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# Calculation of a Switched Inductive-Capacitor Generator

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**Abstract**—A method for calculating a switched inductive-capacitor generator has been developed that makes it possible to determine the voltages, currents, power, and efficiency of the generator taking into account the parameters of its elements in a pulse-frequency mode of power supply of an active-inductive load. To increase the efficiency of the generator, the voltage across the capacitor and the power of the generated current pulses in the load, it is necessary to increase the source voltage, the switching voltage of the dynistors (Shockley diodes), the switching frequency and duty cycle, the number of capacitor-charging periods, and the time constant of the inductive storage, as well as reduce the capacitance of the capacitor. A generator with a source voltage of up to 48 V and a current-pulse frequency in a load of 1 Hz can have a pulse energy of up to 12 kJ, an average power of up to 12 kW with an efficiency of up to 0.89 and a pulse power of up to 35 MW. It is possible to connect the generator to a source with an insufficient dc voltage level for charging the capacitor, with the voltage across the charged capacitor (639–3060 V) being able to be tens of times higher than the source voltage (12–48 V).

**Keywords:** switch, inductive storage, capacitor, current, voltage

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High-power current pulses with a repetition rate of up to 100 Hz or higher are required by a number of active-inductive consumers. Such consumers include technological laser equipment, pulse electric welding devices, and equipment for electrohydraulic, magnetic-pulse, and electrical-discharge machining of metals. Capacitors charged from a dc voltage source (accumulator, rectifier) are widely used in generators for power supply of such consumers. A situation often occurs, especially at autonomous facilities, in which the dc voltage of a source is insufficient for direct charging of capacitors even with the use of a current limiting choke when the voltage across the capacitors may not exceed twice the source voltage [1]. Therefore, to increase the voltage of capacitors, an intermediate circuit is often used consisting of an inverter, transformer, and rectifier from which the capacitors are charged [2, 3]; however, this connection complicates the design of generators and degrades their reliability.

If the source voltage is insufficient to charge a capacitor, one may use an intermediate inductive capacitor storage and commutator, which allow one to increase the voltage on the charged capacitor and, thereby, increase the generated pulse power. The schemes of inductive-capacitor dc pulse voltage converters with an inductive storage device and a semiconductor switch in the form of an IGBT transistor are reported in [4]. These converters operate with parallel connection of the consumer to the output capacitor and are simple and reliable compared to inverter circuits [2, 3], they increase or decrease the voltage of the output capacitor compared to the voltage of the source.

One of the circuits discussed in [4] for charging the capacitor was chosen, which is simple and reliable. This circuit allows using a source with insufficient dc voltage, increasing the voltage on the capacitor being charged. A thyristor switched by dynistors (Shockley diodes) is used to implement the frequency-pulse mode of powering the consumer for its connection to the charged capacitor. This circuit eliminates the possibility of source and commutator current flowing through the consumer, especially in the event of a short circuit at the consumer, which relaxes the specifications for the source and the commutator.

Thus, the switched inductive-capacitor generator (Fig. 1) is designed for reliable supply of consumers by means of powerful pulses of current in the frequency mode even in the case in which the generator is connected to a source with a reduced level of constant voltage insufficient for charging the capacitor. A description is given in [5] of the design elements and the results of experimental studies of such a generator at frequency-pulse power supply of a loaded step-up voltage transformer, which showed the functionality

