ELECTRONICS
AND RADIO ENGINEERING

A Switching Inductive-Capacitor Generator of Powerful Current Pulses

G. V. Nosov[a],* and M. G. Nosova[b],**

[a] *National Research Tomsk Polytechnic University, Tomsk, 634050 Russia*
[b] *Tomsk State University of Control Systems and Radioelectronics, Tomsk, 634050 Russia*
*e-mail: nosov@tpu.ru
**e-mail: nosovamgm@gmail.com

Abstract—A generator is studied that consists of a low-power source with an insufficient DC voltage level for the consumer, a semiconductor switch on an IGBT transistor, an inductive-capacitive link, a thyristor that is switched on by dynistors, and a pulse transformer. The generator is designed to power various consumers with high-power current pulses with a repetition frequency of up to 100 Hz or more. Experimental studies of a generator prototype model showed that in comparison with a low-power source (22 W, 13.8 V), the pulse power and voltage values for a consumer were 2.47 kW and 1122 V. At the same time, the current pulses had an amplitude of 2.2 A, a duration of 20 μs, and a repetition frequency of 50−167 Hz in the consumer's resistance (510 Ω) at a source voltage of 13.8−22.8 V. As the DC voltage of the power supply increased, the number of capacitor-charging current pulses decreased, while the frequency of current pulses in the load increased. The maximum voltage at the capacitor during its charging is 3−5 times higher than the source voltage.

THE ELECTRIC CIRCUIT AND OPERATION OF THE GENERATOR

Generators with electric capacitors that are charged from a DC power source (a battery, a rectifier, and a power supply) and then discharged to the load (consumer) are used to supply power with powerful current pulses to many consumers, Such generators include a switching inductive-capacitor generator with a current-pulse repetition frequency in a load of up to 100 Hz or higher. The objective of this work is to study this generator when it is connected to a DC voltage source of limited power and with an insufficient voltage level for a consumer.

If the DC voltage level of a power supply is insufficient for a consumer, an intermediate AC link is often used, which consists of an inverter, a transformer, and a rectifier that charges capacitors [1, 2]. In [3], we considered inductive-capacitor DC voltage pulse converters with a semiconductor switching element, an IGBT transistor, which operate in the mode of supplying a consumer with a continuous oscillating voltage at the capacitor.

The electrical circuit of one of these converters was used in the generator as a link for increasing the voltage across the capacitor charged with a series of current pulses. A pulse transformer was used to further increase the voltage. A charged capacitor is connected to its primary winding through a thyristor, while the

secondary winding is connected to a load. The thyristor is enabled by including one or more series-connected dynistors in the control circuit, and the capacitor is discharged, thus generating a current pulse in the load. The thyristor is disabled when its current decreases to zero.

The electrical circuit of the generator with the measuring resistors (1 Ω) is shown in Fig. 1. The Sw_1 switch (IGBT-transistor) periodically closes and opens the generator power supply circuit at a frequency f and an off-duty factor $Q > 1$. In this case, the switching period T and the time intervals t_1 (Sw_1 is closed), t_2 (Sw_1 is opened) are:

$$T = 1/f, \quad t_1 = T/Q, \\ t_2 = T - t_1 = T(Q-1)/Q. \tag{1}$$

For the closed Sw_1 switch when a source (VS) of a DC voltage U_e is connected, energy is stored in the magnetic field of a choke (Ch); for the opened Sw_1 when the source VS is disconnected, this energy is transferred to the electric field of the capacitor C, which is charged to the maximum voltage U_{mC} within several Sw_1 switching periods T.

