DOI: https://doi.org/10.15407/techned2024.03.083

# SUB-NANOSECOND SWITCHING OF HIGH-VOLTAGE TRIGATRONS

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*The paper studies the mode of sub-nanosecond switching operation of trigatrons with an operating voltage of up to 1 MV. It is shown that the mode of such activation takes place because of the creation of primary volume streamer in the trigatron discharge gap under the action of a strong non-uniform electric field. The streamer occupies the entire gap and has a weak glow brightness. An estimated analytical calculation of the trigatron switching process in 0.3 ns is given. The process of sub-nanosecond breakdown of a trigatron with an operating voltage of up to 1 MV is presented. During the process the impact ionization after the incoming of a control pulse with a front of no more than 4 ns and an amplitude of 70 kV in the trigatron occurs along the entire length of the discharge gap of down to 12 mm: between the control electrode and opposing main one as well as between the control electrode and the main one covering it. The experimental data on the increase in the brightness of the discharge glow in the trigatron already after the end of the switching process are given.* References 12, figures 6.

***Keywords***: trigatron, volume streamer, sub-nanosecond switching, high-energy electrons.

**Introduction**. The high-voltage switches (dischargers) are widely used in high-voltage technique and various technologies [1]. Among other types of switches, such as magnetic switches and SOS diodes [2], the dischargers (spark gaps) achieve the most minimal switching times, permissible voltages and currents, and have a relatively simple design.

The most challenging task involves starting high-voltage switches. They should ensure a shortening of the front duration of received primary high-voltage pulses (with amplitudes of up to ≈1 MV) from several microseconds to ~1 ns. One of the most rational options for switches to solve this problem are trigatrons, i.e. the controlled three-electrode spark gaps with electric field distortion, in which the control electrode is built into one of the main ones [3].

**Modern understanding of discharge processes in gas gaps when using the pulsed high voltages.** The authors of [4] came to the conclusion that at a higher rate of voltage rise in the discharge gas gap, the primary ionized cloud that precedes the appearance of classical linear streamers has a larger size than at a lower growth rate. The authors of [4] determine the maximum size of the primary cloud based on the fact that the cloud is an ideal conducting ball with radius $R_{max}$, which is determined from the relation: $R_{max}=V/E_{br}$, where $V$ is the voltage applied to the discharge gap, $E_{br}$ is the breakdown strength of electrical field for gas in the discharge gap. The length of the gap $D_g$ is determined by the ratio $D_g=V_{br}/E_{br}$, where $V_{br}$ is the breakdown voltage. This means that $D_g=R_{max}$ when $V=V_{br}$. Consequently, the primary conducting cloud can occupy the entire discharge gap.

The authors of [5] report that in pure nitrogen under nanosecond operation, the classical linear streamers are branched from the primary node (knotweed).

It is stated in [6] that the streamers are growing in the gas gap from the first streamer corona. A streamer corona consists of several tens of streamers, and the consideration of single streamers is too simplified.

The authors of a number of works consider the variants for trigatron closure mechanisms [1, 3, 7]. The modern trigatron was used in [1]. The end of its rod control electrode is short-circuited to a thin round plate located in the main discharge gap parallel to the ends of main electrodes.

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**The aim of the paper** is to investigate the mechanism of trigatron closing that ensures its shortest (sub-nanosecond) switching time and its total operating time (including the delay time and switching time) compared to other mechanisms that provide such closing with an operating voltage of up to 1 MV.

According to our experimental data, in trigatrons with an operating voltage of about 400 kV, the minimum switching time (1–3 ns) is ensured by the inter-electrode gap $D_g$ of no more than 12 mm [8]. This is explained by the fact that the volume with a strong electric field between the control electrode and the opposing main electrode (at $D_g$>12 mm) does not reach this main electrode, as a result the switching time increases. Let the formed cylindrical discharge channel has the plasma with estimated resistivity $\rho=10^{-5}$ Ohm×m, channel length $l=10^{-2}$ m, and channel cross-section $S=10^{-8}$ $m^2$. Then the channel discharge resistance is found as: $R_{ch}=\rho\times l/S=10^{-5}\times10^{-2}/10^{-8}=10$ Ohm. With such $R_{ch}$ and fast switching (1–3 ns) more than 80% of the voltage is to be applied to the load ≥50 Ohm.

It is shown in [7] that the minimum delay time for trigatron breakdown in a few ns occurs with a positive polarity of the control electrode and with a negative polarity of the main high-voltage electrode opposing it. In this case, the control electrode is built into the low-voltage main electrode.

