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DEVELOPMENT OF METHOD FOR FREQUENCY REGULATION OF OUTPUT CURRENT IN HIGH-VOLTAGE TRANSFORMERLESS RESONANT CHARGERS OF CAPACITIVE ENERGY STORAGE DEVICES

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The object of research is high-voltage systems of electric discharge installations for various technological purposes. The work reports solving the problem of enabling the rate of charging of a capacitive energy storage, set by the requirements of a certain high-voltage technology.

The quantitative characteristics of the deviation of the output current of the resonant inverter from the set stabilized value when changing the switching frequency of inverter switches in the range of output voltage change from 0 to 20 kV were determined. Using the Fourier transform of the rectangular input voltage, the frequency regulation possibility of the output current of the charger for capacitive energy storage devices was analyzed. Estimation dependences of the output current of resonant inverter on the load resistance and frequency deviation from resonant frequency were derived. These dependences could be used to implement frequency control over the switching inverter transistors, with the help of which the given effective value of the output current of the resonant inverter is obtained.

A method of frequency regulation of the output current in high-voltage transformerless resonant charging devices of capacitive energy storage devices has been developed. Special feature of this method is that it is based on the frequency dependence of reactive resistances of the inductance and capacitance of the resonant circuit connected in series. Owing to that, it makes it possible to adjust the switching frequency of the inverter's power switches depending on the relative resistance of the load and the specified growth rate of the capacitive energy storage voltage.

The results reported here could be used in the design of benches for testing the electrical strength of high-voltage cables, as well as for the construction of high-voltage transformerless chargers in systems of electric discharge impulse processing of materials

Keywords: frequency regulation, high-voltage transformerless chargers, capacitive storage devices, resonant inverters

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1. Introduction

Testing the electrical strength of the insulation of high-voltage cables with a voltage of 2 kV with a rectified voltage above 70 kV is a mandatory procedure after laying the cable before switching on, and then annually according to rules for the technical operation of consumers' electrical installations [1]. Existing high-voltage stationary installations for testing, for example, at enterprises manufacturing power cables, have significant dimensions and mass (from 400 kg to 18 t). The large size of these installations is due to the capacitive nature of the electrical load (the specific capacitance between the core and the screen for cross-linked polyethylene cables is 330 pF/m with cable lengths from 1 km to 20 km). To charge such a capacity to at least 70 kV, it is necessary to use a high-voltage transformer with a rectifier with a capacity of up to tens of kilowatts. The need to conduct tests of the electrical strength of high-voltage cables after mechanical damage as a result of military operations, or on the routes of cable lines on which construction work is carried out, determines the demand for small-sized high-voltage installations. Such installations are actually powerful high-voltage capacitor chargers, and research into the development of such devices is urgent.

High-voltage transformerless resonance chargers (TlRC) of capacitive energy storage devices (CESD) [2] can become an effective alternative to existing installations for testing the electrical strength of high-voltage cables with a rectified voltage of 70 kV. They could also be used instead of traditional chargers with step-up transformers in systems of electric discharge impulse processing of materials [3, 4]. As shown in [2], such systems will make it possible to significantly reduce the mass and dimensions of capacitor chargers and test facilities based on them. Power sources providing high voltage above 50 kV [5] or below [6, 7] are usually required for electric discharge treatment of dielectric media. In such cases, pulse current generators (PCG) [8] with CESD storage capacitors [9], which form discharge pulses with long current-free pauses [10], are traditionally used.

Development of resonant circuit output current regulation method, which is the charging current of CESD, is an important task, resolving which could allow changing the charging time and, accordingly, the power of the charger. Reducing the power of chargers would a priori lead to an even greater reduction in their mass and dimensions. High-voltage resonant systems are being designed for electric discharge units with storage capacitors. Other initial dynamic characteristics of such systems can be enabled by means of parametric adjustment [10]. An alternative to this approach could be the principle of regulation based on the deviation of initial characteristics [11], which are stochastic in nature [12, 13].

Existing resonant systems with a stabilized output current in CESD charging devices include high-voltage transformers [14, 15], which significantly burden the installations as a whole. The construction of high-voltage transformerless resonant charging devices could make it possible to significantly reduce the dimensions and mass indicators of such devices. Therefore, research in this area is relevant.

2. Literature review and problem statement

In order to construct effective high-voltage transformerless resonant systems for testing the electrical strength of high-voltage cables with rectified voltage, it is necessary to create methods for adjusting the output characteristics of such systems. Due to the fact that such systems are actually capacitor charging devices, it would suffice to develop a method for regulating the output current of the resonant circuit.

When the switching frequency deviates from the resonance frequency, the output current value deviates from the set stabilized value. The effect of such a frequency deviation on the output current of high-voltage transformerless resonant chargers of capacitive energy storage devices has not been investigated in detail. Therefore, to develop a method of frequency control over the output current of the charger, it is first advisable to analyze the interaction of the specified characteristics.

