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POWERFUL GENERATORS OF HIGH-VOLTAGE PULSES WITH NANOSECOND FRONTS

Purpose. Purpose of the article is to show the possibility of joint efficient operation of semiconductor switches and spark arresters in high-powerful high-voltage generators for obtaining nanosecond and shorter pulse fronts on a high-voltage load. Methodology. The variants of generators of power high-voltage pulses with semiconductor switches in the form of IGBT-transistors, SOS-diodes and spark dischargers as pulse front peaking spark gaps are considered. A scheme is proposed for such a generator of high-voltage pulses with nanosecond front on the basis of a linear pulsed transformer in the Tesla scheme. Results. On the complex load of the generator in the form of a serial connection of a gas bubble in water with a discharge in it and a layer of water under the bubble, voltage pulses with an amplitude of 23 kV and current pulses with an amplitude of 15 A were obtained. In this case, the pulse front, both voltage and current, on the levels 0.1-0.9, was approximately 10 ns, and the repetition rate of pulses in the load ranged from 1200 to 5000 pulses per second. Originality. A scheme is proposed for a generator of high-voltage pulses with a nanosecond front. The difference of the proposed generator with a nanosecond front, high pulse repetition rate, using its high-voltage and low-voltage circuits in the discharge circuit, is the presence in its composition of a linear pulse transformer and a system of peaking of pulse front using SOS diodes and spark gaps. Practical value. These generators considered in this work can find wide application in high-voltage technologies, including decontaminating water treatment, water purification by electric discharges. References 11, figures 3.

Key words: **spark gap discharger, generator, switch, transistor, SOS-diode, high-voltage pulse transformer, pulse repetition frequency, capacitive storage, inductance, load resistance.**

Рассмотрены варианты генераторов мощных высоковольтных импульсов с полупроводниковыми коммутаторами в виде IGBT-транзисторов, SOS-диодов и искровыми разрядниками. Предложена схема такого генератора высоковольтных импульсов с наносекундным фронтом. Отличием предложенного генератора с наносекундным фронтом, высокой частотой следования импульсов, с использованием в разрядном контуре его высоковольтных и низковольтных цепей является наличие в его составе линейного импульсного трансформатора и системы обострения фронта импульсов с использованием SOS-диодов и искровых разрядников. Библ. 11, рис. 3.

Ключевые слова: **разрядник, искровой промежуток, генератор, коммутатор, транзистор, SOS-диод, высоковольтный импульсный трансформатор, частота следования импульсов, емкостный накопитель, индуктивность, сопротивление нагрузки.**

Introduction. Modern transistor assemblies with operating voltages up to 10 kV and thyristors as power electronic energy switches in low-voltage circuits of pulse generators make it possible to receive microsecond pulses with an amplitude of 25-500 kV on the load connected to the high-voltage terminals of these generators [1, 2]. Generators with semiconductor switches provide a pulse repetition rate of 50,000 pulses per second [3, 4].

In [3-6], generators are presented on the basis of pulse transformers (PT) and IGBT switches in which PT and reverse diodes in IGBT are used to recover energy not released in the load. In this paper, we present modes in which both the high-voltage and low-voltage PT circuits are involved in the discharge circuits of the generators. IGBT-key can be used both as a closing and as an opening switch. In the figures with the diagrams in this article, L_{lv}, L_{hv} is the inductance of the dispersion and the lead-in conductors in the low-voltage and high-voltage winding of the PT respectively. When the IGBT-key is an opening switch and the magnetization inductance is intermediate energy storage, both the high-voltage and low-voltage circuits of PT participate in the discharge circuit of the high-voltage load.

For peaking of the pulse front, SOS diodes in the high-voltage PT circuit, as well as spark gaps, can be used.

The purpose of the article is to show the possibility of joint efficient operation of semiconductor switches and spark arresters in high-power high-voltage generators for obtaining nanosecond and shorter pulse fronts on a high-voltage load.

