. For electro-discharge nanocarbon synthesis [15], which is characterized by values of $k \leq 0.2$, the current deviation does not exceed 2% with an increase in the frequency by more than 30%, this deviation can be completely ignored and one may use the simple equation (15) to calculate the current for the inverter rectangular voltage.

IV. CONCLUSION

Quantitative characteristics of the deviation of the resonant power supply output current the set stabilized value at frequency control of the inverter switches which allow to receive the stabilized RMS value of the output current, are determined. The output power supply current depends on the switching frequency of the inverter switches inversely, so one can control the output current by increasing the inverter switching frequency. The deviation of the output current from the expected stabilized value depends on the reduced dimensionless load resistance, and the deviation of the inverter switching frequency from the resonant one. For the technical applications in which $k \leq 0,2$, the current deviation does not exceed 2% when the frequency increases by more than 30%. This deviation can be completely ignored and allows to calculate the current value using the equation (15) for the inverter rectangular voltage. In the other cases, the output current and its deviation can be calculated using the equation for the first harmonic, because the result of the calculation with an accuracy of 1% coincides with the result for the sum of the number of harmonics, but requires less resource of the computing system. The results of the calculations

are well coordinated with the experimentally obtained results.

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