The use of resonant systems with a stabilized output current in CESD charging devices is not new [15, 16]. But high-voltage transformers were an integral part of chargers for obtaining high voltage on CESD. The reasons for the use of high-voltage transformers in resonant chargers are justified in [15] to allow for the criterion of the minimum dimensions of the reactive elements of the resonant circuit, but it did not take into account additional dimensions of the transformers themselves. In order to reduce the mass of chargers, it is advisable to remove the transformer from their composition.

Increasing the voltage of capacitors using resonant circuits was studied in [17], but the system in question is not a charging device. Therefore, it is advisable to investigate the use of a resonance system as part of the charging device, which would allow removing the transformer from it.

The issue of optimizing and adjusting the output characteristics of constant current resonant systems has been studied in detail in a number of works [18, 19], but the task of enabling high voltage at the output of such systems has not been addressed. Therefore, authors faced the problem of developing such a method of regulating the output current, which would be effective for achieving a high voltage of CESD.

It should be noted that using inverter frequency converters from the mains frequency to the increased resonant frequency in resonant systems does not cause the problems of reducing the dynamic losses of switching transistors. This is due to the fact that to ensure soft switching of the inverter transistors with switching in the zeros of current and voltage, resonant systems are used, for example, [20, 21].

Thus, the regulation method to be developed should solve all the above-mentioned problems. Let us note the idea and the main difference between the method of frequency regulation of the output current of the resonant system being developed and existing ones. Usually, provision of the specified stabilized current is carried out using parametric regulation, which does not respond to the current state of the load characteristics [14, 18]. The research is based on the task of regulating the current depending on the current voltage on CESD to enable a complex rate of charging according to the requirements of a specific electric discharge technology or a given mode of testing the electrical strength of a high-voltage cable.

The essence of the method is as follows. It is known from [14] that the output alternating current of a single resonant circuit, which contains inductive and capacitive elements, is determined by the inductive resistance of the resonant circuit, which depends on the resonant frequency. That is, by changing the resonant frequency, one can also change the output current. The closest in essence to the method for adjusting the load current of resonant circuits developed in this work is non-resonant tuning of reactive elements [18]. But this method involves changing the parameters of the elements of the resonant circuit, and not the frequency of the input current.

It should be noted that we have earlier developed a method for frequency-parametric regulation by discharge alternating current [22], which cannot be directly applied without improvement to regulate the output current of high-voltage resonant chargers. All this gives reason to assert that it is expedient to carry out a study on developing a new method for frequency regulation of the output current of a transformerless resonant charger to enable high voltage of CESD.

Thus, the proposed study should solve the task of providing a charging current corresponding to the output voltage of a high-voltage transformerless resonant charger of CESD, the research of which is ongoing. The use of a controlled transformerless resonance charger could result in solving the task of reducing the mass and dimensions of high-voltage installations, provided that technological requirements are met.

3. The aim and objectives of the study

The aim of our study is to develop a method for frequency regulation of the output current in high-voltage systems for testing the electrical strength of high-voltage cables with rectified voltage, built on the basis of high-voltage, high-frequency chargers. This will make it possible to enable the necessary amount of charging current according to the requirements of electric discharge technologies and high-voltage cable insulation test methods.

To achieve the goal, it is necessary to solve the following tasks:

– to derive the dependence of output current of the resonant inverter on the load resistance and the deviation of the frequency from the resonant frequency, which are quantitative characteristics of the deviation of the output current from the specified value when the switching frequency of the inverter transistors is changed;

– to carry out mathematical modeling of the output current of the resonant inverter in the vicinity of resonant frequency in order to compare the quantitative characteristics of the deviation of the output current of the resonant circuit according to the sinusoidal and rectangular forms of the input voltage;

– to formulate the essence of the method for frequency regulation of the output current of high-voltage transformerless resonant chargers and carry out its validation.

4. The study materials and methods

4. 1. The object and hypothesis of the study

The object of research is high-voltage systems of electric discharge installations for various technological purposes. The subject of research is electromagnetic processes in high-voltage transformerless resonant devices of capacitive energy storage.

The research hypothesis is as follows. A resonant circuit at the resonant frequency forms a stabilized current regardless of the load resistance. This current is determined only by the input voltage of the inverter and the reactance of the inductive element of the resonant circuit. It partially decreases with a significant increase in the output voltage. As the frequency deviates from the resonant frequency, the reactive resistance and, accordingly, the output current will change. Stabilization of the output current is also disturbed when the switching frequency deviates significantly from the resonant frequency.

The idea of our study is to regulate the output current of the charger by changing the switching frequency of the inverter transistors, but the dependence of current on the switching frequency and the output voltage is not studied in detail. It is necessary to establish a relationship between the output current of the charger and the switching frequency and output voltage in order to construct a correct method for regulating the output current.