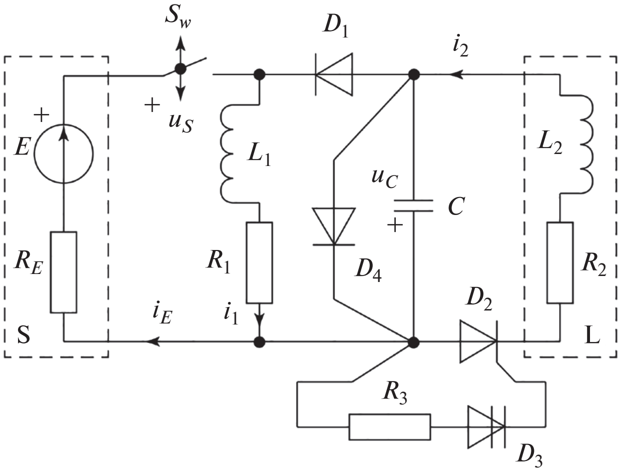

**Fig. 1.** Schematic of switched inductive-capacitor generator: $S$, constant voltage source; $L$, current pulses $i_2$ of the consumer (active-inductive load); $E$ and $R_E$, constant EMF and resistance of dc energy source $S$; $S_w$, semiconductor switch (commutator) on IGBT transistor; $L_1$ and $R_1$, inductance and resistance of inductive energy-storage device; $C$, capacitance of charged capacitor; $D_1$ and $D_4$, semiconductor diodes; $D_2$, thyristor; $D_3$, one or several dynistors connected in series; $L_2$ and $R_2$, inductance and resistance of load $L$; $R_3$, current limiting resistor for dynistors $D_3$; and $i_E$, $i_1$, $i_2$ and $u_S$, $u_C$, currents and voltages as a function of time.

and reliability of the generator. However, the formulas for calculating a commutator inductive-capacitor generator in [5] were not given, and [4] also lacks a method for calculating the frequency-pulse mode. Therefore, the development of a method for designing such a generator in the pulse-frequency mode to determine its efficiency and capabilities is an important task that is of practical interest.

Let us consider frequency-pulse power supply to a consumer represented by active-inductive load $L$. Figure 1 shows a schematic diagram of an inductive-capacitor generator. Let us assume that the inductances and resistances of the source, inductive accumulator, and consumer are roughly fixed and semiconductor diodes $D_1$ and $D_4$, thyristor $D_2$, and dynistors $D_3$ are ideal devices. In this case, we will assume that semiconductor IGBT transistor switch $S_w$ in the "open" state has an infinite resistance and, in the "closed" state, is characterized by constant voltage $U_{\mathrm{CE}}$ between the collector and emitter ($U_{\mathrm{CE}} = 1$–$3$ V). Let us also assume that the inductances and capacitances of the dc voltage and the connecting wires have no appreciable influence on the currents and voltages of the generator. Suppose that, at the time interval associated with current pulse $i_2$, switch $S_w$ is "open" and diode $D_1$ is off, that is, current $i_2$ does not affect currents $i_E$ and $i_1$.

The influence of external factors on the operation of the generator (temperature, humidity, vibration, interference, etc.) is beyond the scope of this article. Switch $S_w$ (IGBT transistor) periodically closes and opens the generator supply circuit with frequency $f_1$ and duty cycle $Q > 1$. If switch $S_w$ is open and the voltage at the terminals of source $S$ is approximately constant and equal to $U_{\mathrm{E}}$, then the calculated value of EMF $E$, switching period $T_1$, and time intervals $t_1$ ($S_w$ "closed") and $t_2$ ($S_{\mathrm{w}}$ "open") will be considered equal:

$$E \approx U_E;\ \ T_1 = 1/f_1;\ \ t_1 = T_1/Q;$$
$$t_2 = T_1 - t_1 = T_1(Q-1)/Q. \tag{1}$$

According to Fig. 1, the generator operates as follows. When switch $S_w$ is closed and source $S$ is connected, currents $i_E$ and $i_1$ increase and the energy of the magnetic field of the inductive storage device ($L_1$, $R_1$) increases. At open commutator $S_w$ and disconnected source $S$ the energy of the inductive storage is transferred to capacitor $C$, which is charged to a certain maximum voltage $U_{mC}$ level during several switching periods $T_1$ of $S_w$ key and $U_{mC}$ is equal to dynistor $D_3$ turn-on voltage. When capacitor voltage $u_C$ reaches value $U_{mC}$, dynistor $D_3$ turns on together with the thyristor $D_2$ and capacitor $C$ is discharged into load $L$ ($L_2$, $R_2$), forming current pulse $i_2$. Generation of current pulses $i_2$ is repeated with period $T_2$ and frequency $f_2 = 1/T_2$ at $f_2 \le f_1$, whereby, to close thyristor $D_2$, it is necessary to reduce its current $i_2$ to zero. In order to separate in time the processes of energy storage in an inductive storage device ($L_1$, $R_1$) and capacitor $C$, semiconductor diode $D_1$ is added, and, to prevent negative voltage at capacitor $C$ during its discharge, semiconductor diode $D_4$ is connected.

