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The Influence of Electrical Isolation between Channels on Multi-Gap Gas Switch Parameters

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Abstract

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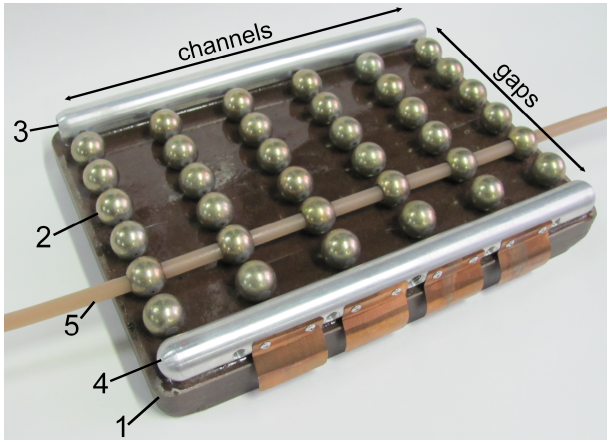
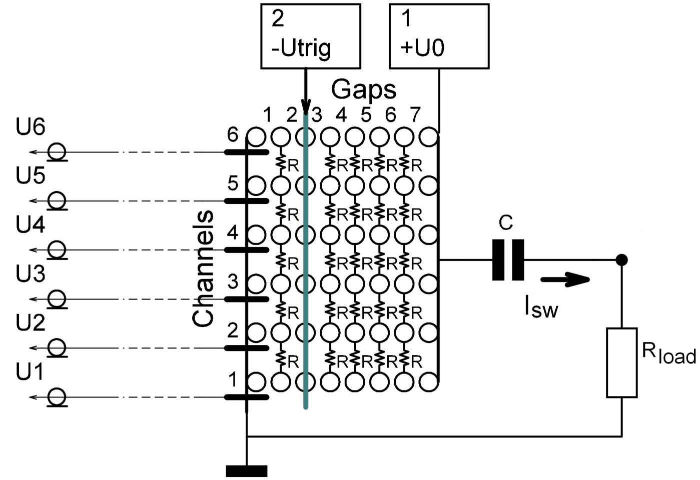
This paper presents the results of calculating the inductance, resistance and dissipated energy of parallel spark channels of a 100 kV multi-gap gas switch at atmospheric pressure. Two multi-gap switch configurations were considered in the presence and absence of electrical isolation between the channels. Electrical isolation between the channels significantly affects the number of parallel ignited channels and their distribution over consecutive gaps and, therefore, the switching characteristics of the switch. Calculation results make it possible to compare the switch parameters in the presence and absence of electrical isolation between the channels and allow us to reasonably choose the parameters of the triggering pulse and the design of the switch.

Multi-channel multi-gap gas switch



Design of the switch: (1) epoxy slab; (2) intermediate ball electrodes; (3, 4) high- and low-voltage end electrodes; (5) triggering wire.



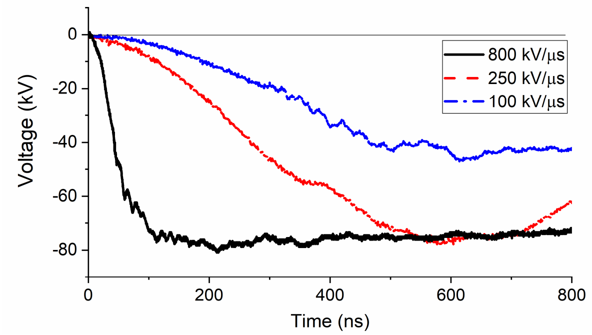
Schematic of the switch and the testbed for switch testing: (1) HV power supply; (2) triggering generator.

The gap between the high-voltage and low-voltage electrodes is divided into seven serial gaps using intermediate ball electrodes with a 22 mm diameter. The length of a single gap is 6 mm. The switch operates in air at atmospheric pressure at voltages up to 100 kV.