The following assumptions are accepted. Developing a method for frequency regulation of the output current in transformerless resonant charging devices of capacitive energy storage devices is carried out under the condition of using a single-circuit resonant inverter. For two-circuit charging systems [19, 23] and recharging of capacitors, additional scientific questions arise [24, 25], which can be investigated later for high-voltage resonant systems.

4. 2. Research methods

Research methods are mathematical modeling and computer simulation. To verify the theoretical results, simulation of a transformerless resonant charger with the proposed method for regulating the output current is carried out using LTSpice.

5. Results of investigating frequency regulation of output current in high-voltage transformerless resonant charging devices

5. 1. Examining the dependence of the resonant inverter output current on load resistance and frequency deviation from resonant

To analyze the dependence of the output current of the resonant inverter on load resistance and the frequency deviation from the resonant frequency, we used the scheme shown in Fig. 1. Fig. 1, *a* shows a diagram of a high-voltage inverter transformerless resonant charger of a capacitive energy storage device C_p. The resonant circuit is formed by the inductance L and the capacitance C_r. The voltage U on the capacity C_r is limited by the voltage on the capacity C_p (exceeds by the voltage of open diodes). Taking into account the fact that the current I through the load connected in parallel with C_r does not depend on load resistance, is stabilized, and is determined only by the resistance of the inductive element of the resonant circuit [14], the voltage U established on the capacity C_r can be set as the voltage drop on active resistance R [15, 26], which is calculated from expression $R=U/I$. It should be noted that the power $p_{Cp}=u_{Cp}i$ of charging the capacitor C_p has an active character because the product of the voltage on the capacitor u_{Cp} and the current i through it is always positive. Due to the simplification of the scheme, by replacing the series-connected rectifier and the capacitor C_p with an active resistance R (Fig. 1, *b*), a rougher model can be obtained. Such a model would make it possible to obtain the dependence of characteristics of the high-voltage transformerless resonant charger of the capacitive storage device on its parameters and the Q factor of the resonant circuit, convenient for analysis. In the scheme shown in Fig. 1*a* the voltage on the capacitor C_p increases during the charging process, and each corresponding value of the voltage U on the capacitor C_p corresponds to a separate value R (Fig. 1, *b*) and vice versa.

Thus, the resonant inverter consists of a connected voltage inverter, a series resonant LC circuit and an active load with resistance R, connected in parallel with the capacitor of the resonant circuit C (Fig. 1, *b*). The output alternating current is determined by the inductive resistance of the resonant circuit ωL, the value of which can be changed by changing the frequency ω. The voltage at the input of the resonant circuit due to the switching of the transistor switches has a rectangular shape, which can be represented as the sum of the harmonics of the Fourier series.

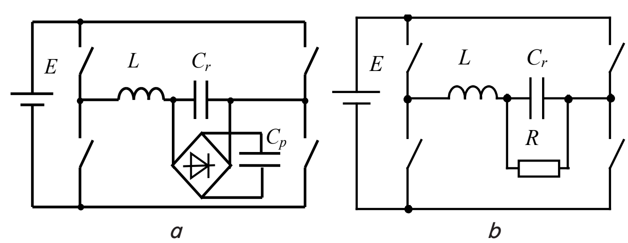

Fig. 1. Diagrams of a high-voltage inverter resonant charger: *a* – structural diagram; *b* – substitution scheme

The total resistance of the circuit (Fig. 1, *b*) for the harmonic case with the resonance frequency ω_0 can be calculated from the formula:

$$Z_{RLC}=\frac{j\omega_0 L\left(1+Rj\omega_0 C\right)+R}{1+Rj\omega_0 C}.$$

The current through the inverter switches for the harmonic case is symbolically equal to $I_L = E/Z_{RLC}$, where I_L and E are the complexes of current and sinusoidal voltage. The voltage and current on load R are equal to:

$$U_R = \frac{E \cdot R}{j\omega_0 L(1 + Rj\omega_0 C) + R}$$

and

$$I_R = \frac{E}{j\omega_0 L + R(j\omega_0 Cj\omega_0 L + 1)}. \tag{1}$$

After algebraic transformations and taking into account the resonance condition $j\omega_0 L = 1/j\omega_0 C$, the formula known from [14] can be derived:

$$I_R = \frac{E}{j\omega_0 L}, \tag{2}$$

which predetermines the independence of the current through the load on load resistance.

The notation of the relative frequency of the inverter (first harmonic) to the resonant frequency, which is determined by the expression $\omega_0 = 1/\sqrt{LC}$ is introduced:

$$q = \frac{\omega_1}{\omega_0}. \tag{3}$$

For the nth harmonic of the frequency $q\omega_0$ from (1), taking into account (3), we obtained:

$$I_{Rn} = \frac{E_n}{jnq\omega_0 L + R\left(1 - (nq)^2\right)}. \tag{4}$$

A variable is introduced that denotes the relative resistance of the load $k = R/\omega_0 L$, Substituting it instead of the load resistance R in (4), it is possible to obtain:

$$I_{Rn} = \frac{E_n}{j\omega_0 L} \cdot \frac{1}{nq\left[1 + jk\left((nq) - (nq)^{-1}\right)\right]}. \tag{5}$$

Expression (5) consists of a dimensional factor, which is equal to expression (2), and a dimensionless factor that depends on dimensionless variables, namely, the relative frequency of the inverter q, the harmonic number n, and the relative resistance of the load k.