Three modes are possible when charging the capacitor:

— continuous current mode $i_1$ when this current is nonzero at all periods of $T_1$ of commutation $S_w$;

— intermittent current mode $i_1$ when this current reaches zero for a certain number of $T_1$ periods of commutation $S_w$; and

— pulsed current operation $i_1$ when this current reaches zero in all $T_1$ commutation periods of $S_w$.

Let us restrict our consideration to the pulsed mode of the current $i_1$ of the inductive storage device ($L_1$, $R_1$) when practically all energy of the inductive storage device during each period of $T_1$ is transferred to capacitor $C$ and a small part of it is lost as heat, mostly in resistance $R_1$ of inductive storage device.

The formulas follow to calculate the generator voltages and generator currents obtained considering (1) from solving equations of electric circuit [6] at the following time intervals of the $k$-th switching period of switch $S_w$ at $k = 1, 2, \ldots, N$.

(1) Time interval $(k-1)T_1 < t < (k-1)T_1 + t_1$ when electromagnetic energy is stored in an inductive

storage device. Commutator $S_w$ is closed, diodes $D_1$ and $D_4$ are locked, and thyristor $D_2$ is closed. Then,

$$\begin{gathered} i_E = i_1 = \frac{U_E - U_{CE}}{R_E + R_1}\left\langle 1 - \exp\left\{-\frac{[t-(k-1)T_1]}{\tau}\right\}\right\rangle; \\ i_2 = 0;\quad u_C = U_{k-1};\quad u_S = U_{CE}; \\ \tau = \frac{L_1}{R_E + R_1};\quad I_{m1} = \frac{U_E - U_{CE}}{R_E + R_1}\left[1 - \exp\left(-\frac{t_1}{\tau}\right)\right]; \\ W_m = \frac{L_1 I_{m1}^2}{2};\quad W_U = U_E \int_{(k-1)T_1}^{(k-1)T+t_1} i_E dt \\ = \frac{U_E (U_E - U_{CE}) t_1}{R_E + R_1}\left\{1 - \frac{\tau}{t_1}\left[1 - \exp\left(-\frac{t_1}{\tau}\right)\right]\right\}; \\ P_{mU} = U_E I_{m1};\quad \eta_m = \frac{W_m}{W_U} = \left(1 - \frac{U_{CE}}{U_E}\right) \\ \times \frac{[1 - \exp(-t_1/\tau)]^2}{2[(t_1/\tau) - 1 + \exp(-t_1/\tau)]};\quad P_U = W_U f_1, \end{gathered} \tag{2}$$

where $U_E$, V, is dc voltage at the output of source $S$ when commutator $S_w$ is open; $U_{CE}$, V, is dc voltage between the collector and emitter of closed switch $S_w$; $\tau$, s, is the time constant of currents $i_E$ and $i_1$; $U_{k-1}$, V, is the constant capacitor voltage at the interval in question determined from calculation at the previous time interval; $I_{m1}$, A, is the maximum value of currents $i_E$ and $i_1$ at moment of time $t = (k-1)T_1 + t_1$, $W_m$, J, is the maximum energy stored in the inductive storage; $W_U$, J, is the energy given by the source; $P_{mU}$ and $P_U$, W, are the maximum and average power of the source; and $\eta_m$ is the efficiency of energy transfer from the source to the inductive storage device.

(2) Time interval $(k-1)T_1 + t_1 < t < t_{mk}$ when energy $W_m$ is transferred from the inductive storage device to the capacitor. Switch $S_w$ is open, diode $D_1$ is open, diode $D_4$ is closed, and thyristor $D_2$ is closed; then,

