A compact high-current “field-distortion” gas switch with increased lifetime of sharp trigger electrode

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Abstract. A compact 40 kV, 80 kA low-jitter triggered gas switch of “field-distortion” type was developed. The electrode system of the switch includes two main electrodes with toroidal working surface and a disk type trigger electrode. A stable operation for a long time without degradation of dynamic parameters (time delay, jitter), which is resulted from erosion of sharp edge of the trigger electrode, was achieved by the decreasing of its diameter and removing the disk edge from zone between the tops of the main electrodes. Switch tests showed that for positive polarity of applied voltage $U$ equal to 0.75 of self-breakdown voltage $U_{sb}$ and negative trigger pulse of $2/3U$ the total time delay including the rise time of the trigger pulse of 15 ns is about 27 ns and jitter is $\approx 1$ ns. A stable operation of 10 simultaneously triggered switches is observed with the maximal deviation of closing time within 5 ns. No degradation of the switch parameters were registered for more than 200 pulses at switching currents of $\approx 60$ kA in amplitude.

1. Introduction

Triggered gas spark switch with a trigger electrode in the form of a disk with a thin (sharp) edge located in the gap between two main electrodes are widely used in pulsed power generators [1, 2]. In technical literature, they are called switches “triggered by field-distortion” or simply “field-distortion” switches. This name reflects the effect of a strong enhancement of the electric field at the edge of the trigger electrode with a change in its potential relative to the potential of the electric field at its location. The main advantages of the “field-distortion” switches are a small switching-on time delay and a small its deviation. They are resulted from the fast development of the discharge in a highly divergent field at the edge of the trigger electrode. The initial stage of the discharge in a highly divergent field, similar to the corona discharge, provides the appearance of initiating electrons in the gap resulted in the fast development of the discharge with the increasing of the trigger pulse voltage. The most significant disadvantage of the typical design of the “field-distortion” switches with the trigger disk located between tops of the main torus shaped electrodes is a relatively small service life. Lifetime is limited by the degradation of the dynamic characteristics, in particular, by the increasing of the deviation of the switching-on time, resulted from disk edge damages in the form of erosion and melting at high switching currents.

Below we present the design and the test results for the “field-distortion” switch with main toroidal electrodes and a trigger electrode reduced in diameter, whose thin edge is removed from zone between the electrode tops and is located in the inner peripheral region of the gap.
The switch is designed for use in a low-inductance capacitor-switch assembly. The assembly is a capacitive energy storage module that combines in a single design two capacitors of 0.35 μF, 40 kV each and a common switch. [3]. A set of 10 such modules are used in the system of primary pulsed powering of the 20-stage linear pulse transformer with output voltage of 800 kV, designed for a fast (300 ns) charging of a pulse forming line of a high-current electron accelerator [4].

The results of tests of the separate switch and the performance of 10 synchronously operating switches, used in the accelerator power supply system, show that the modification of the electrode system allows to increase the service life while maintaining a small time delay and a small spread of the switching-on time.

2. Design of the switch

The design of the switch is shown in figure 1.

![Figure 1. Design of the switch](image)

The switch has the dismountable metal case divided into two parts. The lower part 1 is welded to a case cover of the capacitor assembly. The insulating insert 2 with the installed in its base high-voltage electrode 3 is hermetically sealed in the metal case. In the capacitor-switch assembly, this electrode is connected to the midpoint of the two capacitors which is under a high charging voltage. The second electrode 4 is installed at the top of the insulating insert. It is connected to the metal case of the switch and is under zero potential (grounded). The rod 6 of the disk trigger electrode is fixed on the insulating sleeve 5 inside electrode 4. The discharge current sensor (Rogowsky coil) 7 is installed between the two parts of the switch metal case in the annular groove in the insulating insert 2. Dried air is used as a working gas in the switch. The working pressure is in a range up to 4 atm. The gas is pumped into the switch and removed from it through the axial channel in the rod of the trigger electrode. A gas system with a vacuum receiver and solenoid valves is used for purging of the switch. It provides a fast gas removing after discharge with products of the erosion of the electrodes. The design of the metal case of the switch allows its opening for inspection, cleaning or replacing the trigger electrode without disturbing the sealing of the capacitor assembly.