These results are generalized for the case of rectangular input voltage.

The shape of the voltage at the input of the resonant circuit $e(t)$ is rectangular with the amplitude U_m and the period $T=2\pi/\omega$, and its expansion into the Fourier series takes the following form:

$$e(t) = \frac{4 \cdot U_m}{\pi} \cdot \sum_{n=1}^{\infty} \frac{\sin(n\omega t)}{n}, n = 1,3,5..., \tag{6}$$

where n is the voltage harmonic number.

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

$$E_{nm} = \frac{4 \cdot U_m}{\pi} \cdot \frac{e^{j0}}{n}. \tag{7}$$

The amplitude module of load current for n harmonic is obtained from (5) taking into account (7):

$$I_{Rnm} = \frac{4U_m}{\pi\omega_0 L} \cdot \frac{1}{n^2 q\sqrt{1 + \left(k\left((nq) - (nq)^{-1}\right)\right)^2}}. \tag{8}$$

The effective value of the current through the load is determined in terms of the amplitudes of each harmonic as follows:

$$I_R = \sqrt{\frac{I_{m1}^2}{2} + \frac{I_{m3}^2}{2} + \frac{I_{m5}^2}{2} + \ldots + \frac{I_{mn}^2}{2}}. \tag{9}$$

By substituting (8) for (9), we get:

$$I_R = AB, \tag{10}$$

where the factor $A = 2\sqrt{2} \cdot U_m/\pi\omega_0 L$ is dimensional and the factor B is dimensionless:

$$B = \sqrt{\sum_{n=1}^{\infty} \frac{1}{(2n-1)^4 q^2 \left[1 + \left(k\left(((2n-1)q) - ((2n-1)q)^{-1}\right)\right)^2\right]}}.$$

For the rectangular voltage of the inverter, the sum of the series (10) at $k=0$, $q=1$ taking into account $f_0 = \omega_0/2\pi$ equals:

$$I_R = \frac{U_m}{4\sqrt{3} f_0 L}. \tag{11}$$

For the harmonic case (sinusoidal shape of the input voltage), the effective value of load current is obtained from (5), using the effective value of the sinusoidal emf $e(t)$ and $n=1$ instead of E_n:

$$I_R = \frac{E}{\omega_0 L} \cdot \frac{1}{q\sqrt{1 + \left(k\left(q - q^{-1}\right)\right)^2}}. \tag{12}$$

In expression (12), the factor $1/q\sqrt{1 + \left(k\left(q - q^{-1}\right)\right)^2}$ is dimensionless, and the factor $E/\omega_0 L$ is dimensional. Notation introduced:

$$I_{SC} = \frac{E}{\omega_0 L} \tag{13}$$

Expressions (10) and (12) reflect the dependence of output current I_R on the relative deviation of the frequency of the inverter from the resonance q for different values of the relative resistance of load k.

The inverse dependence of q on I_R is represented implicitly, therefore (10) and (12) should be represented in tabular form (Table 1), the value of which is calculated according to expression (10), that is, for the rectangular shape of the input voltage.

From Table 1 we determine q, which will provide the output current I_R required by the requirements of the electric discharge technology of material processing. Each technology reported in the current paper requires a certain type of change in the charging current depending on the current resistance of the load. Three colors in Table 1 highlight three typical options for changing the charging current: pink – the maximum possible slightly decreasing current;

green – decreasing current for slower charging of CESD; blue – almost constant current.

Table 1

Dependence of the output current I_R of high-voltage transformerless resonant chargers for capacitive energy storage devices depending on the relative frequency q and relative load resistance k

K	*Q*					
	1.0055	1.007	1.009	1.0135	1.025	1.05
0–4	0.995	0.993	0.991	0.987	0.976	0.862
4–10	0.986	0.983	0.98	0.971	0.94	0.477
10–15	0.981	0.976	0.968	0.946	0.868	0.272
15–20	0.974	0.965	0.95	0.909	0.778	0.187
20–35	0.964	0.95	0.926	0.863	0.689	0.142
25–30	0.952	0.931	0.898	0.814	0.61	0.114
30–35	0.938	0.909	0.867	0.763	0.542	0.095
35–40	0.922	0.886	0.834	0.714	0.485	0.082
40–45	0.904	0.861	0.8	0.668	0.437	0.072
45–50	0.885	0.835	0.766	0.625	0.397	0.064
50–60	0.866	0.809	0.733	0.586	0.364	0.057

5. 2. Mathematical modeling of the output current of resonant inverter in the vicinity of resonant frequency

Fig. 2 shows dependences of the relative output current of resonant inverter on the relative frequency of inverter q and the relative resistance of load k, calculated according to expression (12) and according to expression (10) for the sum of ten harmonics. In Fig. 2, the value of k is located on the abscissa axes. In Fig. 2, *a*, the value of the dimensionless value of the current $I(q,k)/I(q,0)$, is located on the ordinate axis, reduced to the current $I(q,0)$ (where $k=0$, which corresponds to the short-circuit mode of the load). In Fig. 2, *b*, along the ordinate axes are the dimensionless value of the current reduced to the current at $q=1$: $I(q,k)/I(1,0)$. That is, these dependences make it possible to estimate how the values of currents relate to different values of q.