$$\begin{gathered} i_E = 0;\quad i_1 = C p_1 B_{1k} \exp\{p_1[t - t_1 - (k-1)T_1]\} \\ + C p_2 B_{2k} \exp\{p_2[t - t_1 - (k-1)T_1]\};\quad i_2 = 0; \\ u_C = B_{1k} \exp\{p_1[t - t_1 - (k-1)T_1]\} + B_{2k} \\ \times \exp\{p_2[t - t_1 - (k-1)T_1]\};\quad p_{1,2} = -\frac{R_1}{2L_1} \\ \pm \sqrt{\frac{R_1^2}{4L_1^2} - \frac{1}{L_1 C}};\quad B_{1k} = \frac{I_{m1} - p_2 C U_{k-1}}{C(p_1 - p_2)}; \\ B_{2k} = \frac{p_1 C U_{k-1} - I_{m1}}{C(p_1 - p_2)};\quad t_{mk} = (k-1)T + t_1 \\ + \frac{1}{(p_1 - p_2)} \ln\left(\frac{p_1 p_2 C U_{k-1} - p_2 I_{m1}}{p_1 p_2 C U_{k-1} - p_1 I_{m1}}\right); \\ U_k = \frac{(p_1 C U_{k-1} - I_{m1})}{C p_1}\left[\frac{p_2(p_1 C U_{k-1} - I_{m1})}{p_1(p_2 C U_{k-1} - I_{m1})}\right]^{\frac{p_2}{p_1 - p_2}}; \\ u_S = U_E + u_C;\quad U_{Sk} = U_E + U_k, \end{gathered} \tag{3}$$

where $p_{1,2}$, 1/s, are roots of the inductive storage-capacitor characteristic equation; $B_{1k}$ and $B_{2k}$, V, are integration constants; $t_{mk}$, s, is the moment of closing of diode $D_1$ when current $i_1$ reaches a zero value; and $U_k$ and $U_{Sk}$, V, are momentary voltages across the capacitor $u_C$ and commutator $u_S$.

(3) Time interval $t_{mk} < t < kT_1$ when energy from the inductive storage device is not transferred to the capacitor. Commutator $S_w$ is open, diodes $D_1$ and $D_4$ are off, and thyristor $D_2$ is closed. Then,

$$i_E = i_1 = i_2 = 0;\quad u_C = U_k;\quad u_S = U_E. \tag{4}$$

(4) Time interval $t_{mN} < t < NT_1$ when $k = N$ and at $t = t_{mN}$, voltage $u_C$ on the capacitor has reached maximum value $U_{mC} = U_N$ in which dynistor $D_3$ and thyristor $D_2$ open up and capacitor $C$ discharges into the load $L_2$ and $R_2$. Thus, switch $S_w$ is open, diodes $D_1$ and $D_4$ are off, and thyristor $D_2$ is on. Then,

$$\begin{gathered} i_E = i_1 = 0;\quad i_2 = C p_3 B_3 \exp\{p_3[t - t_{mN}]\} \\ + C p_4 B_4 \exp\{p_4[t - t_{mN}]\};\quad u_C = B_3 \\ \times \exp\{p_3[t - t_{mN}]\} + B_4 \exp\{p_4[t - t_{mN}]\}; \\ W_{mC} = \frac{C U_{mC}^2}{2};\quad f_2 = \frac{f_1}{N};\quad P_R = W_{mC} f_2; \\ p_{3,4} = -\frac{R_2}{2L_2} \pm \sqrt{\frac{R_2^2}{4L_2^2} - \frac{1}{L_2 C}};\quad B_3 = \frac{p_4 U_{mC}}{p_3 - p_4}; \\ B_4 = -\frac{p_3 U_{mC}}{p_3 - p_4};\quad I_{m2} = -C p_3 U_{mC}\left(\frac{p_4}{p_3}\right)^{\frac{p_3}{p_3 - p_4}}; \\ P_{mR} = I_{m2}^2 R_2;\quad t_{m2} = t_{mN} + \frac{\ln(p_4/p_3)}{p_3 - p_4}; \\ \eta_C = \frac{0.5C\left(U_{mC}^2 - U_0^2\right)}{N W_U};\quad U_{mS} = U_E + U_{mC}, \end{gathered} \tag{5}$$

where $N$ is the number of current pulses $i_1$ used to charge capacitor $C$; $t_{mN}$, s, according to (3), is equal to $t_{mk}$ at $k = N$; $p_{3,4}$, 1/s, are the roots of the characteristic equation of the capacitor-load contour; $B_3$ and $B_4$, V, are integration constants; $U_{mC}$, V, is the maximum charging voltage of capacitor $C$ at moment $t = t_{mN}$; $W_{mC}$, J, is the maximum energy stored in capacitor $C$, which is equal to the energy dissipated as heat in load resistor $R_2$ during one current pulse $i_2$; $f_2$, Hz, is the frequency of repetition of $i_2$ current pulses; $I_{m2}$, A, is the maximum value of current $i_2$ at moment of time $t_{m2}$; $P_{mR}$ and $P_R$, W, maximum and average power of current $i_2$ in load resistance $R_2$; $\eta_C$ is the net efficiency of charging of capacitor $C$ during $N$ periods of $T_1$; $U_0$, V, is the initial voltage on capacitor $C$ at moment $t = 0$; and $U_{mS}$, V, is maximum voltage at open switch $S_w$ at moment $t_{mN}$.