The ball electrodes are divided into six groups, forming six parallel channels. The voltage across the gaps is distributed using a resistive voltage divider, in which the resistors are connected in series in one of the channels between the high- and low-voltage electrodes. Resistors *R* are connected between the electrodes of adjacent channels, ensuring that the voltage is distributed over the electrodes in all the other channels. In the first case, ***R* ~1 MΩ, the channels can be considered electrically isolated and independent of each other**. In the second case, ***R*~0, the channels are electrically coupled**.

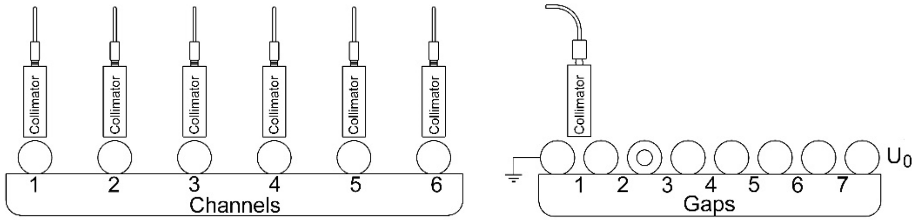
Switch-testing apparatus

The number of channels in the switch gaps was determined using an experiment with a capacitive energy storage device C=20 nF (two series-connected capacitors GA35426, 100 kV, 40 nF) and a load R_{load}=3.8 Ω. Three triggering voltage pulses $U_{trig}(t)$ with an amplitude of 80 kV and voltage rise rates of 100, 250 and 800 kV/µs were used.

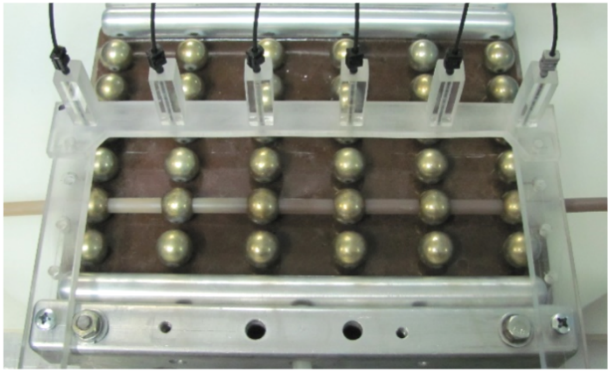


Triggering pulse waveforms.

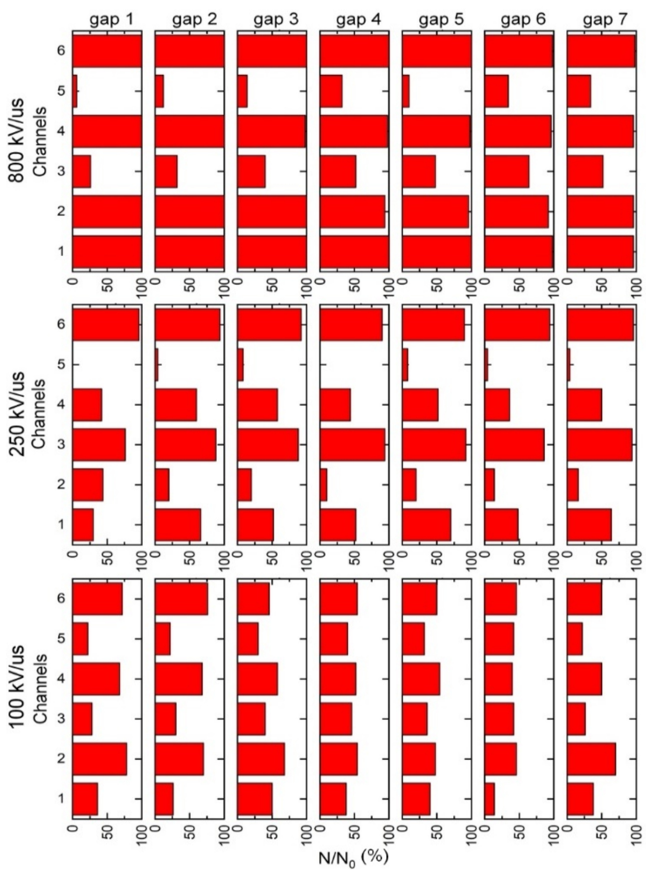
An optical system was used to determine the number of channels in the switch gaps. The system consisted of six collimators with an extended hole, the light from which is fed through a fibre to a photodiode with a pre-amplifier circuit. Statistics on the number of channels were collected under different operating conditions, allowing us to calculate the probability of igniting the spark channels for each of the switch gaps.