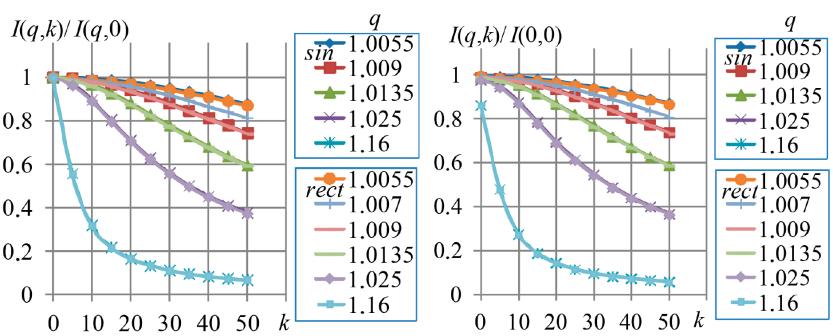

Fig. 2. Dependences of the relative output current of resonant inverter on the relative frequency of inverter q and the relative resistance of load k for sinusoidal (sin) and rectangular (rect) shapes of the input voltage. The relative output current is reduced to *a* – to the current $I(q,0)$ at current frequency q; *b* – to the current at resonance frequency $q=1$

To obtain current values in amperes, it is necessary to multiply the dimensionless current values by dimensional factors from expressions (10) and (12).

5. 3. Essence of the method for frequency regulation of the output current of high-voltage transformerless resonant chargers and its validation

As shown above, the dependence of q on I_R is represented in an implicit form, so it is advisable to represent the dependences of the dimensionless part (10) or (12) in tabular form.

The shape of the I_R charging current plot depending on the voltage on R (which in our studies simulates voltage on the capacitive storage device) is always determined by the electric discharge technology. So, in some cases, a constant charging current is required, and in others, a slowly falling, rapidly falling, increasing, etc. To enable the desired shape of the charging current plot, it is enough to set the trajectory of switching the switching frequency of inverter transistors in the table built according to expressions (10) or (12) (for example, Table 1), but with a smaller step k and q.

A new method for frequency regulation of the charging current in inverter high-voltage transformerless resonance charging devices of CESD has been developed, which implies sequentially changing the switching frequency of inverter depending on the current CESD voltage and the given trajectory of change in the charging current according to the requirements of electric discharge technologies. The developed method involves performing actions that should be divided into two stages. The first stage is preparatory, and the second stage is directly the stage of current regulation in the process of CESD charging.

The preparatory stage implies performing actions to calculate the specified trajectory of current regulation, which depends on the relative resistance of load k:

– set the values of k and q, starting with the values $k=0$ and $q=1$ with a positive fixed step, which can be both constant and variable according to the given algorithm;

– calculate for each k and q the value of the dimensionless part of the current according to expression (12) and fill in a two-dimensional table, each row of which is calculated for k=const, and a column for q=const;

– choose one of the dependences $I_R(k)$ of the current value on the relative load k for different technologies, represented in tabular form (for example, Table 2), given by the technology;

– in the table of the dependence of current I_R of high-voltage transformerless resonant chargers of capacitive energy storage devices on the relative frequency q and the relative load resistance k, the current values corresponding to the trajectory of the change in the charging current according to the given high-voltage technology are determined. The cells of this table are marked with a color corresponding to the color of the selected dependence $I_R(k)$ from the table of current regulation trajectories, and a pair (k, q) for each value I_R is recorded in the memory of the output current regulation system. The sequence of cells of the same color makes up the trajectory of current regulation, which depends on the relative resistance of load k.

This trajectory specifies the sequence (algorithm) of changing the switching frequency of inverter transistors q relative to the load resistance k.

The stage of current regulation in the process of CESD charging is as follows:

a) start the charger under mode $k=0$, for which the switching frequency of inverter transistors q is determined by the cell in the first row of the table of the dependence of output current I_R on the relative frequency q and the relative resistance of load k, which corresponds to the selected trajectory;

b) determine the current value of k by calculating, for example, from expression $k=Q\cdot|U|/(Q\cdot E-|U|)$ [26], based on the value of output voltage (measured or obtained from the feedback channel);

c) set the switching frequency of inverter transistors q according to the constructed current regulation trajectory depending on the current k;

d) operations (b) and (c) are repeated in a cycle until the output voltage reaches the value specified by the technology;

e) discharge CESD to the technological load, for example, with the help of an unregulated or regulated high-voltage commutator, after which repeat operations from (a) to (d) until the processing time specified by the technology expires.