The experimental studies of the trigatron at an operating voltage of up to 1 MV show that the delay time of the trigatron breakdown of 1 ns with a sub-nanosecond jitter can be achieved when the control electrode is located in high-voltage electrode with positive polarity and when the control voltage pulse with a front duration of no more than 40 ns and a magnitude of approximately 70 kV is applied between the control electrode and the main high-voltage electrode of positive polarity covering it [8]. In this case, at 70 kV the positive potential of the control electrode $U_c$ will be greater than positive potential of the covering main electrode $U_m$ and at $U_m$=400 kV $U_c$=470 kV. The multiple increase in the potential of the control electrode makes it possible to create a significantly greater strength of an essentially ununiform electric field at the edge of the rod control electrode and in the space between the end of the control electrode and the main electrode surface opposing it. The field strength $E_0$ at the sharp edge of the end of the control electrode in the gap between the control electrode and the main one opposing it is determined by using the formula [9]:

$$E_0=\frac{U_0}{r}\left(\ln\frac{2d}{r}\right)^{-1}, \tag{1}$$

where $U_0\equiv U_c$ is the control electrode potential. The remaining notations are shown in Fig. 1.

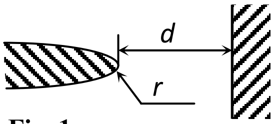

**Fig. 1**

In Fig. 1: $r$ is the radius of the tip, $d$ – is the distance from the end of the rod electrode to the plane. At $U_0$=470 kV, $r$=0,1 mm, $d$=10 mm according to (1) we obtain $E_0$=(470/0,1)/ln(2×10/0,1)≈4700/7≈670 (kV/mm).

Probably, after the incoming of the control pulse, but before reaching the maximum potential and electric field strength at the control electrode (in our case, $U_0$=470 kV, $E_0$≈670 kV/mm=670 MV/m), the process of generating the high-energy electrons begins in a strong electric field throughout the discharge gap of the trigatron. This explains the possibility of obtaining a delay time and a switching time of less than 1 ns in a trigatron with operating voltages of up to 1 MV. The authors of [10] point out that in strong electric fields, the intensity of which exceeds 26 MV/m, the electrons with the initial energy of a few eV can become runaway.

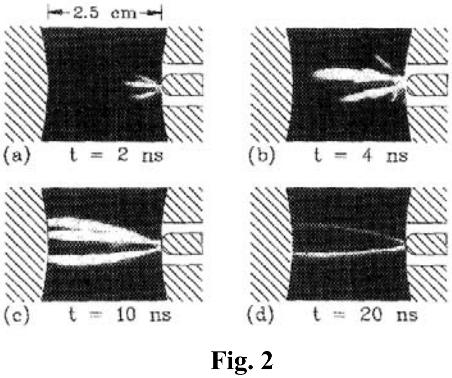

**Fig. 2**

The authors of the review [11] write that their experiments and numerical modelling have shown that during increasing voltage the beam of runaway electrons is observed, and its time duration is in the range of 50–200 ps.

The authors of [3] experimentally using the high-speed photography showed the development of streamers over time (Fig. 2), they close a trigatron discharge gap with length of 2.5 cm in a few nanoseconds. Fig. 2 presents the sequence of high-speed photographs showing the development of cathode-directed streamers in the main discharge gap of the trigatron under the following conditions: positive polarity for the control gap, negative polarity for the main gap. The minimum delay and switching time experimentally obtained in megavolt trigatrons are approximately equal to 1 ns [7]. This is less than the time of streamer growth through the discharge gap.

Fig. 3 shows the volumetric plasma formations (primary clouds) at the tip of a needle electrode (see [10]) at a pressure of 1 atm. Here the electron density is presented at the top and the electric field strength is