The switch electrodes are made of stainless steel. The outer diameter of the torus of the grounded electrode is 32 mm, its inner diameter is 16 mm. The high-voltage electrode has the outer diameter of 22 mm. Its torus shaped working surface rises to ≈1 mm and has the diameter of the inner recess of about 9 mm.
The trigger electrode is a hollow metal rod, smoothly expanding and converting into a sharp edge disk of 15.8 mm in diameter, 0.2 mm smaller than the inner diameter of the torus of the grounded electrode. The sharp edge of the disk is located at the axial distance ≈0.8 mm from the torus top of the grounded electrode. This position corresponds to the position of the equipotential surface with a potential of 1/3 of the applied voltage $U$. The same voltage $U/3$ is applied to the trigger electrode during the capacitors charging. This voltage is provided by a resistive divider in the trigger pulse generator.

The calculated picture of equipotential lines in the inter-electrode gap for the trigger electrode voltage $U_{tr}=U/3$ is shown in figure 2a.

![Equipotential lines plot](image)

(a) (b)

**Figure 2.** Equipotential lines plot: a – for initial state at $U_{tr}=U/3$ (the equipotential lines step is 0.05 $U$) and b – for trigger electrode voltage $U_{tr}=-U$ (the lines step is 0.1 $U$). $r$ and $z$ – are radial and axial coordinates respectively.

It is seen that for the designed electrode system, the trigger electrode, which is under voltage $U/3$ with respect to the grounded electrode, practically does not introduce a distortion in the field distribution in the inter-electrode gap. This is confirmed by direct comparing of the results of numerical calculations of the potential distribution and breakdown voltage $U_{br}$ for two situations: without trigger electrode and with it installed in the position shown in figure 2.

The switch is triggered by applying to the trigger electrode a pulsed voltage of opposite polarity. The equipotential lines plot calculated for the trigger electrode voltage $U_{tr}=-U$, where $U$ is voltage applied to the switch, is shown in figure 2b. As can be seen, “field-distortion” effect resulted in the gathering of the equipotential lines at the edge of the trigger electrode with the formation of a highly divergent electric field. The multiple increasing in the field strength at the edge of the trigger electrode ensures a short time delay of the breakdown of the switch. Under these conditions it is determined mainly by the time of development of the spark channels.

3. Test results and discussion

During the static tests (with a slow rise of the applied voltage), the self-breakdown voltage $U_{br}$ was measured as a function of the gas pressure. The trigger electrode potential, equal to $U/3$, was set by the voltage divider of three identical resistors of 47 Meg. Comparison of the data obtained with the results
of calculations shows that in the operating range of the gas pressure \( p \leq 4 \text{ atm} \) the difference of the measured and calculated values of \( U_{br} \) does not exceed 5\%.

The dynamic characteristics of the switch were measured during its operation in the capacitor-switch assembly. The schematic of a circuit for measurements is shown in figure 3.

![Figure 3. Circuit schematic for dynamic tests of the switch as the part of the capacitor-switch assembly.](image)

The measurements were carried out using a separate capacitor-switch assembly \((C_1 \text{ and } C_2)\) with shorted output cables \((TL_2 \text{ and } TL_3)\), i.e. when the assembly is running in a mode of a short-circuit load. In such mode, the discharge current has oscillating shape with the largest for given voltage amplitude. At full charging voltage \( U=40 \text{ kV} \), the amplitude of the first half-wave of the current through the switch reaches \( \approx 120 \text{ kA} \). Taking into account that for the real working conditions the amplitude of the current does not exceed 80 kA, most measurements with a separate assembly in the short-circuit mode were carried out at voltages of \( U \leq 25 \text{ kV} \). The dynamic characteristics were measured for new switches and also for switches used for a long time in capacitor assemblies at the accelerator.

During the measurements a trigger pulse with amplitude of \( 2U/3 \) was applied to the trigger electrode with polarity opposite to the initial voltage of \( U/3 \) (set by the divider \( R_2, R_3 \)). The trigger pulse is generated by the closing of the switch \( S_2 \). It connects the lower plate of the capacitor \( C_3 \) initially charged to the voltage of \( 2U/3 \) to the common bus (ground). The resulting jump of the potential of the upper plate of \( C_3 \) is transmitted to the trigger electrode by coaxial cable \((TL_1)\) and a damping resistor \( R_1 \) of 50 Ohm. The pulse voltage at the trigger electrode \( U_{tr} \) was measured using a high-voltage probe \( (1:1000) \) Tektronix 6015A. Rogowsky coil built into the switch was used for measurement of the discharge current flowing through the switch \( (I_{sw}) \).

Typical oscilloscope traces of the voltage at trigger electrode \( U_{tr} \), the discharge current \( I_{sw} \) and the current derivative are shown in figure 4. The data shown are obtained with positive polarity of the charging voltage \( U \) for the next conditions: \( U=20 \text{ kV}, p=1.5 \text{ atm}, U/U_{br}=0.61 \).