For stable operation of the generator, it is necessary to close thyristor $D_2$ reliably when decreasing its cur-

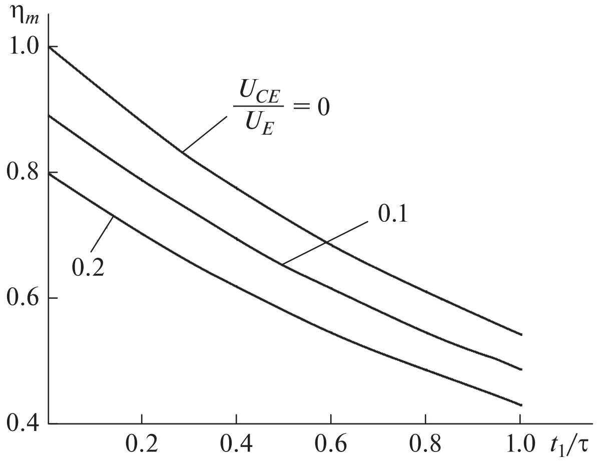

**Fig. 2.** Calculated energy transfer efficiency $\eta_m$ from the source to the inductive storage when $U_{CE}/U_E = 0$, 0.1, and 0.2.

rent $i_2$ to zero when commutator $S_w$ is open. Therefore, during an aperiodic transient of current $i_2$ when roots $p_{3,4}$ (5) are real, negative, and nondegenerate, the following conditions must be fulfilled:

$$C > \frac{4L_2}{R_2^2};\quad t_p \approx \frac{5}{|p_3|};\quad t_{mN} + t_p < NT_1, \tag{6}$$

at complex-conjugate roots $p_{3,4}$ (oscillatory transient process),

$$C < \frac{4L_2}{R_2^2};\quad \omega = \sqrt{\frac{1}{L_2C} - \frac{R_2^2}{4L_2^2}};\quad t_p \approx \frac{\pi}{\omega};\quad t_{mN} + t_p < NT_1, \tag{7}$$

where $t_p$, s, is the duration of the current pulse $i_2$ and $\omega$, 1/s, is the angular frequency of current $i_2$.

In turn, to realize the pulsed mode of current $i_1$ according to (1), (3) at $k = 1$, when $t_{mk} = t_{m1}$ has the greatest value, it is necessary to fulfill the inequality

$$t_{m1} = t_1 + \frac{1}{(p_1 - p_2)}\ln\left(\frac{p_1p_2CU_0 - p_2I_{m1}}{p_1p_2CU_0 - p_1I_{m1}}\right) < T_1,$$

from which, at $U_0 \approx 0$ and $R_1 \approx 0$, we can obtain condition for capacitor $C$:

$$C_m = \frac{4t_2^2}{\pi^2 L_1} > C. \tag{8}$$

For stable operation of the generator in the pulse-frequency mode, the values of $C$, $L_1$, $L_2$, and $R_2$ must satisfy the inequalities (6)–(8).

To assess the efficiency of the generator considered calculations were carried out using formulas (1)–(8). Figure 2 shows the calculated curves of energy-transfer efficiency $\eta_m$ from source $S$ to the inductive storage device as a function of relative duration $t_1/\tau$ of closed commutator $S_w$ at different relative values of voltage between the collector and emitter $U_{CE}/U_E = 0$, 0.1, and 0.2.

From Fig. 2 and formulas (1, 2), it follows that, in order to increase efficiency $\eta_m$, it is necessary to increase frequency $f_1$, duty cycle $Q$, voltage of source $U_E$, and the time constant (to increase inductance $L_1$ and decrease resistance $R_E$, $R_1$).