This voltage is determined by the voltage of switching D_4; when the capacitor voltage reaches U_{mC} this enables the D_3 thyristor, the capacitor discharges through the primary winding of the transformer Tr,
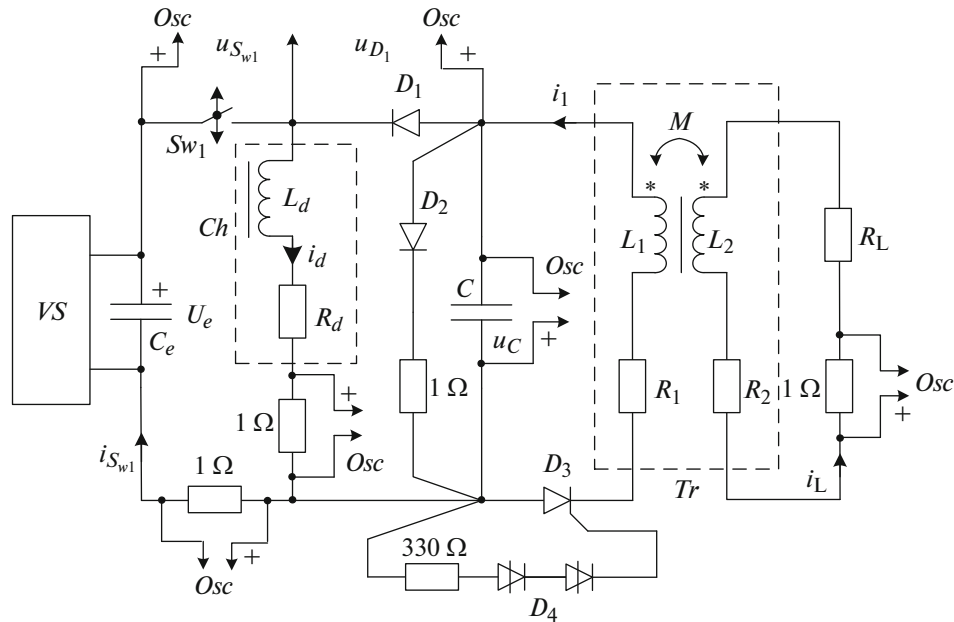
Fig. 1. The electrical circuit of generation and recording of currents and voltages: (*VS*) DC voltage source (a channel of the Mastech HY3003D-2 power supply), (*Osc*) UNI-T UTD2025CL oscilloscope of the UTD-2000L series, 25 MHz; (*Sw*₁) 5P40.10GDA1-20-12-B88 DC solid-state relay, f = 500 Hz; (D_1, D_2) VSHFA16TB120-N3 diodes (16 A, 1200 V, 76 A/µs), (D_3) T242-80-7 thyristor (80 A, 700 V), (D_4) KN102A and KN102B; (*Tr*) transformer: two 2000NM E-shaped 20 × 28 ferrite cores, 0.1-mm gap, w_1 = 8 turns, w_2 = 250 turns ($L_1 \approx 0.167$ mH, $R_1 < 0.1$ Ω, $L_2 \approx 157$ mH, $R_2 \approx 1.4$ Ω, $M \approx 5$ mH); (*Ch*) choke: two 2000NM E-shaped 20 × 28 ferrite cores, 2-mm gap, w = 194 turns ($L_d \approx 10.9$ mH, $R_d \approx 0.4$ Ω); (C_e) 3 ECAP470 uF/63 V, 105°C electrolytic capacitors (1410 µF, 63 V), (*C*) 3 CBB-685-400V-685J-CL2 capacitors (20.9 µF, 400 V); (R_L) 5W510RJ-510 Ω resistor; and 5W1RJ (1 Ω) and 5W330RJ (330 Ω) resistors.

and a current pulse i_L is generated in the load R_L. The capacitor charging and discharging and the generation of current pulses i_L are periodically repeated at the frequency $f_L < f$. In order to separate the energy storage processes in the choke and capacitor in time, a D_1 semiconductor diode is installed; the D_2 semiconductor diode is connected to the capacitor to prevent the possible occurrence of a negative voltage at the capacitor during its discharge.

Two modes are possible during the capacitor charging: the continuous current i_d mode of the choke, when this current does not reach zero during most periods T of switching Sw_1 and the pulse current mode of the choke, when this current during most Sw_1 switching periods reaches zero. Based on the necessity to periodically disable the D_3 thyristor after the capacitor discharges, the pulse current mode of the choke appears to be most acceptable.