With the appearance of the trigger pulse, the initially positive voltage of the trigger electrode \( \approx 6.5 \text{ kV} \) is decreased and then changes its sign. When it reaches a certain negative level \( \approx -7 \text{ kV} \) for the trace 3 in figure 4) the breakdown occurs between the trigger and high-voltage electrodes. The appearance of a conductive plasma channel between these two electrodes leads to a fast increasing of the trigger electrode voltage. Voltage rise is limited by the completion of the discharge channel in the second gap between trigger and grounded electrodes with the appearance of the discharge current in the circuit. Time delay of the breakdown between the trigger and grounded electrodes relative to the breakdown of the first gap is shown in figure 5 by two cursors. The fast growth of the current
derivative coincides in time with a sharp drop of the trigger electrode voltage after the breakdown of the second gap. Taking it as the moment of the switching-on, the time delays of the closing of the gaps and entire switch were measured as a function of the applied voltage and the gas pressure.

The measurements were carried out in series of 20 pulses for each of the regimes with gas purging between the pulses. The average switching-on time-delay from the beginning of the trigger pulse for conditions at which the ratio of the charging and self-breakdown voltages \( U/U_{br} = 0.75 \) was 27±1 ns. The rise time of the trigger pulse before the closing of the first gap was 15 ns and the time delay of the closing of the second gap (relative to breakdown of the first one) – 12 ns. For \( U/U_{br} = 0.6 \) the total delay of the switch is increased to 32 ns, and the rms deviation – up to 2 ns. At \( U/U_{br} = 0.5 \) the total delay is 37±2 ns. We note that for the negative polarity of the charging voltage \( U \) and, respectively, the positive trigger pulse the switching-on time delay and its spread are increased under the same measurement conditions.

For estimations of degradations of the static and dynamic characteristics during the operation the comparative measurements were made for two switches: a new one, after a short training of the electrodes in the self-breakdown mode (~20 pulses), and for the switch taken for tests from one of 10 capacitor-switch assemblies after \( \approx 200 \) cycles of discharge in the operating modes of the accelerator. Note that for typical modes of accelerator operation the amplitude of the discharge current through the switch varies from 40 kA to 60 kA, and the estimated values of the flowing charge correspond to \((1\pm2) \times 10^{-2} \) C/pulse.

Visual inspection of the trigger electrode of the used switch shows no significant damages of the electrode surface or melting its edges. Figure 5 shows the photograph of the "grounded" electrode assembly of the used switch with the trigger electrode installed in the working position.

Figure 4. Oscilloscope traces of voltage at trigger electrode (3), discharge current (2) and discharge current derivative (1) measured at \( U=20 \) kV, \( p=1.5 \) atm, \( U/U_{br}=0.61 \). The arrows at left side of the picture indicate the positions of zero lines of the corresponding traces.

Figure 5. Photograph of the electrode of the switch after \( \approx 200 \) pulses in the operating mode of the accelerator.
Comparative tests did not show differences in the dynamic characteristics of the switches. The measured time delays for both switches tested under the same conditions differ by no more than 1 ns. No differences were recorded in the voltage of the static breakdown.

4. Conclusion
The results obtained in this paper show that the electrode system of the “field-distortion” switch, modified as described above, provides a long-term operation with a small time delay and a small spread of the switching-on time. Ten such switches in the ten capacitor-switch assemblies are currently used in the primary pulsed power system of a high-current electron accelerator based on 20-stages linear pulse transformer with output voltage of 800 kV [4]. In a typical operating mode with a charging voltage $U=36$ kV, pressure of air $p=3.5$ atm ($U/U_{br} \approx 0.6$), the maximum time spread of all ten synchronously triggered switches does not exceed 5 ns. This ensures good repeatability and reproducibility of the accelerator radiation parameters during medical and biological experiments [5].

The design of the electrode system of the switch is, in fact, an intermediate variant between the typical design of the systems of “field-distortion” switches and trigatron type switches, in which a thin rod is used as a trigger electrode [2]. By analogy with the current redistribution in a trigatron switch, which was observed by optical measurements in [6], it can be assumed that the same effect may take place in this switch. As a result of radial expansion of the plasmas at the edge of the trigger electrode a part of the discharge current may flow directly between the main electrodes without closing through the trigger electrode. It can explain small damages of the trigger electrode at high discharge currents observed in this work. Confirmation of this assumption requires additional studies to determine the position and size of the current-heated area of the plasmas by optical methods.

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