Figure 3 shows resulting efficiency $\eta_C$ of capacitor $C$ charging as a function of $N$ periods of $T_1$ of switch $S_w$ and corresponding efficiency $\eta_m$. The plots of efficiencies $\eta_C$ and $\eta_m$ are obtained when $R_E = 0$, $t_1/\tau = 0.1$, $U_{CE}/U_E = 0.1$, $Q = 2$, and $U_0 = 0$ and different capacitances $C$ when coefficient $a$ takes values of $a = C_m/C =$ 1, 5, and 10. Figure 4 shows the dependence of relative maximum voltage on capacitor $U_{mC}/U_E$ versus number $N$ of switching periods $T_1$ of switch $S_w$ calculated with the same parameters as in the dependences plotted in Fig. 3. It follows from Figs. 3 and 4 that the resulting charging efficiency of the capacitor $\eta_C$ and its maximum voltage $U_{mC}$ increase with increasing number of commutation periods $N$ and reduction of capacitor capacitance $C$ and it is always the case that $\eta_C < \eta_m$.

To assess the capabilities of the generator, one may look at Table 1, which shows the results of the calculations by formulas (1)–(8) for the following parameters: $U_E = 12$, 24, and 48 V; $U_{CE} = 2.5$ V; $f_1 = 200$ Hz; $Q = 2$; $L_1 = 0.1$ mH; $\tau = 10t_1 = 25$ ms; $R_E = R_1 = 2\ \text{m}\Omega$; $U_0 = 0$; $C = 0.1C_m \approx 2500\ \mu\text{F}$; $N = 200$; $f_2 = 1$ Hz; $L_2 = 0.1L_1 = 10\ \mu\text{H}$; and $R_2 = \sqrt{8L_2/C} = 0.179\ \Omega$ (aperiodic transient current process $i_2$). According to the calculations increasing the source voltage $U_E$ results in the increase of the following quantities: the voltage $U_{mC}$ across the capacitor, the amplitudes of currents $I_{m1}$, $I_{m2}$, energy stored in the capacitor $W_{mC}$, efficiency $\eta_C$, average $P_U$, $P_R$ and maximum $P_{mU}$, $P_{mR}$ powers, the relative values of $U_{mC}/U_E$, $P_{mR}/P_{mU}$, and $P_{mR}/P_U$. Thus, the duration of current pulse$i_2$ in a load is $t_p \approx 1.909$ ms, the rise time from zero to maximum $I_{m2}$ is 0.139 ms at allowed voltage $U_{mS} = 651$–3108 V at a high-power IGBT transistor, for example, having parameters of 3300 V/1500 A [7]. Thus, it is possible to implement a generator with an average power up to 15 kW and efficiency up to 0.89 for power supply of various technological apparatuses in the frequency-pulse mode [1].

For experimental verification of calculated relations (1)–(8), a prototype model of a switched inductive-capacitor generator (Fig. 1) has been implemented with the structural elements indicated in [5]. Source $S$ of dc voltage $U_E \approx 8$ V at $R_E \approx 1\ \Omega$ (the measuring resistor) was a power unit with adjustable voltage $U_E$. A solid state dc relay on an IGBT transistor with a switchable current up to 20 A and a maximum open switch voltage of up to 1200 V were used as semiconductor commutator $S_w$. The datasheet values of the voltage between collector and emitter in closed relay

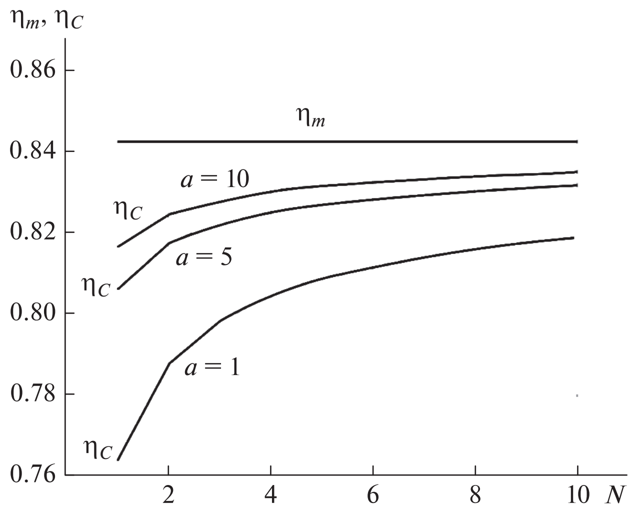

**Fig. 3.** Energy transfer efficiency $\eta_m$ to the inductive storage and the resulting efficiency of capacitor charging $\eta_C$ as a function of $N$ periods of switching at $a = C_m/C = 1, 5, 10$; $R_E = 0$; $t_1/\tau = 0.1$; $U_{CE}/U_E = 0.1$; $Q = 2$; and $U_0 = 0$.