If the quality factor of the choke is $q = 2\pi f \tau_d \gg 1$ with its inductance L_d, resistance R_d, and time constant $\tau_d = L_d/R_d$, then, without allowance for the measuring resistors (1 Ω), the pulse current mode of the choke can be provided if the capacitance C of the capacitor satisfies the condition:

$$C_m = \frac{4t_2^2}{\pi^2 L_d} > C. \qquad (2)$$

THE PROTOTYPE GENERATOR MODEL

The prototype generator model consists of the following elements (Fig. 1).

One channel of a controlled two-channel Mastech HY3003D-2 power supply unit (MASTECH, Hong Kong, China) was used as the source *VS* of a DC voltage U_e. The maximum output values of one channel are 30 V and 3 A. Three parallel-connected ECAP470 uF/63 V, 105°C electrolytic capacitors (Taiwan) with a total capacitance of $C_e \approx 1410$ µF and a voltage of up to 63 V (analogs of a K50-35 capacitor) are connected to the voltage-source output to reduce the voltage amplitudes at the Sw_1 switch and at the inner elements of the source when opening the Sw_1 switch.

A 5P40.10GDA1-20-12-B88 solid-state DC relay (ZAO Proton-Impul's, Orel, Russia) based on an IGBT transistor serves as the controlled Sw_1 switch and has the following parameters: the interrupted current is up to 20 A; the maximum voltage in the disconnected state is up to 1200 V; the switching frequency is up to 100 kHz; the switching time is 5 µs; the residual

voltage in the closed state is $U_{res} < 2.5$ V, and its measured average value is $U_{res} \approx 1.4$ V.

For protection, the output power terminals of the Sw_1 relay are shunted by an SN2-1A varistor for 1200 V (AS Energiya, Korolev, Russia) and a VS-HFA16TB120-N3 diode (www.vishay.com) with parameters of 16 A, 1200 V, and 76 A/μs, which is oppositely connected in parallel to the relay (both are not shown in Fig. 1).

The relay operates under the control of unipolar rectangular voltage pulses u_{con} with an amplitude of 8 V, an off-duty factor of $Q = 2$, and a frequency of $f = 500$ Hz, which are fed through a current-limiting 426.6-Ω resistor to the relay input, thus providing an input pulse current of 15 mA. The conditional power contacts of the Sw_1 relay are opened at the control voltage $u_{con} = 0$ and closed at $u_{con} = 8$ V.

A DC voltage source of $12-15$ V with a supply current of at most 30 mA is connected to the relay supply terminals via a current-limiting 50-Ω resistor. Regulated sources of the ED-1 laboratory complex (OOO Uchebnaya Tekhnika, Chelyabinsk, Russia) are used as a source of rectangular control-voltage pulses and a relay power source, which are not shown in Fig. 1. As a result, at a frequency of $f = 500$ Hz and an off-duty ratio of $Q = 2$, the Sw_1 switch, according to (1), provides $T = 2$ ms and $t_1 = t_2 = 1$ ms.

To provide pulsed periodic energy storage in the magnetic field, a choke Ch with a magnetic conductor of two E-shaped 20×28 2000HM ferrite cores (Ferropribor, St. Petersburg, Russia) was manufactured. A 2-mm air gap is provided between the cores of the magnetic conductor. The choke winding with a number of turns of $w = 194$ is wound with PET-155 wire with a copper diameter of 1.18 mm. A 0.1-mm-thick Mylar film is placed between the wire layers and provides insulation. The measured parameters of the choke at 25°C are as follows: $L_d \approx 10.9$ mH, $R_d \approx 0.4$ Ω, and the mass is 0.7 kg; in this case, $\tau_d \approx 27$ ms $\gg t_1$ and $q \approx 85.6 \gg 1$.

The D_1 and D_2 are both of the VS-HFA16TB120-N3 type (www.vishay.com) with parameters of 16 A, 1200 V, and 76 A/μs.

According to condition (2), when $C_m \approx 37.2$ μF, we choose a capacitor in the form of three CBB-685-400V-685J-CL2 parallel-connected film capacitors (ELECYINGFO, China) with a total measured capacitance of $C = 20.9$ μF and a maximum voltage of 400 V.