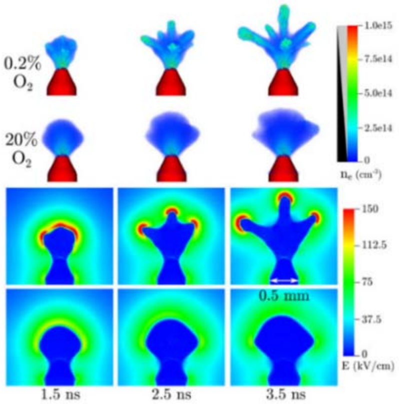

**Fig. 3**

given in the cross section (at the bottom). In contrast to the needle electrode (see Fig. 3) with a characteristic transverse size (diameter) of ≈0.5 mm, the diameter of the rod control electrode (with a sharp circular edge with a radius of curvature of ≈0.1 mm at the flat end) in trigatrons is ≈5 mm. The operating electric intensities in high-voltage trigatrons at voltages of up to 1 MV significantly exceed the voltages with a field maximum of 150 kV/cm (in Fig. 3). Let us take into account that the transverse size (diameter) of the primary ionized cloud around the needle electrode in Fig. 3 is approximately three times more than the diameter of the needle electrode. Let us assume that the characteristic transverse size of the primary cloud is three times larger than the diameter of the control electrode, i.e. ≈1.5 cm. In this case, the cross-sectional area of the primary cloud will be $S_1$=2.25 cm$^2$. With such a cross section, the inductance of the trigatron discharge gap with a length of $D_g$≤12 mm is significantly less than in the case of single spark channel.

**Estimated calculation of the electron concentration and current in the discharge gap of a trigatron in a low-resistance discharge circuit with channelless sub-nanosecond switching.** For the calculation we use the trigatron discharge gap from [8]. Fig. 4 shows a sketch of this gap.

In Fig. 4: *1*, *2* are the main electrodes of the trigatron with holes for the gas input and output; *3* is the control rod electrode with rod diameter dr=5 mm; *4* is the metal cylinder with a disk-shaped outer part that protects the dielectric housing *5* from discharge products; number 6 with arrow indicates the primary volumetric streamer, shown in the shaded area, covering the entire discharge gap; PG is the pulse generator; *R* is the low-resistance low-inductive load; $D_g$ is the main discharge gap, $D_g$ ≤12 mm; $D_m$ is the diameter of each of the two main electrodes, $D_m$=24 mm; *d* is the hole diameter in the high-voltage main electrode, *d*=8 mm; *a* is the distance from the inner surface of cylinder 4 to the outer surface of electrode *2*, *a*=9 mm. The control electrode *3* protrudes inside the main discharge gap by 0.5–1 mm.

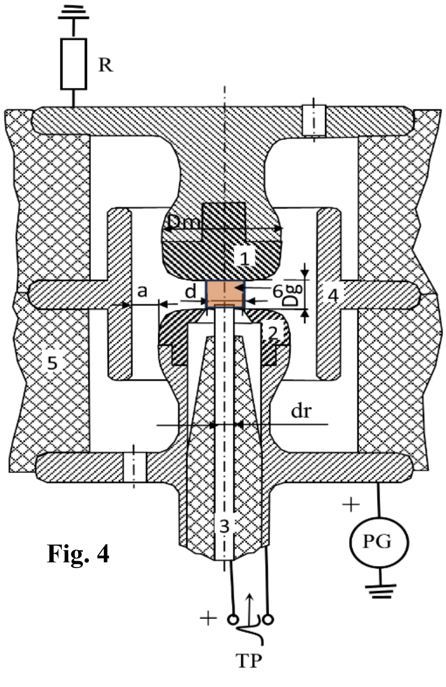

**Fig. 4**

It is known that the gas pressure $p=NkT$, where $N$ is the concentration, i.e. the number of ideal gas molecules per unit volume; $k$ is Boltzmann's constant, $k$=1,38*10$^{-23}$ J/deg; $T$ is the absolute gas temperature in degrees Kelvin. In our trigatrons we used SF$_6$ gas under pressure of up to 1 MPa [8].

At $p$=10$^6$ Pa, $T$=300 K $N$=$p$/($kT$)=10$^6$/(1,38*10$^{-23}$*300)=10$^{27}$/4,14= =2,415*10$^{26}$(m$^{-3}$)=2,415*10$^{20}$(cm$^{-3}$). $N$=2,415*10$^{26}$ m$^{-3}$.

For this value of $N$, according to the plot in Fig. 5, taken from [12], the electric field strength, at which the process of impact ionization begins, is approximately equal to $E$≈1,7*100*(10$^{-21}$ Vm$^2$)*2,415*10$^{26}$ m$^{-3}$≈4,1*10$^7$ V/m=410 kV/cm.