The developed method for frequency regulation of the charging current corresponds to the characteristics of parametric regulation – the selection of parameters of resonant circuit (L, C), and frequency – changing the parameter (inductive resistance) of the resonant circuit. The devised method requires the use of large-volume tables and the execution of the current regulation trajectory task algorithm, which specifies the sequence (algorithm) of changing the switching frequency of inverter transistors q relative to the load resistance k. To implement such algorithms, modern microcontroller devices are used.

The method for frequency regulation of the output current is implemented as follows. We begin the preparatory process. Set the values of k and q, starting with the values of $k=0$ and $q=1$ with a positive fixed step, for example, for k the step $h_k=1$, for q the step $h_q=0.005$. Calculate for each k and q the value of the dimensionless part of the current according to expression (12) and fill in a two-dimensional table similar to Table 1, each row of which is calculated for k=const, and a column for q=const.

Choose one of the dependences $I_R(k)$ specified by the technology, for example from Table 2. The diagram of dependence of the relative current on the relative load according to Table 2 is shown in Fig. 3.

According to the given algorithm, the trajectory of switching the switching frequency of inverter transistors is built in Table 1. As a selection algorithm from Table 1 specified in Table 2 current, one can use the method of least squares. As a result, one of the trajectories is obtained highlighted in Table 1 by formatting the corresponding cells. Each trajectory corresponds to a certain high-voltage technology.

Table 2

Current value depending on the relative load k for different technologies (table of current control trajectories)

K	$I_R(k)$ first (Tp1) trajectory	$I_R(k)$ second (Tp2) trajectory	$I_R(k)$ third (Tp3) trajectory
0–10	0.86	0.99	0.99
10–20	0.86	0.98	0.97
20–30	0.86	0.96	0.93
30–40	0.86	0.94	0.86
40–50	0.86	0.90	0.80
50–60	0.86	0.87	0.73

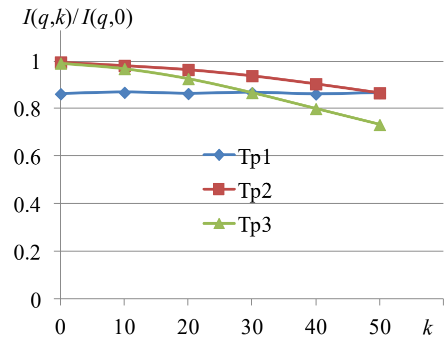

Fig. 3. Dependence diagram of the relative output current of resonant inverter on the relative resistance of load for each selected trajectory of switching the inverter transistors

After the preparatory process is completed, the CESD charging process is carried out, which we shall consider using the example of the first trajectory Tp1, in which the CESD charging is carried out by direct current.

The charger is started under the $k=0$ and $q=1.05$ mode (Table 1), which is determined by the first line of the constructed trajectory of switching the switching frequency of inverter transistors (Table 2). Determine the current value of k, calculated according to the given algorithm from the value of voltage on the load resistance. According to the value of the current k, proceed to the next cell of Table 1 according to the selected trajectory from Table 2. The process continues until the set value k is reached, which in the example is 50.

For validation of the developed method, simulation was carried out using LTSpice tools. Fig. 4 shows the scheme for simulation (Fig. 4, *a*) and the simulation results (Fig. 4, *b*). To simulate the control system for switching the frequency of the resonant circuit, SW switches S1–S7 controlled by pulse voltage on voltage sources with terminals a–g were used. The switching time is shown in Fig. 4, *b*. As shown above, the rectangular voltage source with a frequency equal to or higher than the resonant frequency can be replaced with a sinusoidal voltage source. Therefore, in the diagram in Fig. 4, *a*, the sinusoidal voltage sources were used with a frequency calculated for the adjustment trajectories Tp1–Tp3 according to Table 1. As can be seen from Table 1, only one trajectory requires switching the frequency (change of the parameter q), and the other two implement the charging of CESD at a constant frequency (q=const) are shown in Fig. 4, *a* by circuits with one power source. The parameters of an experimental sample of a high-voltage transformerless resonant charger were used for simulation: $L=22.3$ mH, $C_r=3.2$ nF, $f_0=19320$ Hz, $C_p=0.1$ μF.

To compare the results of simulation with the results of calculations based on the above expressions, the voltage on CESD for each k was calculated using expressions $f=qf_0$, $U_{calc}=2\pi fLI_Rk$, I_R was calculated from expression (12) (Table 3). Calculated (solid lines) and obtained from simulation (markers) voltage values on CESD, as well as the calculated frequency values (the same for calculation and simulation) are shown in Fig. 5.