The charged capacitor is connected to the primary winding of the transformer Tr using a T242-80-7 low-frequency thyristor (D_3) (Elektrovypryamitel, Saransk, Russia) with these parameters: the average current is 80 A and the repetitive voltage in the disabled state is 700 V. This thyristor is enabled using a series connection of a current-limiting 5W330RJ resistor (330 Ω) and two, KN102A and KN102B (www.katod-anod.ru/rd/kn102), dynistors (D_4) in its control circuit. The certified switching-on voltages of the dynistors are 20 and 28 V,

respectively. Experimentally, their switching-on voltage was approximately the same and equal to 36 V; when they were connected in series, the switch-on voltage was 72 V. As a result, the maximum voltage at the capacitor must be equal to $U_{mC} \approx 72$ V.

The thyristor is turned off when its current i_1 decreases to zero. Therefore, the duration of the current pulse i_1 must be much shorter than the time interval $t_2 = 1$ ms (1); this is provided by the capacitance value of the capacitor ($C = 20.9$ μF) and the parameters of the transformer (L_1, L_2, M, R_1, R_2) and load (R_L).

The pulse transformer Tr with a magnetic conductor of two E-shaped 20×28 2000NM ferrite cores, which are identical to those of the choke, was manufactured in order to increase the voltage across the load R_L in comparison with the maximum voltage U_{mC} across the capacitor. An air gap of 0.1 mm is provided between the cores of the magnetic conductor for their demagnetization by unipolar current pulses i_1.

The primary (external) and secondary (internal) windings are located on a common plastic frame with a wall thickness of 1.25 mm. The primary winding has a single layer and consists of three parallel windings, each of which is wound with a PET-155 wire with a copper diameter of 1.18 mm and a number of turns of $w_1 = 8$. The secondary winding has a number of turns of $w_2 = 250$ and is wound with a PET-155 wire with a copper-wire diameter of 0.8 mm; a 0.1-mm-thick Mylar film is placed between the layers of this wire.

Between the primary and secondary windings an 0.6-mm-thick insulation made of electrically insulating PVC tape is placed, which has a thickness of 0.15 mm and is declared by the manufacturer for a breakdown voltage of 6 kV, presumably rated for 1 mm (Safeline, China). The following parameters of the transformer were measured at 25°C: $L_1 \approx 0.167$ mH, $R_1 < 0.1$ Ω, $L_2 \approx 157$ mH, $R_2 \approx 1.4$ Ω, $M \approx 5$ mH, $w_2/w_1 \approx 31$, and the mass is 0.7 kg.

A 5W510RJ resistor with a resistance of $R_L = 510$ Ω is used as the load. A UNI-T UTD2025CL-model digital oscilloscope (Osc) of the UTD-2000L series (Uni-Trend Technology Limited, Dongguan, China) is used to record voltages. In this case, the voltages that are picked off the 1-Ω measuring resistors (5W1RJ) are used to register currents. The same resistor is placed in the circuit of the D_2 diode to convert the remaining energy of the capacitor into heat if the polarity of its voltage changes during its discharge. The 5W1RJ, 5W330RJ, and 5W510RJ resistors are manufactured in Russia (AS Energiya, Korolev).