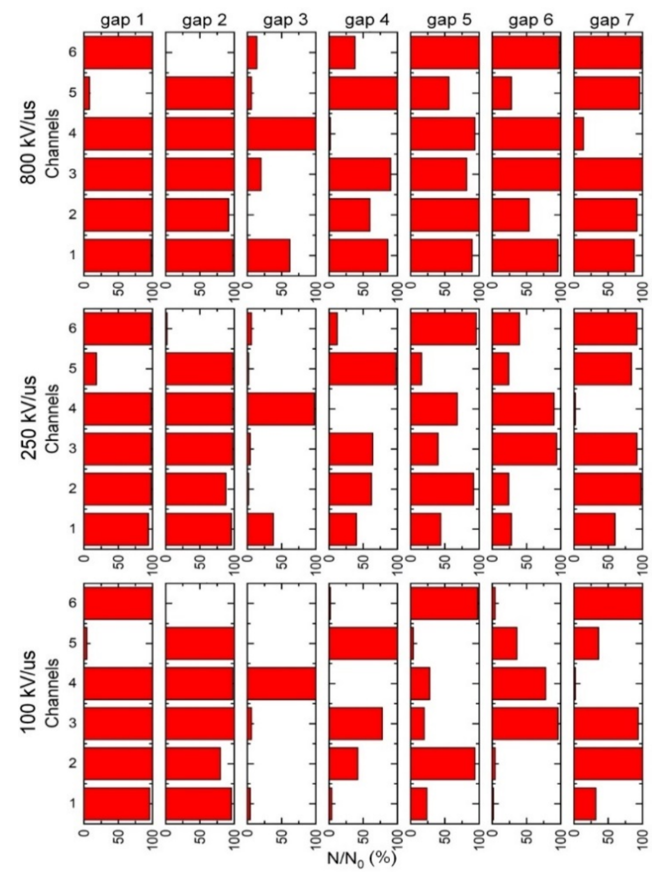
Front and side views of the switch and arrangement of the collimators.



Probability of ignition of spark channels in the gaps



Probability of ignition of spark channels in the gaps of the switch **with** electrical isolation between the channels, for rise rates of the triggering pulse of 800, 250 and 100 kV/µs.



Probability of ignition of spark channels in the gaps of the switch **without** electrical isolation between the channels, for rise rates of the triggering pulse of 800, 250 and 100 kV/µs.

Electrical isolation between the channels significantly affects the number of parallel ignited channels and their distribution over consecutive gaps. If there is electrical isolation, the number of channels in all the gaps is approximately the same and is determined by the number of channels initiated in the triggering gap (Gap 3). If there is no electrical isolation, only one channel is mainly ignited in the triggering gap, although the number of parallel channels increases with the breakdown of subsequent gaps due to an increase in overvoltage. The largest number of channels is realised in the gaps breaking through last (Gaps 1, 2 and 7).