In uniform field in the main discharge gap of the trigatron with a self-breakdown voltage $U_{sb}$=400 kV, before the incoming of the control voltage pulse, the voltage $E_{main}$ in the discharge gap with length $D_g$=1 cm is about $E_{main}$=$U_{sb}$/$D_g$=400 kV/cm. After the incoming of the control pulse with a front of no more than 4 ns and an amplitude of 70 kV, which increases the potential of the control electrode above 400 kV, the process of impact ionization occurs in the gap $D_g$ of the trigatron in a fraction of a nanosecond. The process of impact ionization in a trigatron (see Fig. 4) occurs along the entire length $D_g$≤12 mm: between the control electrode and the main one opposing it (here more intensively) as well as between the control electrode and the main one enveloping it. Let us choose the average impact ionization coefficient α for the entire discharge gap according to the plot in Fig. 5 from [12]: α/$N$=4 in units of 10$^{-22}$m$^2$.

Then α=$N$*4*10$^{-22}$m$^2$==2,415*10$^{26}$ *4*10$^{-22}$m$^{-1}$=4*2,415*10$^4$m$^{-1}$≈10$^3$cm$^{-1}$.

We choose α/$N$=4, and not more, since in the process of impact ionization, the electrons can be attached to molecules and atoms. We take into account in the calculation that $I=Sen_ev_e$; $R=U/I$; where $S$ is the cross-sectional area through which the current flows; $e$ is the electron charge, $e$=1.6*10$^{-19}$ Cl; $n_e$ is the electron concentration; $v_e$ is the electron drift velocity; *I, U, R* are the current, voltage and resistance in the discharge circuit, respectively. In the calculation we use the continuity equation for electrons and the assumptions given in [7] for spark gaps controlled by an electron beam.

$$\frac{\partial n_e}{\partial t} = -\frac{\partial n_e \nu_e}{\partial x} - \beta n_e n_+ + (\alpha - \eta) n_e \nu_e . \tag{2}$$

In accordance with [7], we accept that $\frac{\partial n_e \nu_e}{\partial x} = 0$ due to the quasi-neutrality of the plasma, the electron sticking coefficient η is significantly less than the impact ionization coefficient α, β=0, i.e. we do not take recombination into account under the assumption of short current-rise times.

For the same reason, we do not take into account the effect of space charge. Then (2) is simplified to

$$\frac{\partial n_e}{\partial t} = \alpha n_e \nu_e . \tag{3}$$

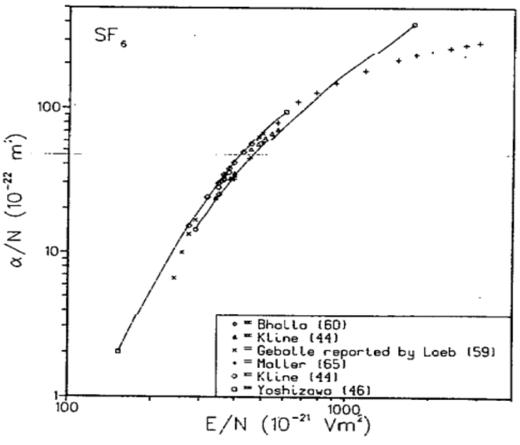

**Fig. 5**

As follows from (3) $\frac{\partial n_e}{n_e} = \alpha \nu_e \partial t$ and then after integration we obtain:

$$\begin{aligned} &\ln\left(n_e / n_{e0}\right) = \int_0^{t_d} \alpha \nu_e dt, \\ &n_e = n_{e0} \exp\left(\int_0^{t_d} \alpha \nu_e dt\right). \end{aligned} \tag{4}$$

Based on the data from scientific articles and the above, we will assume as a first approximation that α=Const=$10^3$ cm$^{-1}$[12], $v_e$=Const=$10^8$ cm/s [10, 11]. The upper limit of the integral in (4) $t_d$ is the end of the time interval of the trigatron discharge (breakdown) from the moment of the beginning (lower limit of the integral in (4), zero time) of the impact ionization process in the discharge gap after the incoming of the control voltage pulse, including the time of voltage fall at the main discharge gap of the trigatron, until the moment when the voltage on this gap drops to ≈0.1 of the voltage value at it at the moment when the fall begins. Let us take that $t_d$=0.3 ns.

The authors of [7] indicate that for spark gaps at pressure $p$>1 atm, the operation of which is initiated by an electron beam, it is possible to eliminate the discharge channel at initial voltages exceeding the static breakdown.

In the case of a discharge in a high-voltage trigatron with a pressure in the discharge gap $p$>1 atm, the role of the initiating electron beam play a control voltage pulse that distorts the electric field in the discharge gap to a value $E_0$≈670 kV/mm.