THE EXPERIMENTAL RESULTS

Figure 2 shows waveforms of the voltage u_C across the capacitor at different output voltages U_e of the power supply. These curves allow us to find the follow-
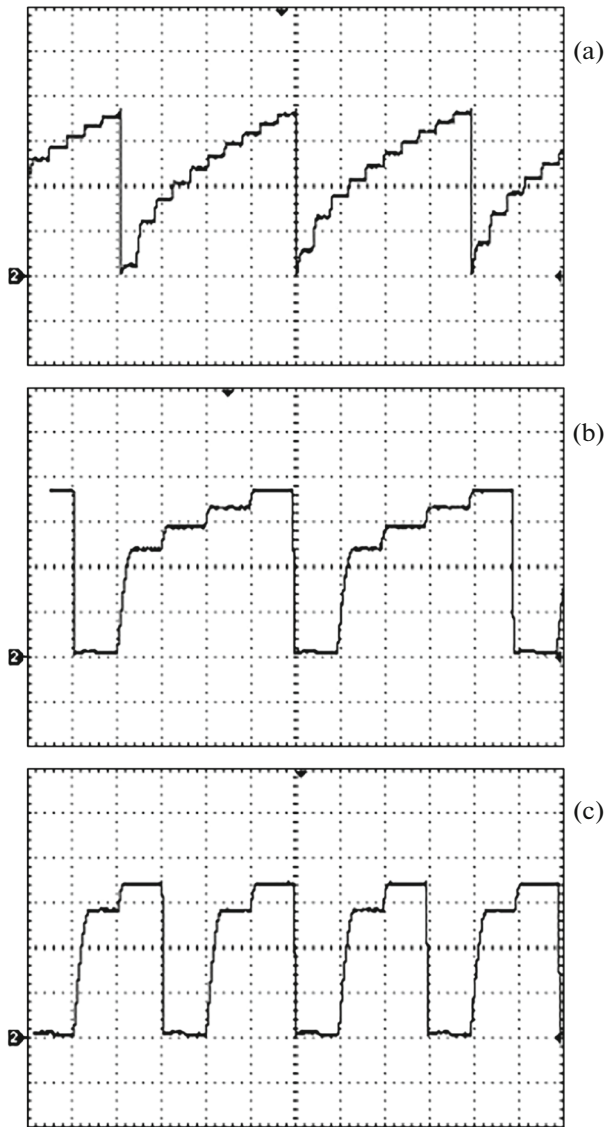
Fig. 2. Oscillograms of the voltage u_C at the capacitor: (a) for a source voltage of $U_e \approx 13.8$ V, the sweep is 5 ms/division; (b) for $U_e \approx 19.5$ V, 2 ms/division; and (c) for $U_e \approx 22.8$ V, 2 ms/division. The vertical scale is 20 V/division. The left mark is the zero level.

Fig. 3. An oscillogram of the voltage across the 1-Ω resistor that corresponds to the current i_L in the load $R_L = 510$ Ω. The vertical scale is 500 mV/division, the horizontal scale is 50 μs/division. The left mark is the zero level.

ing values: $U_{mC} \approx 72$ V, the period T_c of the voltage u_C, f_L, the number of capacitor-charging current pulses N, $K_{UC} \approx U_{mC}/U_e$: (Fig. 2a) $U_e \approx 13.8$ V, $N \approx 10$, $T_c \approx 0.02$ s, $f_L \approx 50$ Hz, $K_{UC} \approx 5.2$; (Fig. 2b) $U_e \approx 19.5$ V, $N \approx 5$, $T_c \approx 0.01$ s, $f_L \approx 100$ Hz, $K_{UC} \approx 3.7$; and (Fig. 2c) $U_e \approx 22.8$ V, $N \approx 3$, $T_c \approx 0.006$ s, $f_L \approx 167$ Hz, $K_{UC} \approx 3.2$.

Figure 3 shows a waveform that corresponds to the current i_L in the load $R_L = 510$ Ω. The following can be found on this basis: the current i_L pulse duration (FWHM) is 20 μs, the amplitude of this current is $I_{mL} \approx 2.2$ A, the voltage amplitude across the load is $U_{mL} = R_L I_{mL} \approx 1122$ V, the amplitude of the load power
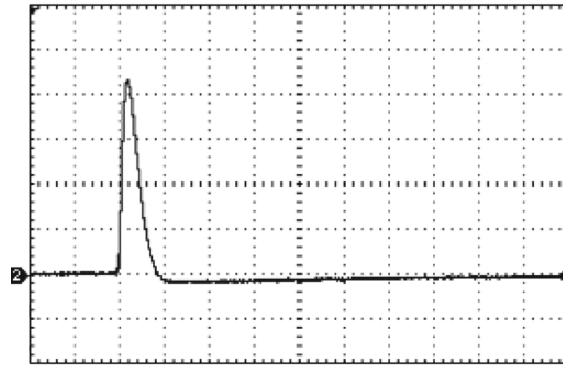
is $P_{mL} = U_{mL} I_{mL} \approx 2.47$ kW, and for $U_e \approx 13.8-22.8$ V, the voltage step-up ratio is $K_U = U_{mL}/U_e \approx 81-49$. The amplitude of the current i_L in the primary winding of the transformer can be estimated as $I_{m1} \approx (w_2/w_1)I_{mL} \approx 69$ A.