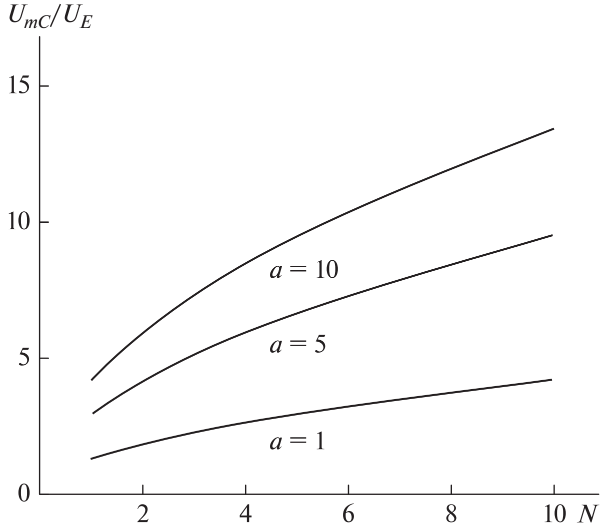

**Fig. 4.** Relative maximum voltage across capacitor as a function of $N$ commutation periods at $a = C_m/C = 1, 5, 10$; $R_E = 0$; $t_1/\tau = 0.1$; $U_{CE}/U_E = 0.1$; $Q = 2$; and $U_0 = 0$.

state $U_{CE} < 3$ and ≈ 2 V is assumed in calculations. By means of voltage control of the relay, switching frequency $f_1 = 500$ Hz and duty cycle $Q = 2$ were set. The inductive storage had a ferrite magnet wire (two W-core) with air gap of 2 mm and the following parameters with a measuring resistor of 1 Ω: $L_1 \approx 10.9$ mH, $R_1 \approx 1.452$ Ω, and mass 0.7 kg. To fulfill condition (8) when $C_m \approx 37.2$ μF, a $C = 20.9$ μF capacitor was used. A coil was used as active-inductive load $L$ with a measuring resistor (1 Ω) and additional resistors at which $L_2 \approx 0.155$ mH and $R_2 \approx 7.24$ Ω, aperiodic transient current $i_2$ was provided, and conditions (6) were fulfilled. As a result, we obtained $U_E \approx 8$ V, $R_E \approx 1$ Ω, $U_{CE} \approx 2$ V, $T_1 = 2$ ms, $t_1 = 1$ ms, $\tau = 4.445$ ms, $t_1/\tau = 0.225$, $U_{CE}/U_E = 0.25$, and $a = C_m/C = 1.779$.

Experiments were carried out using the above-specified parameters of a generator with dynistors $D_3$ (Fig. 1) having different switching voltages, which corresponded to maximum capacitor voltages $U_{mC} \approx 36$, 72, and 135 V.

To illustrate the processes of charging and discharging of capacitor $C$, a typical experimental oscillogram is shown in Fig. 5a of voltage $u_C$ on a capacitor with period $T_2 \approx 22$ ms corresponding to charging by $N = T_2/T_1 \approx 11$ pulses and discharging at $U_{mC} \approx 36$ V and $U_0 \approx 0$. Figure 5b shows the calculated time dependence of voltage across capacitor $u_C$ within period $T_2 = 22$ ms at $N = 11$ obtained by formulas (1)–(5) for parameters of the experimental generator model in which the calculated maximum voltage across capacitor appeared to be $U_{\mathrm{mC}} \approx 37$ V at $U_0 = 0$.

