Triggered gas switch with a sharply non-uniform electric field at the electrode with negative potential

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Abstract. The paper presents the results of studies for two triggered high-pressure gas switches intended for pulse-periodic capacitive storages with the stored energy level of about 100–1000 J. The operating voltage of the first switch is up to 50 kV, for the second switch is over 200 kV. A feature for both switches is a configuration with a sharply non-uniform field at the electrode with negative potential. In the charging process of a capacitive energy storage, a corona-streamer discharge occurs in the switch, the current of which increases with increasing voltage. Cathode discharge plasma shields a sharp cathode edge and local areas of inhomogeneity with increased emission and also gives a uniform flow of initiating electrons into the gap of the switch. As a result, conditions in the discharge gap vary slightly from pulse to pulse.

1. Introduction

High-pressure gas switches are widely used in high-current high-voltage pulse-periodic generators. The spark switches for capacitive storages with the stored energy level of about 100–1000 J are of interest for industrial applications [1–3]. Providing of triggering stability and the longest life time in a pulse repetition mode are current problems for such types of the switches.

In high-current switches one of the reasons for loss of triggering stability is the electrodes erosion. When microareas with enhanced electron emission occur at the cathode as the result of previous pulse, breakdown voltage of discharge gap decreases and varies greatly from pulse to pulse. The emission current of initiating electrons is also unstable. In this case, the triggering stability can be obtained by specially created corona discharge from the cathode electrode. The space charge of the corona discharge in pre-breakdown stage significant distorts the initial sharply non-uniform electric field distribution in the gap and changes the breakdown voltage. Cathode discharge plasma shields a sharp cathode edge and microareas with enhanced electron emission, leading to the uniform flow of initiating electrons into the switch gap. Thus the conditions in the discharge gap changes insignificant from pulse to pulse and cathode surface condition does not affect the switch operation. This approach is successfully used in the spark switches in the self-breakdown mode for capacitive storages with pulsed charging [4–6]. In this case stable breakdown voltage is present only on the rising edge of the charging voltage pulse. Breakdown voltage value is determined to the switch gas pressure, which must be maintained and adjusted during the pulse repetition operation mode.
Controlled triggering mode allows switch to be used under slowly rising or dc applied voltages. For example, the possibility to control the gas switches with sharply non-uniform electric field was considered in [7–9].

This paper presents the results of studies of triggering stability of the controlled switch with sharply non-uniform electric field at the cathode and with preliminary ignition of the corona discharge.

2. Experimental setup
Experimental arrangement for investigation of triggered gas switches is presented in figure 1. The switch consisted of two gaps formed by high-voltage (1), triggering (2) and ground (3) electrodes. A cathode (1) was a tube made of 100-µm-thick copper foil. The diameter of the cathode was 40 mm. The use of such cathode construction eliminates the sharp edge smoothing and changing the ignition conditions of the corona discharge with a large number of pulses. The triggering (2) and ground (3) electrodes were the plane electrodes made of stainless steel. The triggering electrode potential is near to zero while charging the capacitive storage $C$. At low voltages value emission centers occurred on the cathode electrode with sharply non-uniform electric field and corona-streamer discharge was ignited. The discharge current increased as the voltage increases during the charging of capacitive storage $C$. After charging was completed, triggering voltage pulse of positive polarity was applied to the electrode (2). Electric field strength increased and initiated the sequential breakdown of the switch gaps $d_1$ and $d_2$.

Figure 1. Experimental arrangement for investigation of triggered gas switches with sharply non-uniform electric field: 1 – high-voltage electrode, 2 – triggering electrode, 3 – ground electrode.

Two modifications of the spark switch were investigated. The first modification was designed for commutation of microsecond capacitive energy storage charged from a dc voltage source up to 30–50 kV. The switching energy was 100–300 J. The second modification was intended for commutation of high-voltage capacitive energy storage with pulsed charging during about 100 µs to the voltage above 200 kV. In this modification switching energy was up to 1 kJ.

Two modifications of the spark switches were similar in general. The switches operated in dry air, the air pressure was varied from 1 to 4 atm. For the first modification the gap between high-voltage (1) and triggering (2) electrodes was $d_1 = 24$ mm and the gap between triggering (2) and ground (3) electrodes was $d_2 = 12$ mm. For the second modification the gap lengths were $d_1 = 38$ mm and $d_2 = 19$ mm.

Charging voltage of the capacitive storage $U_0$, triggering voltage pulse $U_{trig}$ and load voltage $U_{load}$ were measured. The delay time between triggering voltage pulse and load voltage were determined from the oscillograms. The switching time jitter (1-$\sigma$) was calculated in series of 150 pulses.