Calculation of switch parameters

The characteristics of the switch are determined by variable resistance and inductance. Inductance and resistance, as well as dissipated energy in the spark channels of a seven-gap switch, can be written as:

$$\begin{cases} L_{SW}(t) = \sum_{i=1}^{7} L_i(t) \\ R_{SW}(t) = \sum_{i=1}^{7} R_i(t), \\ E_{SW}(t) = \sum_{i=1}^{7} E_i(t) \end{cases} \quad (1)$$

where $L_i(t)$, $R_i(t)$ and $E_i(t)$ are the parameters of the system of parallel spark channels in gap i. We assumed that the current through a single channel in the gap is:

$$I_i(t) = I_{SW}(t)/N_i, \quad (2)$$

where $I_{SW}(t)$ is the switch current and N_i is the number of spark channels in gap i.

The Braginskii model gives an expression for the radius of the channel:

$$r_i(t) = r(0) + \left(\frac{4}{\rho_0 \pi^2 \xi \sigma}\right)^{1/6} \left(\int_0^t |I_i(t)|^{2/3} dt\right)^{1/2}, \quad (3)$$

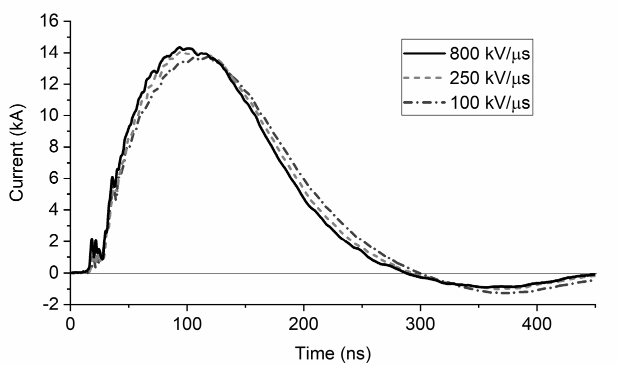
where $r(0)$~0.05 mm and is the initial channel radius, ρ_0=1.2·10^{-3} g/cm^3 is the gas density at which the discharge occurs, σ=300 (Ω·cm)$^{-1}$ is the specific electrical conductivity and ξ≈4.5 is a dimensionless constant. Using (3), we can calculate the inductance, resistance and dissipated energy of a system of N_i parallel spark channels in each of the seven gaps.

$$L_i(t) = \frac{1}{N_i}\left[\frac{\mu_0}{2\pi} l \left(\ln\frac{2l}{r_i(t)} - 1 + \frac{4r_i(t)}{\pi l} - \frac{r_i(t)^2}{2l^2}\right)\right], \quad (4)$$

where l=6 mm and is the channel length.

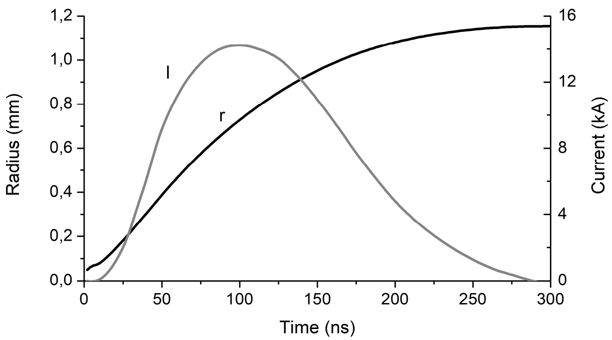
$$R_i(t) = \frac{1}{N_i} \cdot \frac{l}{\pi r_i(t)^2 \sigma} = \frac{1}{N_i} \cdot \frac{l}{\left(\frac{4\pi\sigma^2}{\rho_0 \xi}\right)^{1/3} \int_0^t |I_i(t)|^{2/3} dt + \pi\sigma r(0)^2}, \quad (5)$$

$$E_i(t) = \int_0^t I_{SW}(t)^2 R_i(t) \cdot dt.. \quad (6)$$

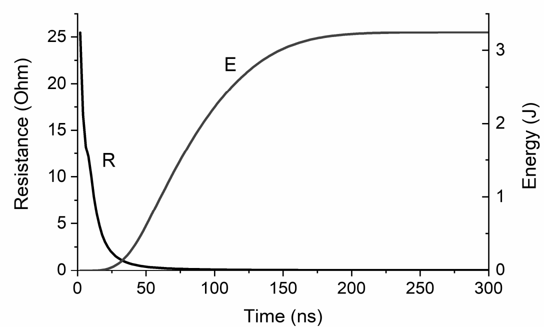


Switch current waveforms for rise rates of the triggering pulse of 800, 250 and 100 kV/μs.