The authors of [3] give for the initial natural number of free electrons near the tip of the rod control electrode of a trigatron with a diameter of 5 mm the value of several hundred electrons at a pressure $p$=1 atm in the discharge gap. Let us take that $n_{e0}$=100 cm$^{-3}$. Then, taking into account that α=Const=$10^3$ cm$^{-1}$, $v_e$=Const=$10^8$ cm/s, $t_d$=0.3 ns, we obtain:

$$n_e = n_{e0} \exp\left(\int_0^{t_d} \alpha v_e dt\right) = n_{e0} \exp\left(\alpha v_e t_d\right) = 10^2 \exp\left(10^3 \cdot 10^8 \cdot 0{,}3 \cdot 10^{-9}\right) = 10^2 \exp(30) = 10^2 \cdot 10^{13} = 10^{15}\,\text{cm}^{-3}.$$

$i=jS=en_e v_e S$. Let us take $S$=2 см$^2$, then $i$=1,6*$10^{-19}$*$10^{15}$*$10^8$*2=3,2*$10^4$ A. If the load with $R$=10 Ohm allows such a current value, the internal resistance of the generator PG is close to zero, and the voltage at its output $U_{PG}$=390 kV, then the resistance $R_G$ of the gap when a current $i$=3.2*$10^4$ A flows in the discharge circuit will be: $U_{PG}=i(R_G+R)$, $R_G=U_{PG}/i-R$=390 kV/32 kA–10 Ohm≈(12–10) Ohm=2 Ohm. In this case the voltage drop across the discharge gap will be: $iR_G/\ i(R_G+R)$=2/(2+10)≈0,17, or 17% of the voltage of the PG generator. The process of reducing the resistance of the discharge gap will be continued until the energy in the load $R$ is completely released.

If the primary ionization region does not cover the entire discharge gap when the potential at the control electrode reaches its maximum, then a non-ionized region remains near the low-voltage main electrode. Only capacitive current can flow in this region. Let us estimate the capacitive resistance $X_{cn}$ of this region using the formula $X_{cn}≈t_f/C_n$, where $t_f$ is the duration of the front of the control pulse ($t_f$=2*$10^{-9}$ s), and $C_n$ is the capacitance of the remaining non-ionized region. Let us consider $C_n$ as the capacitance of a flat capacitor, taking the length of this area $l_n$=1 mm=$10^{-3}$ m, and the cross-sectional area $S_n$=2 cm$^2$=2*$10^{-4}$ m$^2$.

Then $C=\varepsilon_0\varepsilon S_n/l_n=8{,}85*10^{-12}$ F/m*1*2*$10^{-4}$ m$^2$/$10^{-3}$ m≈1,8*$10^{-12}$F, (here $\varepsilon_0$ is the dielectric constant, ε is the dielectric permittivity) and $X_c\approx t_f/C=2*10^{-9}/1{,}8*10^{-12}\approx1{,}1*10^3$ Ohm. $X_{cn}=1{,}1*10^3$ Ohm. $X_{cn}=1{,}1*10^3$ Ohm is greater than the load impedance $Z$, which usually does not exceed several hundred ohms. This means that before the ionization region covers the entire gap, most of the voltage from PG lies on the gap.

**The process of sub-nanosecond breakdown of the trigatron.** Before the incoming of a control pulse of positive polarity, a pre-breakdown voltage (for example, from 360 to 400 kV) is applied to the discharge gap of the trigatron. The electric field throughout the volume of the gap is close to uniform with the pre-breakdown voltage and there is small amount of free electrons. After the incoming of the control pulse, the potential of the control electrode increases in a few nanoseconds over the initial 360–400 kV. The field throughout the gap (with length Dg≤12 mm) becomes sharply ununiform in a fraction of a nanosecond. Its intensity exceeds the breakdown strength. The process of volumetric impact ionization starts throughout the gap. The number and concentration of free electrons in the volume of the discharge gap grows exponentially, and this leads to a sub-nanosecond increase of current. The process of volumetric impact ionization in the gap allows to increase to several tens of kiloamperes in fractions of a nanosecond the current in the discharge gap with length $D_g$=10 mm at cross-section area of the primary cloud $S$=2 cm$^2$. The current can reach these values if the amplitude of voltage pulses from PG generator is several 100 kV, and the total resistance of external discharge circuit is $Z\approx10$ Ohm. But even with such a small $Z\approx10$ Ohm, up to 90% of the voltage from the generator is applied to the load as a result of sub-nanosecond switching of the trigatron. With a higher resistance load, the resulting current will decrease and the voltage applied to the load will increase, approaching to 100%.