3. Electric field distribution
Evolution of the electric field distribution in the spark switch during the charging of capacitive storage was calculated using the two-dimensional hydrodynamic corona discharge model with two-moment and drift-diffusion approximations. In the model the distance between edge of high-voltage electrode and ground electrode was 2 cm, gas pressure (75% N$_2$ and 25% O$_2$) was 4.2 atm. The voltage pulse
with the rate of pulse rise $3 \text{kV} \cdot \mu \text{s}^{-1}$ was applied to the cathode. The list of reactions and their rate coefficients included in the model is given in [10].

Simulation results are presented in figure 2. As the result of quasi-stationary discharge ignition, sharply non-uniform density distributions for all kinds of charged species are formed. These distributions are typical of a classical corona discharge. In the domain with increased electric field the maximum values of electron density ($10^{11} \text{cm}^{-3}$), $\text{O}_2^-$ density ($10^{12} \text{cm}^{-3}$) and $\text{O}_4^+$ density ($10^{13} \text{cm}^{-3}$) are reached at the distance 0.2 mm approximately. In the rest of the gap the transfer domain of the ion current is formed. After ~ 50 µs the sharply non-uniform electric field distribution in the transfer domain evolved into the almost uniform distribution. This is ensured by a small imbalance of $\text{O}_4^+$ and $\text{O}_2^-$ ion densities.

![Figure 2](image.png)

**Figure 2.** Quasi-stationary plasma distribution and electric field strength distribution (the distance between edge of cathode and ground electrode is plotted on the abscissa).

4. Results

4.1. First switch modification

For the first modification of the triggered switch the corona-streamer current was measured in order of values of 1 µA at the air pressure 1 atm and charging voltage 18 kV. During charging the capacitive storage the discharge current amplitude reaches 100 µA. Self-breakdown voltage is about 49 kV at atmospheric pressure, which corresponds to the average electric field strength value $20 \text{kV/cm}$.

The operating pressure range of the switch at the charging voltage of the high-voltage capacitive storage $U_0 = 30–50 \text{kV}$ is shown in figure 3. Out of range of the operating pressure a self-breakdown of the switch or not triggering are possible.

![Figure 3](image.png)

**Figure 3.** Operating pressure range for the first switch modification.
Figure 4 shows the switch jitter in the various operating conditions. According to experimental data for the triggering voltage with pulse rise rate $5 \text{kV} \cdot \text{ns}^{-1}$ and amplitude value $100 \text{kV}$ the switch jitter reaches the value $10 \text{ns}$ in the operating voltage range $35–50 \text{kV}$. The switch jitter increases by 2–4 times when rise rate decreases to $0.1 \text{kV} \cdot \text{ns}^{-1}$.

![Figure 4](image1)

**Figure 4.** Dependence of the switch jitter on the voltage. Rise rate and amplitude of the triggering voltage pulse $5 \text{kV} \cdot \text{ns}^{-1}$, $100 \text{kV}$ (a) and $0.1 \text{kV} \cdot \text{ns}^{-1}$, $45 \text{kV}$ (b).

### 4.2. Second switch modification

For the second switch modification the ignition voltage of the corona-streamer discharge is 20–30 % of the self-breakdown voltage value. The corona discharge current amplitude reaches $10 \text{mA}$. The self-breakdown voltage is $105 \text{kV}$ at the pressure $1.8 \text{atm}$ and increases to $200 \text{kV}$ with pressure increasing to $3.5 \text{atm}$.

The operating pressure range of the spark switch at the charging voltage of the high-voltage capacitive storage $U_0 = 110, 165, 220 \text{kV}$ is shown in figure 5. The switch jitter values at the triggering voltage with pulse rise rate $0.25 \text{kV} \cdot \text{ns}^{-1}$ and amplitude value $100 \text{kV}$ are presented in figure 6. The switch jitter value is about $100 \text{ns}$.

![Figure 5](image2)

**Figure 5.** Operating pressure range for thesecond switch modification.

![Figure 6](image3)

**Figure 6.** Dependence of the switch jitter on the air pressure. Rise rate and amplitude of the triggering voltage pulse $0.25 \text{kV} \cdot \text{ns}^{-1}$, $100 \text{kV}$. 
5. Conclusion
The results of studies of triggering stability of the three-electrode controlled gas switch intended for pulse-periodic operation mode are presented. The distinctive feature of the triggered gas switch is application of discharge gap configuration with sharply non-uniform electric field at the electrode with negative potential, which ensures the ignition of the corona-streamer discharge during charging the capacitive energy storage.

The operating voltage and pressure ranges are experimentally determined, which provide the steady controlled triggering of the gas switch. The possibility of reaching the 10 ns switch jitter is presented. Triggered gas switch does not impose strict requirements to the operating pressure.

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