Table 2 lists the results of experiments and calculations by formulas (1)–(5) for different switching voltages of dynistors for the experimental generator model. According to these results, with an increase in the turn-on voltage of dynistors and the corresponding maximum voltage on capacitor $U_{mC}$, frequency $f_2 = 1/T_2$ of current $i_2$ in the load decreases with the increase of its amplitude $I_{m2}$ and power $P_{mR}$. Maximum voltage $U_{mS}$ at the commutator $S_w$ exceeds maximum voltage at the capacitor $U_{mC}$ by roughly the value

**Table 1.** Results of generator calculation at different source voltages $U_E$

| $U_E$ | $U_{mC}$ | $I_{m1}$ | $I_{m2}$ | $W_{mC}$ | $\eta_C$ | $P_{mU}$ | $P_{mR}$ | $P_U$ | $P_R$ | $\frac{U_{mC}}{U_E}$ | $\frac{P_{mR}}{P_{mU}}$ | $\frac{P_{mR}}{P_U}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| V | V | A | kA | kJ | – | kW | MW | kW | kW | – | – | – |
| 12 | 639 | 226.0 | 2.90 | 0.51 | 0.740 | 2.71 | 1.51 | 0.69 | 0.51 | 53.24 | 556.5 | 2190 |
| 24 | 1446 | 511.5 | 6.57 | 2.61 | 0.838 | 12.28 | 7.73 | 3.12 | 2.61 | 60.25 | 629.7 | 2478 |
| 48 | 3060 | 1082 | 13.91 | 11.71 | 0.886 | 51.96 | 34.62 | 13.21 | 11.71 | 63.75 | 666.4 | 2622 |

**Table 2.** Results of experiments and calculations of the experimental generator model

| Experiment | | | | | | Calculations | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $U_{mC}$ | $U_{mS}$ | $T_2$ | $N$ | $I_{m1}$ | $I_{m2}$ | $U_{mC}$ | $U_{mS}$ | $I_{m1}$ | $I_{m2}$ | $P_{mU}$ | $P_{mR}$ | $\frac{U_{mC}}{U_E}$ | $\frac{P_{mR}}{P_{mU}}$ |
| V | V | ms | – | A | A | V | V | A | A | W | W | – | – |
| 36 | 44 | 22 | 11 | 0.53 | 4.2 | 37 | 45 | 0.49 | 4.1 | 3.92 | 122 | 4.62 | 31 |
| 72 | 76 | 76 | 38 | 0.53 | 6.4 | 69 | 77 | 0.49 | 7.6 | 3.92 | 418 | 8.62 | 107 |
| 135 | 140 | 260 | 130 | 0.53 | 16 | 128 | 136 | 0.49 | 14.1 | 3.92 | 1439 | 16 | 367 |

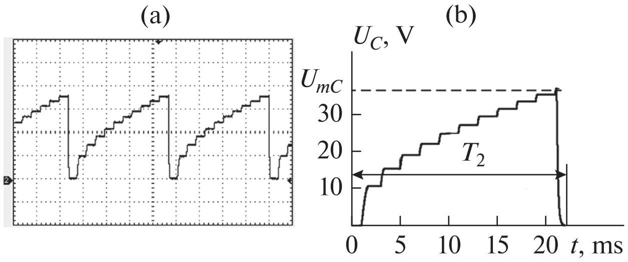

**Fig. 5.** (a) Oscillogram and (b) calculated time dependence of voltage $u_C$ on capacitor $C = 20.9$ μF at $N \approx 11$, $T_2 \approx 22$ ms, $U_{mC} \approx$ 36–37 V, and $U_0 \approx 0$. Vertical scale, 10 V/div; horizontal, 5 ms/div; (a) left mark, zero level.

close to voltage of the source $U_E$. At the same time, maximum voltages $U_{mC}$ and power $P_{mR}$ of the load are much higher than corresponding voltages $U_E$ and power $P_{mU}$ of the source.

Voltages $u_C$ (Fig. 5), as well as the experimental and calculated values of voltages and currents given in Table 2, approximately correspond to each other, indicating the reliability of the method of calculation, the correct choice of parameters of the generator elements, and that the evaluation of the effectiveness and capabilities of the generator under consideration in the pulse-frequency mode of operation was correct.

## CONCLUSIONS

(1) The proposed method of calculating the switched inductive-capacitor generator allows us to determine the voltages, currents, power, and efficiency of the generator taking into account the parameters of its elements in the frequency-pulse mode of power supply of an active-inductive load.

(2) The reliability of the method is confirmed by the approximate coincidence of the calculated and experimental values of voltages and currents of experimental model of the generator. The technique can be used in designing generators with an average power up to 15 kW for power supply of various apparatuses in frequency-pulse mode.

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## CONFLICT OF INTEREST

The authors declare that they have no conflict of interests.

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