Choice of generator scheme. Schemes with SOS-diodes were developed by Russian scientists [1, 7]. But in these generators in the SOS-diodes' pumping circuits, inductance choke with saturation (magnetic keys) are used, which reduce the efficiency of the generators. Fig. 1 shows the circuit diagram of the generator with IGBT switches in the low-voltage circuit of PT in the form of a linear pulse transformer (LPT) and with a SOS switch in the high-voltage circuit of PT without throttles with saturating. The operation of the generator in the case of using T (IGBT) as a closing switch is described in [8]. With a low-resistance load with impedance ≤10 Ohm and the need to allocate in it of all the energy from C_{hv} in each pulse, it is required to minimize inductances of dissipation of high-voltage and low-voltage winding (L_{sh}, L_{sl}) of pulse transformer (PT). This can be done by applying a linear pulse transformer (LPT) as an PT [1]. The replacement circuit of the generator with the lead to the primary winding of the LPT is shown in Fig. 2. Given leaded values are marked with a prime ('). The ferromagnetic magnetic core LPT is divided into sections. Each section is wound with a single-turn primary winding, in the circuit of which there are series-connected capacitive storage C_{lv} and switch T (in Fig.1 IGBT- switch). The total primary winding consists of a series of single-turn primary windings wound each on its own section. The secondary winding is also single-turn, but covers all sections of the magnetic circuit. The design of LPT provides the minimum inductance of leakage L_s and inductance of magnetization L_μ (here L_s<<L_μ as well as in

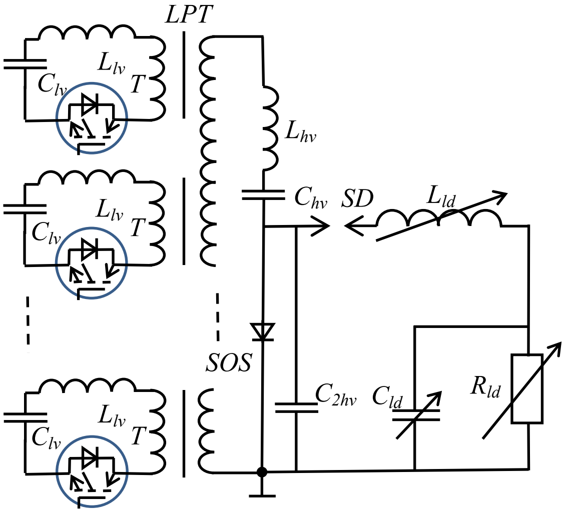

Fig. 1. Schematic circuit diagram of the generator with IGBT switches

traditional PT). Therefore, the duration of the transient response of the LPT is shorter than that of traditional PT. The transformation ratio of the step up transformer LPT is $k_t = n$, where n is the number of sections (or primary windings forming the total primary winding). In Fig. 2 $C_{lv\Sigma}=nC_{lv}$, $L_{lv\Sigma}=L_{lv}/n$, $L_{\mu\Sigma}= L_{\mu}/n$, L_{μ} – magnetization inductance of one section of LPT, T_{Σ} is a total IGBT switch consisting of n sectional IGBT switches T connected in parallel. Low values of L_s and L_{μ} lead to an increase of the current in the generator. This increases the switch requirements for the currents being passed. The modern IGBT module is capable of transmitting a current of 1200 A, can withstand a voltage of 3300 V and has an on-time of significantly less than 1 µs, and a shutdown time of approximately 1 µs (for example, IGBT module MIO 1200-33E10).