The operation of the generator is also illustrated by oscillograms in Figs. 4 and 5, which correspond to the voltage u_C in Fig. 2a for $U_e \approx 13.8$ V and $N \approx 10$.

Figure 4a shows an oscillogram of the voltage across the 1-Ω resistor, which is similar to the current i_{Sw_1} of the Sw_1 switch. The pulse current i_{Sw_1} with an amplitude of 1.6 A corresponds to the capacitor charging and discharging, while pulses with an amplitude of 1.05 A correspond only to the capacitor charging. As a result, for the maximum generated power of the power supply $P_{me} = 13.8 \times 1.6 \approx 22$ W, the power gain was $K_P = P_{mL}/P_{me} \approx 112$.

Figure 4b shows an oscillogram of the voltage across the 1-Ω resistor that corresponds to the choke current i_d. The dual current pulse i_d with an amplitude of 1.4 A corresponds to the capacitor charging and discharging, while pulses with an amplitude of 0.95 A correspond only to the capacitor charging.

An approximate largest maximum value of the voltage u_{Sw_1} can be calculated as follows: $U_{mSw_1} \approx U_e + U_{mC} = 85.8$ V, which approximately corresponds to an experimental value of 80 V.

Figure 5a shows an oscillogram of the voltage u_{Sw_1} across the Sw_1 switch that reflects the operation of the generator: nine voltage pulses with increasing amplitudes correspond to the capacitor charging, while the tenth voltage pulse obviously corresponds to the capacitor charging and discharging. Figure 5b shows the voltage waveform u_{D_1} across the D_1 diode: D_1 is disabled at negative voltage values and enabled for $u_{D_1} \geq 0$. Nine voltage pulses with increasing amplitudes u_{D_1} corre-
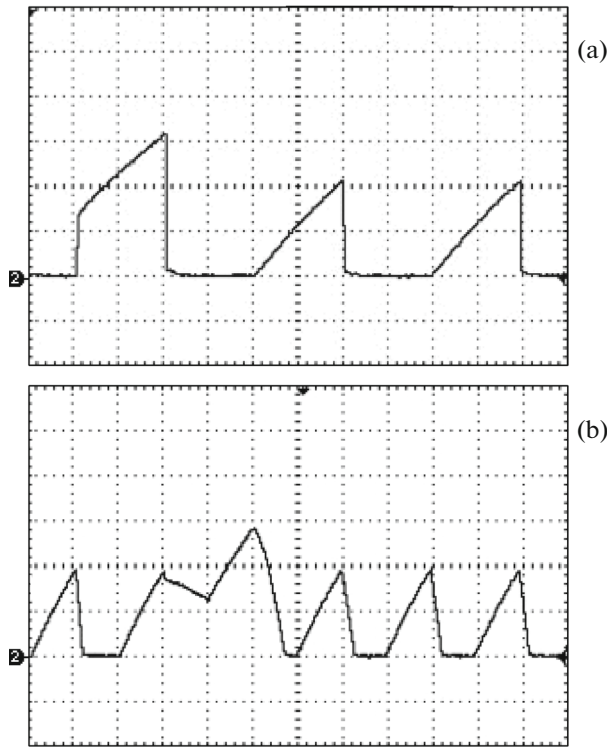
(a)

(b)