A trigatron with operating voltages of up to 1 MV can provide the sub-nanosecond switching and a sub-nanosecond increase of the voltage and current to a maximum (sub-nanosecond front) in a low-resistance load due to volumetric impact ionization throughout the discharge gap with an electrically high-strength gas under a pressure of ≈1 MPa. In this case, the average coefficient of impact ionization should be $\alpha\geq10^3$ cm$^{-1}$, and the average electron drift velocity $v_e\approx10^8$ cm/s. Among the free electrons in the ionized volume there may be a certain number of runaway electrons. After finishing the switching process, in most cases the process of transferring the energy from the PG generator to the load has just begun. In this case, the volume discharge in the trigatron turns into a corded (contracted) discharge with the formation of one or more completed classical streamer channels, and then spark channels. As the processes of lacing and development of spark channels occur, their conductivity increases, and the voltage across the discharge gap continues to decrease. The process of formation and development of spark channels is slower than the process of switching using primary volumetric impact ionization throughout the discharge gap of the trigatron. This volume is faintly luminous [11]. The brightness of the spark channels is much stronger. Our experiments with trigatrons have shown that the brightness of the glow in the discharge gap of the trigatron increases sharply after the end of the switching process, as is illustrated in Fig. 6 (see [8]).

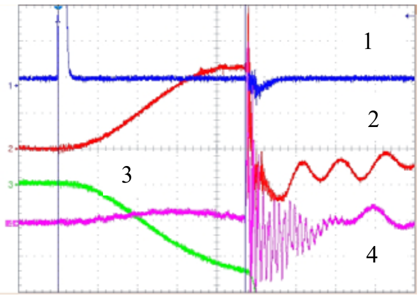

**Fig. 6**

Fig. 6 shows the oscillograms [8] of the process during trigatron breakdown (2 μs/div): the control signal of the Fitch generator is represented by 1; the pulse voltage between the main electrodes of the trigatron is displayed by 2; the light pulses observed at the spark gaps of the Fitch generator cascades and at the connetion of the trigatron discharger is given by oscillogram 3; oscillogram 4 corresponds to the positive polarity pulse on the control electrode of the trigatron. The sub-nanosecond switching provides a picosecond jitter, when switching the trigatrons, and parallel operation of several or more trigatrons. The trigatrons can operate both in single pulse mode and in frequency mode.

**Conclusions.** 1. The estimated analytical calculation of the electron concentration and current in the discharge gap of the trigatron for an operating voltage of up to 400 kV showed the possibility of sub-nanosecond operation of the trigatron with switching in volumetric mode. The current in the gap can reach several 10 kA and the concentration of free electrons can be $10^{15}$ cm$^{-3}$ in 0.3 ns.

2. The review of the present state of research concerning the discharge processes in various electrode systems allows us to conclude that at the nanosecond and shorter characteristic times of discharge development, the primary volumetric plasma formations (volume streamers) and runaway electrons play an important role.

3. The presented process of sub-nanosecond breakdown of a trigatron shows how a trigatron with operating voltages of up to 1 MV can provide the sub-nanosecond switching and current growth to a maximum (sub-nanosecond front) in a low-resistance load because of volumetric impact ionization throughout the discharge gap with an electrically high-strength gas under a pressure of about 1 MPa.

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УДК 621.316.933.1

## СУБНАНОСЕКУНДНА КОМУТАЦІЯ ВИСОКОВОЛЬТНИХ ТРИГАТРОНІВ

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*Досліджено режим субнаносекундного спрацьовування тригатронів з робочою напругою до 1 МВ. Показано, що режим такого спрацьовування має місце завдяки створенню в сильному неоднорідному електричному полі в розрядному проміжку тригатрону первинного об’ємного стримеру, який займає весь проміжок і має слабку яскравість світіння. Надано оцінний аналітичний розрахунок процесу спрацьовування тригатрону за 0.3 нс. Представлений процес субнаносекундного пробою тригатрону з робочою напругою до 1 МВ, за якого ударна іонізація після приходу керуючого імпульсу з фронтом не більше 4 нс і амплітудою 70 кВ в тригатроні відбувається по всій довжині розрядного проміжку не більше 12 мм: між керуючим електродом, а також між керуючим електродом і основним, що його охоплює. Наведено експериментальні дані про зростання яскравості світіння розряду в тригатроні вже після закінчення процесу комутації.* Бібл. 12, рис. 6.

***Ключові слова***: тригатрон, об’ємний стример, субнаносекундна комутація, високоенергетичні електрони.

Надійшла 01.04.2024
Остаточний варіант 07.05.2024