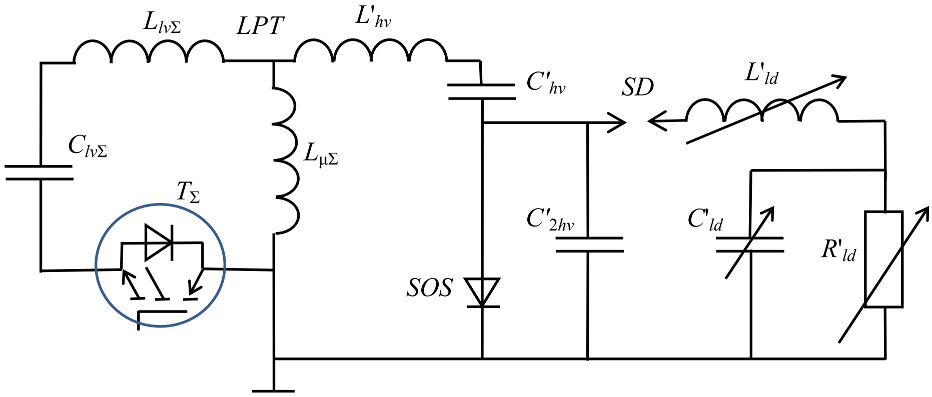

Fig. 2. Scheme of substitution for generator

Considering that the total primary winding consists of n constituent primary windings, each of which includes one MIO 1200-33E10 module with the corresponding driver as IGBT switch, at $n = 25$ the commutators of the total primary winding are able to pass the current $I_{max} = 30$ kA. And the calculated current I_{calc} in the discharge circuit through the total primary winding at R_{ld}=8 Ohm is approximately equal to $I_{calc}\approx U'_{hv}/R'_{ld}$. For U'_{hv}=300 V, $R'_{ld}=R_{ld}/n^2$=0.0128 Ohm, $I_{calc}\approx$23.4 kA. $I_{max}>I_{calc}$ [8]. Hence, IGBT-switches can work together with SOS-switches in the discharge circuits of high-power high-voltage generators. Advantages of semiconductor switching systems with IGBT in high-power generators over of switching systems with spark gaps are a higher permissible repetition rate (up to hundreds of thousands of pulses per second), high stability of pulses on the load. In addition, such a switching system provides the ability to control the switching times of IGBT switches on and off and full synchronization of their operation in parallel operation. However, as a final high-voltage switch it is advisable to use a spark gap, since spark dischargers are the most high-speed high-voltage switches that allow obtaining the minimum (subnanosecond) durations of the high voltage pulse fronts on the load. The permissible frequency of following into a load of high-power high-voltage pulses with a nanosecond front is currently limited, probably, by spark gaps at a level of several thousand pulses per second by using forced cooling of their electrodes. The considered generators can find wide application in high-voltage electrotechnologies, including at disinfecting water treatment, water purification by means of electric discharges [9-11].

One of the most promising variants of the scheme of a high-power high-voltage generator operating on the R_{ld}-L_{ld}-C_{ld} load is shown in Fig. 2. After the SOS-diode is pumped back and the current is switched to the capacitance C'_{2hv}, this capacitance is charged during a time interval (half-cycle) $T/2\approx\pi[(L_{\mu\Sigma}+L'_{hv})\ C'_{2hv}]^{1/2}$, if $C'_{2hv}<<C'_{hv}$, the closing switch SD does not work, and $L_{\mu\Sigma}$ acts as an intermediate energy store. However, to switch the energy to the load R'_{ld}-L'_{ld}-C'_{ld}, the switch *SD* (spark discharger) should work, preferably closer to the end of the half-period $T/2$. Then C'_{2hv} with an energy close to the maximum is connected to the R'_{ld}-L'_{ld}-C'_{ld} load during the switching time. The shorter the switching time, the shorter the pulse front duration formed on the R'_{ld}-L'_{ld}-C'_{ld} load.

Such a scheme allows one to obtain nanosecond pulses with amplitude of hundreds of kilovolts and more on the load by using a linear pulse transformer as a step-up pulse transformer having one turn in the secondary winding and a high-speed spark gap as the closing switch SD. Such an arrester allows achieving switch times in units of nanoseconds or less.

Experimental results. Fig. 3 shows the oscillograms of the current and voltage pulses on the load R_{ld}-L_{ld}-C_{ld}. The load of the generator was a serial connection of a gas bubble in water with a discharge in it and a layer of water under the bubble, that is, the load was nonlinear. Therefore, in the diagram (Fig. 1, 2), the inductance, capacitance and active resistance of the load are shown by variables (general case). The electrode system of the generator in which this nonlinear load was located was a «high-voltage metal rod – a low-voltage (grounded) metal ring under the rod». The oscillograms were obtained in an experimental setup using a simplified scheme in which there is no branch of C'_{hv}-SOS, and the capacitance C'_{2hv} is connected directly to the ends of the secondary winding of the *LPT* transformer. It follows from the oscillograms that the voltage and current curves are phase shifted relative to each other, the voltage amplitude on the load is approximately 23 kV and the current amplitude is about 15 A. The voltage and current pulse forms are aperiodic decaying with superimposed oscillations with a period of approximately 20 ns. The half-height duration for the voltage pulse was approximately 120 ns, and for the current pulse, about 60 ns. The duration of the pulse front, both voltage and current, over the levels 0.1-0.9 was approximately 10 ns. The repetition rate of pulses to the load ranged from 1200 to 5000 pulses per second. As a voltage sensor, a capacitive voltage divider was used, and a low-inductive current shunt was used as the current sensor. The recording device was a digital oscilloscope RIGOL DS1102E with a bandwidth of 100 MHz. Therefore, when recording pulses with characteristic times less than 10 ns, errors are possible.

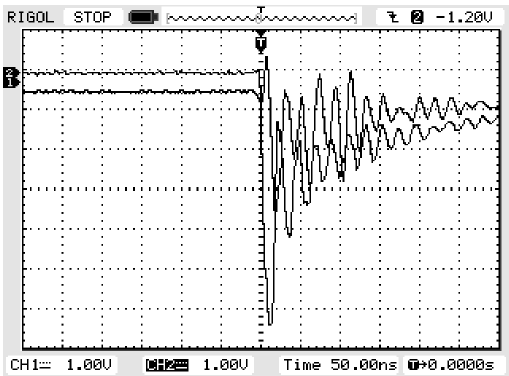

Fig. 3 Typical oscillograms of voltage pulse (1) and current pulse (2) on the load R_{ld}-L_{ld}-C_{ld}

The value of the division along the process axis for the voltage oscillogram (curve 1) is 7.65 kV/div, and for the current oscillogram (curve 2), 2.4 A/div.