The slight discrepancy in the voltage on CESD is explained by the fact that the switching of frequencies took place in the vicinity of the calculated points k (Fig. 4, *b*). But even such a deviation provides an almost linear dependence of voltage plot on time.

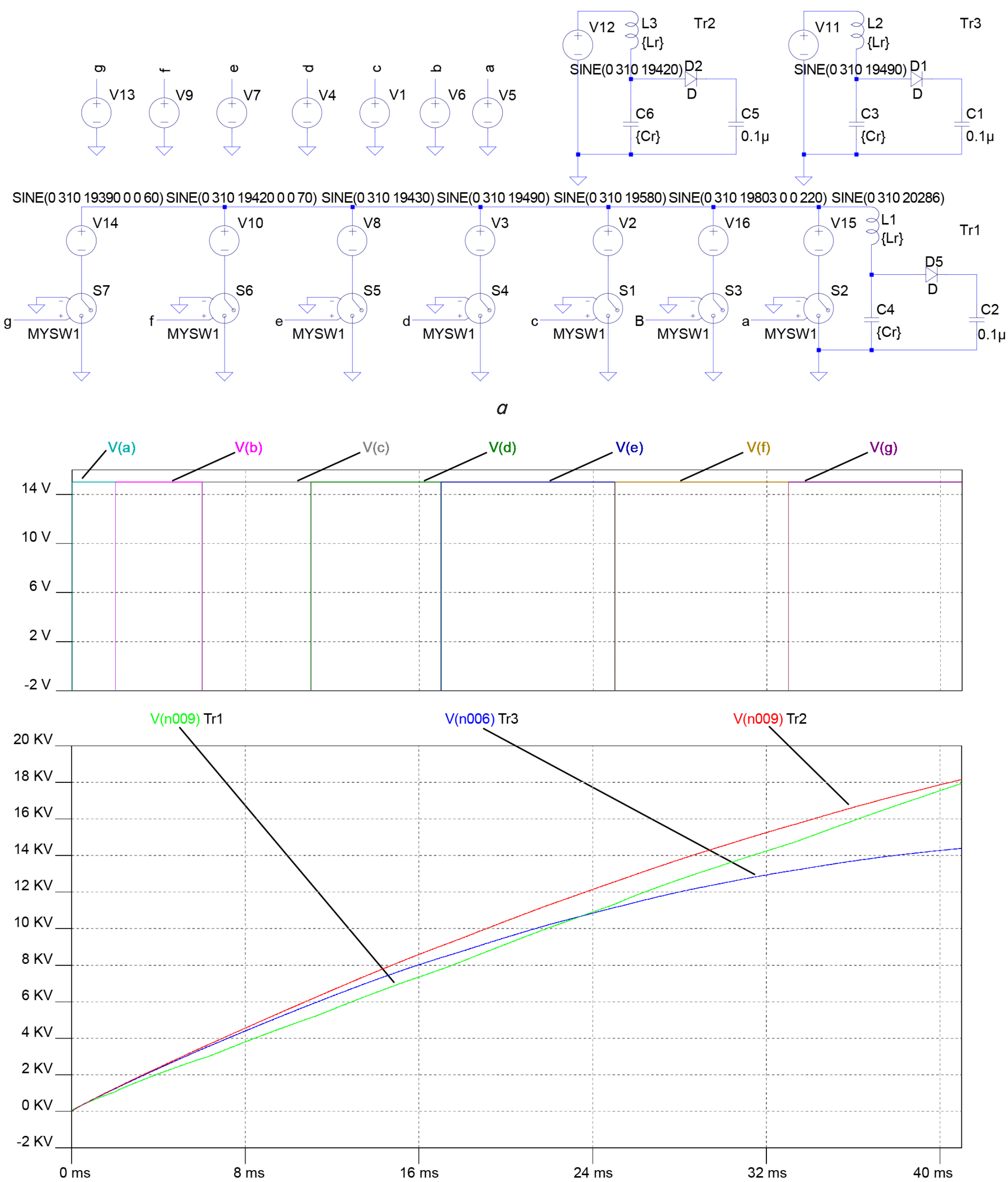

Fig. 4. Scheme and results of simulating the implementation of the method for frequency regulation of the charging current of capacitive energy storage device: *a* – scheme of the LTSpice model; *b* – simulation results in LTSpice

Table 3

Results of calculating the voltage on CESD for Tp1

k	q	f, Hz	ωL, Ohm	U_{calc}, kV	U_{LTC}, kV	SW
0–4	1.05	20286	2.842	1.17	1.06	a
4–10	1.025	19803	2.775	2.86	2.66	b
10–20	1.0135	19580	2.743	5.66	5.1	c
20–30	1.009	19490	2.731	8.45	7.7	d
30–40	1.007	19435	2.723	11.24	11.33	e
40–50	1.0055	19420	2.721	14.04	14.6	f
50–60	1.004	19390	2.717	16.82	17.9	g