Fig. 4. Oscillograms of the voltages across the 1-Ω resistors corresponding to (a) the current i_{Sw_1} of the Sw_1 switch, the sweep is 500 μs/division and (b) the current i_d in the choke. The sweep is 1 ms/division. The source voltage is $U_e \approx 13.8$ V. The vertical scale is 500 mV/division. The left mark is the zero level.
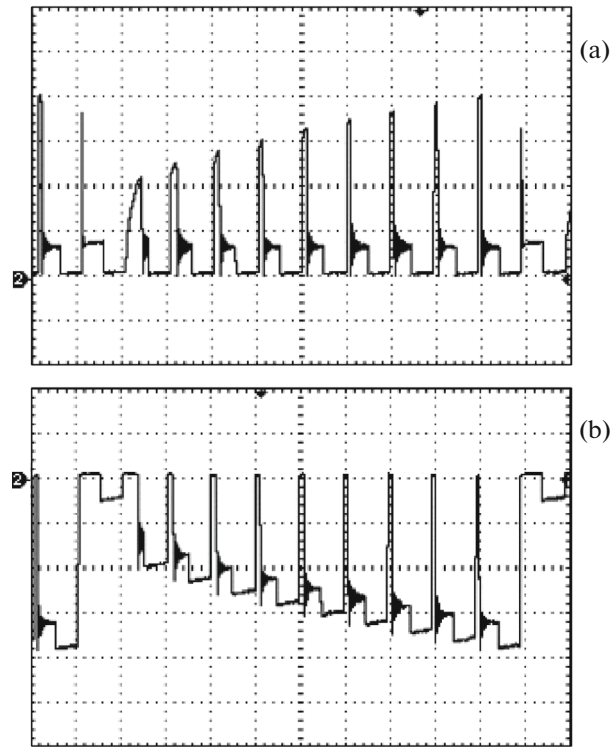

(a)

(b)

Fig. 5. Oscillograms of (a) the voltage u_{Sw_1} at the Sw_1 switch and (b) the voltage u_{D_1} across the D_1 diode. The source voltage is $U_e \approx 13.8$ V. The vertical scale is 20 V/division, the horizontal scale is 2 ms/division. The left mark is the zero level.

spond to the capacitor charging, while the tenth pulse with the smallest voltage amplitude u_{D_1} obviously corresponds to the capacitor charging and discharging. The lowest voltage u_{D_1} that disables the D_1 diode can be approximately estimated as $U_{mD_1} \approx -U_{mSw_1} = -85.8$ V, which is close to the experimental value of −76 V.

CONCLUSIONS

A switching inductive-capacitor generator with a semiconductor switching element—an IGBT transistor, whose prototype model generated pulse power and voltage values $P_{mL} \approx 2.47$ kW and $U_{mL} \approx 1122$ V at an ohmic load of $R_L = 510$ Ω, was investigated. When the power-supply voltage changed in the range $U_e = 13.8-22.8$ V, the obtained voltage step-up ratio was $K_U = U_{mL}/U_e \approx 81-49$; for a power-supply voltage of $U_e = 13.8$ V and its power of $P_{me} \approx 22$ W, the pulse-power gain was $K_P = P_{mL}/P_{me} \approx 112$. The generator prototype operated reliably at these parameters without adjustments and shutdowns, providing current pulses with an amplitude of 2.2 A, a duration of 20 μs, and a repetition rate of 50−167 Hz, when the source voltage

changed in the range $U_e = 13.8-22.8$ V. As the power-supply voltage U_e increased, the number of pulses N of the capacitor-charging circuit decreased, while the frequency f_L of current pulses in the load increased. The maximum voltage at the capacitor ($U_{mC} \approx 72$ V) resulting from its charging is $K_{UC} \approx 5-3$ times higher than the power-supply voltage ($U_e = 13.8-22.8$ V).

REFERENCES

1. Kovalenko, Yu.V., Pureskin, D.N., Savkin, V.Ya., Senkov, D.V., and Yakovlev, D.V., *Instrum. Exp. Tech.*, 2016, vol. 59, no. 6, pp. 802−807. https://doi.org/10.1134/S0020441216050092

2. Livshits, A.L. and Otto, M.A., *Impul'snaya elektrotekhnika* (Pulse Electrical Engineering), Moscow: Energoatomizdat, 1983.

3. Shabalin, N.G., Feoktistov, V.P., and In'kov, Yu.M., *Russ. Electr. Eng.*, 2011, vol. 82, no. 8, pp. 429−432. https://doi.org/10.3103/S1068371211080116

Translated by A. Seferov