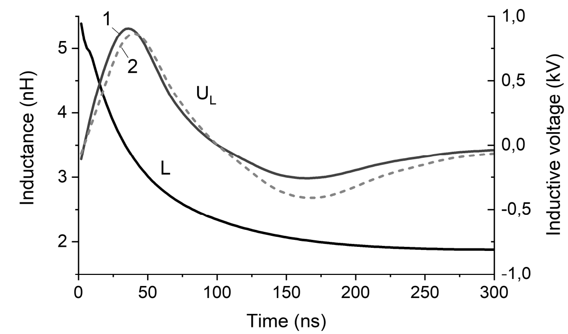
Examples of the parameters when the entire discharge current flows through the single channel



Radius of the channel *r* with current *I*.



Resistance *R* and dissipated energy *E* of a single channel.



The inductance of one channel *L* and the inductive voltage drop across it U_L:

1– $L(t) \cdot dI/dt$; 2– $(3.2 \cdot 10^{-9}) \cdot dI/dt$.

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1) Number of parallel channels with a probability of ignition of more than 90% at different triggering pulse rise rates;
2) the energy dissipated in the switch and the equivalent constant inductance of the spark channels for all seven gaps, calculated using Equations (1)–(6).

$\frac{dU_{trig}(t)}{dt}$, kV/µs	Gap 1, N_1	Gap 2, N_2	Gap 3, N_3	Gap 4, N_4	Gap 5, N_5	Gap 6, N_6	Gap 7, N_7	E_{SW}, J	L_{SW}, nH
Switch with electrical isolation between the channels									
800	4	4	4	4	4	3	3	13.34	6.9
250	1	1	1	1	1	1	2	21.76	21.5
100	1	1	1	1	1	1	1	22.54	23.1
Switch without electrical isolation between the channels									
800	5	5	1	2	3	4	4	14.75	9.3
250	5	4	1	1	1	2	2	18.01	14.9
100	5	4	1	1	1	1	2	18.60	16.5

At a triggering pulse rise rate of ~800 kV/µs, the dissipated energy is ~13.3 J for the switch with electrical isolation between channels and ~14.7 J for the switch without electrical isolation between channels. With a decrease in the triggering pulse rise rate from 800 to 100 kV/µs, the loss of switching energy increases by a factor of ~1.7 for the switch with electrical isolation between channels and less than ~1.3 for the switch without electrical isolation. The energy dissipated in the switch without electrical isolation between channels becomes less than in the switch with electrical isolation at a low triggering pulse rise rate (100–250 kV/µs). The inductance of the channels in the switch without electrical isolation at 100–250 kV/µs triggering pulse rise rate is also lower.

Conclusion

The parameters of a multi-channel multi-gap atmospheric pressure switch were calculated in the presence and absence of electrical isolation between the channels. The electrical isolation between the channels significantly affects the number of parallel ignited channels and their distribution over consecutive gaps and, therefore, the switching characteristics of the switch. At a high triggering voltage pulse rise rate (~800 kV/μs), a larger number of spark channels are ignited in the switch with electrical isolation between the channels and the characteristics of this switch are better. At a low triggering voltage pulse rise rate (less than 250 kV/μs), better characteristics are realized in the switch without electrical isolation between the channels. Thus, the switch without isolation between the channels has an advantage when a trigger pulse with a low rise rate is used.