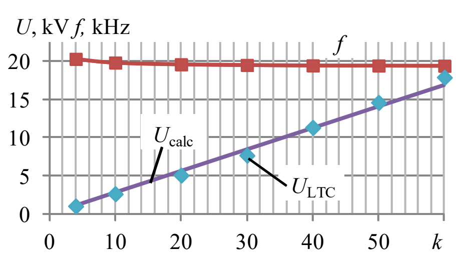

Fig. 5. Calculated and obtained from simulation by means of LTSpice voltage values of the capacitive energy storage device, as well as the calculated frequency values

6. Discussion of results of frequency regulation of the output current in high-voltage transformerless resonant charging devices

Analysis of our simulation results (Fig. 2) revealed that the dimensionless multipliers of expressions (10) for the rectangular input voltage and (12) for the sinusoidal input voltage, calculated for the same k and q, practically coincide. The difference in the values of the dimensionless factors calculated by expressions (10) and (12) for the same $k=50$ and $q=1.16$ is 0.72 %. For smaller values of k and q, this discrepancy is even smaller. This allows us to draw a conclusion about the possibility of using the simpler formula (12) even for the rectangular shape of the input voltage. That is, the output current and its deviation can be calculated only for the first harmonic. This is due to the fact that the result of the calculation with an accuracy of 1 % coincides with the result for the sum of a series of harmonics but requires a smaller resource of the computing system of the control controller.

Analysis of the voltage plots corresponding to each charging current adjustment trajectory (Fig. 4, *b*) shows that a constant charging current is implemented for Tp1, which is confirmed by the linear dependence of voltage on CESD on time. For Tp2, Tp3, the rate of increase of CESD voltage decreases over time, which is caused by a decrease in the charging current as k increases (Table 1). The value of k in Fig. 4, *b* is given for the case of constant charging current (Tp1), according to which k is proportional to the CESD voltage.

Thus, a new method for frequency regulation of the output current in inverter transformerless resonance charging devices of CESD has been developed. It uses the frequency dependence of reactive resistances of the inductance and capacitance of the resonant circuit connected in series and the adjustment of the switching frequency of power switches of the inverter depending on the relative resistance of load k. The application of the developed method in control systems of technological installations makes it possible to enable the specified output current of the resonant inverter, which is determined by a specific electric discharge technology.

The developed method for regulating the output current of resonant inverter can be applied to other technical applications that simultaneously require stabilization of the output current and high voltage at the output of the source. For example, electric discharge production of carbon nanomaterials from carbon-containing gases [27, 28], in which a high voltage of up to 30 kV is required to close the discharge gas channel with a frequency of up to 20 kHz, or spark plasma sintering [29]. For such applications, a resonant power source with a series resonant circuit, which provides an almost constant operating current in a wide range of changes in the load voltage, is optimal [30].

The following should be noted as a limitation of this method. Devising the method for frequency regulation of the output current in transformerless resonant charging devices for capacitive energy storage devices is carried out under the condition of using a single-circuit resonant inverter.

The following should be noted as a drawback of the developed method. All analytical dependences are obtained for the case of a single half-cycle rectifier charger. In the case of using another scheme, for example, a rectifier-multiplier voltage, the calculated dependences need to be adjusted.

7. Conclusions

1. Quantitative characteristics of the deviation of output current of the resonant inverter from the given stabilized value when changing the switching frequency of the inverter transistors have been determined. These include the dependence of output current of the resonant inverter on load resistance and the frequency deviation from the resonant frequency. Thus, the deviation of the charging current from the maximum possible (up to 8 %) at the value of the relative resistance $k=50$ (corresponding to the CESD voltage of 15 kV at the charging current $I_{SC}=115$ mA) is insignificant for a switching frequency greater than the resonant frequency by 0.55 % ($q=1.0055$). As q increases, the deviation of the charging current increases.

Analytical dependences of the charging current on the switching frequency of the inverter power switches and the relative resistance of load k were obtained. They could be used for frequency regulation of the output current of a resonant CESD charger with a rectangular shape of the input voltage, which is formed as a result of commutation of the inverter switches.

2. Mathematical modeling of the output current of resonant inverter in the vicinity of resonant frequency was carried out. A comparison of the quantitative characteristics of the deviation of output current of the resonant circuit according to the sinusoidal and rectangular forms of the input voltage showed that the output current and its deviation can be calculated for the first harmonic. This is justified by the fact that the result of its calculation with an accuracy of 1 % coincides with the result for the sum of a series of harmonics but requires less resources of the computing system of control controller.

3. The essence of the developed method for frequency regulation of the output current in inverter high-voltage transformerless resonance charging devices of CESD has been formulated. This method is based on the frequency dependence of reactive resistances of the inductance and capacitance of the resonant circuit connected in series. It consists in the sequential change of the switching frequency of the inverter depending on the current voltage of CESD and the given trajectory of change in the charging current. Validation of the developed method by means of LTSpice showed that the application of the obtained theoretical dependences allows for the regulation of charging current according to the requirements of high-voltage technologies.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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