Conclusions. A scheme of a high-voltage pulse generator based on a linear pulse transformer using IGBT-switches in its low-voltage circuits is proposed. In the high-voltage part of the generator it is proposed to use SOS-diodes as switches, and spark-gap dischargers as the final power switches. The advantages of the proposed scheme of a high-power generator with a R_{ld}-L_{ld}-C_{ld} load are shown: the possibility of obtaining high-voltage pulses with nanosecond and shorter fronts on the load at a repetition rate of up to several thousand pulses per second. These advantages are confirmed experimentally. A typical oscillogram of voltage and current pulses is shown on a nonlinear load in the form of a series connection of a gas bubble in water with a discharge in it and a layer of water under the bubble. The half-height duration for the voltage pulse was approximately 120 ns, and for the current pulse, about 60 ns. The duration of the pulse front, both voltage and current, over the levels 0.1-0.9 was approximately 10 ns.

The generators considered in this work can find wide application in high-voltage technologies, including decontaminating water treatment, water purification by electric discharges.

REFERENCES

1. Mesiats G.A. *Impul'snaia energetika i elektronika* [Pulsed power and electronics]. Moscow, Nauka Publ., 2004. 704 p. (Rus).

2. Muhammad H. Rashid. *Power electronics handbook: devices, circuits, and applications handbook*. Edited by Muhammad H. Rashid. 3rd ed. Butterworth-Heinemann is an imprint of Elsevier 30 Corporate Drive, Suite 400, Burlington, MA 01803, USA; Linacre House, Jordan Hill, Oxford OX2 8DP, UK, 2011. 1390 p.

3. Boyko N.I., Evdoshenko L.S., Zarochentsev A.I., Ivanov V.M., Konyaga S.F. The high-voltage complex with two high frequency generators that regulate modes of corona and barrier discharges when processing gaseous hydrocarbons. *Technical Electrodynamics*, 2012, no.2, pp. 105-106. (Rus)

4. Boyko N.I., Bortsov A.V., Evdoshenko L.S., Ivanov V.M. Generators of high-voltage pulses with a repetition rate of 50000 pulses per second. *Instruments and Experimental Techniques*, 2011, vol.54, no.4, pp. 533-541. **doi: 10.1134/s0020441211030225.**

5. Boyko N.I., Bortsov O.V., Evdoshenko L.S., Ivanov V.M., Ivankina A.I., Tur A.N. Pulsed corona discharge ionization with enlarged zone of ionization: physical fundamentals of obtaining and the perspective fields of application. *Electrical Engineering & Electromechanics*, 2004, no.3, pp. 98-104. (Rus). **doi: 10.20998/2074-272X.2004.3.20.**

6. Boyko N.I., Bortsov O.V., Evdoshenko L.S., Zarochentsev O.I., Ivanov V.M. Using pulsed corona discharge with enlarged zone of ionization for the conversion of toxic gaseous waste. *Electrical Engineering & Electromechanics*, 2007, no.4, pp. 64-65. (Rus). **doi: 10.20998/2074-272X.2007.4.16.**

7. Vasil'ev P.V., Lyubutin S.K., Pedos M.S., Ponomarev A.V., Rukin S.N., Sabitov A.K., Slovikovskii B.G., Timoshenkov S.P., Tsyranov S.N., Cholakh S.O. A SOS-Generator for technological applications. *Instruments and Experimental Techniques*, 2011, vol.54, no.1, pp. 54-60. **doi: 10.1134/s0020441211010118.**

8. Boyko N.I. Powerful high-voltage generators with the semiconductor switches. *Technical Electrodynamics*, 2014, no.5, pp. 92-94. (Rus).

9. Locke Bruce R. Environmental applications of electrical discharge plasma with liquid water – a mini review. *International Journal of Plasma Environmental Science & Technology*, 2012, vol.6, no.3, pp. 194-203.

10. Preis S., Panorel I.C., Kornev I., Hatakka H., Kallas J. Pulsed corona discharge: the role of ozone and hydroxyl radical in aqueous pollutants oxidation. *Water Science & Technology*, 2013, vol.68, no.7, p. 1536-1542. **doi: 10.2166/wst.2013.399.**

11. Vanraes P., Nikiforov A.Y., Leys C. Electrical discharge in water treatment technology for micropollutant decomposition. *Plasma science and technology – progress in physical states and chemical reactions*. 2016, Chapter 15, pp. 428-478. **doi: 10.5772/61830.**

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