Formation of the voltage pulses up to 400 kilovolts with front pulse less than 10 nanoseconds

B A Kozlov¹ and D S Makhanko²

¹Ryazan State Radio Engineering University, 59/1 Gagarina St., Ryazan, 390005, Russia
²PLASMA, JSC Research Institute of Gas-Discharge Devices, 24 Tsiolkovsky St., Ryazan, 390023, Russia

E-mail: mahdim@rambler.ru

Abstract. This work presents basic information about the design, manufacturing technology, and application of small-sized sealed-off spark-gaps in metal-ceramic design with hydrogen filling up to 120 atmospheres at an operating voltage of 100-400 kV with switching energy of up to 10 Joules in pulsed X-ray flaw detectors. The main factors affecting the mechanical strength and stability of the spark-gap operation are described. The results of an experimental study of the switching characteristics of the RO-49 spark gap-sharpeners are presented.

1. Introduction
Small-sized pulse spark gap-sharpeners for voltages of 100-400 kV and switching energy up to 10 J are destined for the formation of nanosecond high-voltage pulses in high-voltage pulse devices. This type of two-electrode metal-ceramic spark gaps of high pressure is produced in a sealed-off form and is intended mainly for portable pulsed X-ray equipment, electron-optical converters, and accelerator equipment. The use of spark gap-sharpeners can significantly reduce the size and weight of devices, sharply reduce the inductance of the discharge circuit and the energy losses of the equipment.

2. Construction and technological aspects of the creation of small-sized sealed-off spark gap-sharpeners
Currently, two enterprises in Ryazan - JSC "Plasma" and LLC "Pulse Technologies" are involved in the industrial production of spark gap-sharpeners.

Figure 1 shows a schematic of a nanosecond X-ray source.

![Figure 1. A schematic of a nanosecond X-ray source.](image)
When the key K is closed, the pre-charged storage capacitor $C_1$ is discharged through the primary winding of the pulse transformer T. At the same time, a high voltage pulse in the form of a sinusoid occurs in its secondary winding. The rise time of the voltage of the first half-wave of the damped sine wave to the amplitude value is about $10^{-6}$ s and is determined by the parameters of the circuit of the secondary circuit of the transformer (the inductance of the secondary winding of the transformer and the capacitance $C_2$, which is the total capacitance of the secondary circuit, including the constructive capacitance of the casing of X-ray source, the interelectrode capacitance of the spark gap and the inter-turn capacitance of the transformer). When charging the capacitor $C_2$ to the breakdown voltage of the spark gap SG, its breakdown occurs and a high-voltage pulse with a steep front within 1 ns is applied to the electrode system of the X-ray tube Re, determined by the switching time of the spark gap.

Figure 2 shows a structural schematic of a compact pulsed X-ray emitter.

Figure 2. A structure schematic of a compact pulsed X-ray emitter.

The pulse transformer 1, after exposing its primary winding to a voltage pulse of 15-20 kilovolts, charges the constructive capacitance between the body of the spark gap-sharpener 2 and the body of the X-ray apparatus 4 for a time of 1-2 microseconds. After spark gap 2 is triggered, the constructive capacitance is discharged to the X-ray tube 3 along the circuit with a minimum inductance.

The purpose of the spark gap-sharpener is to significantly reduce the duration of the first front of the high-voltage pulse, which ensures the breakdown of the vacuum or gas-discharge gap with overvoltage. The output parameters of the X-ray emitter and its resource depend on the parameters of such pulses [1].

After the creation of pulsed X-ray flaw detectors, it became necessary to develop and commercially produce sealed-off metal-ceramic spark gap-sharpeners in a wide range of dynamic breakdown voltages from 100 to 400 kV. Based on the experience of laboratory developments of the RFNC "Research Institute of Experimental Physics" in the JSC "Plasma", since 1972, research and development work has been carried out on the development and industrial production of spark gap-sharpeners in a wide range of dynamic breakdown voltages. Based on the research results, a series of gas-filled sealed-off high-pressure spark gap-sharpeners (up to 120 Atm) in a metal-ceramic design was developed in the breakdown voltage range from 100 to 400 kV, with nanosecond and subnanosecond switching time and a resource of $3\times10^6$ pulses.

Table 1. The main characteristics of mass-produced spark gap-sharpeners of JSC "Plasma".

| Model | Dynamic breakdown voltage (kV) | Pulse current (kA) | Switched energy (J) | Overall dimensions, d×H (mm) | Resource (pulses) |
|-------|-------------------------------|-------------------|---------------------|-----------------------------|------------------|
| RO-48 | 100-140                       | 0.4               | 0.5                 | 40×69                       | $3\times10^6$   |
| RO-43 | 140-190                       | 1                 | 2                   | 50×80                       | $3\times10^6$   |
| RO-49 | 180-250                       | 1                 | 6                   | 70×90                       | $3\times10^6$   |
| RO-50 | 180-260                       | 1                 | 8                   | 65×94                       | $3\times10^6$   |

Figure 3 shows the mass-produced spark gap-sharpeners RO-43, RO-48, and RO-49, used in the production of domestic pulsed X-ray devices for flaw detection.
Figure 3. Mass-produced spark gap-sharpeners RO-43, RO-49, and RO-48.

Figure 4. The construction of the serial spark gap-sharpener RO-49.

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The device consists of an anode unit 1, a cathode unit 3 and a casing 2. The mechanical strength is determined by the strength of the casing itself since the couplings of metal with ceramics are compensated and only compressive forces are tested after filling with the working gas. The casing and components are connected by argon-arc welding and additionally, to enhance the rigidity and reliability of the design of the spark gap, anode unit 1 is connected to the casing 2 by a threaded connection. A silver solder PSr-72V with a melting point of 780°C is used for soldering the cathode node. It is also necessary to consider that to ensure high quality, metalized ceramics must be soldered at the lowest possible temperatures and exposures. The electrodes in the spark gap are made of a special tungsten alloy VNG-7-3 and have a Bruce profile, which provides high stability of actuation and erosion resistance of the electrodes.

This construction of the spark gap is able to withstand the internal pressure of the working gas of more than 100 Atm, which allows you to get a switching time of fewer than 0.5 ns. The choice of the interelectrode distance and the pressure of the gas to be filled, usually hydrogen, is determined by the requirement for the switching time and the dynamic breakdown voltage.

The spark gap-sharpeners works as follows: when a high-voltage pulse voltage is applied to the gap between the electrodes, its breakdown occurs, and the voltage pulse caused by the current flow in the discharge circuit is released on the load. In this case, the steepness of the rise of the voltage pulse at the load is determined by the switching time of the spark gap and the inductance of the discharge circuit. During the action of a pulsed voltage between the electrodes, the distribution of the electric field potential along the forming conical surface of the insulator and between the electrode terminal of the cathode node and the casing depends on their mutual location and configuration [2].
For the effective operation of a pulsed X-ray tube with explosive emission in an X-ray machine, it is necessary to have the shortest possible switching time of the spark gap (less than 1 ns) and its stable operation, which is ensured by the correct choice of geometric shapes and optimal size ratios of the spark gap parts, as well as the correct choice of the interelectrode distance $S$ and the pressure of the gas to be filled [3].

It is known that the switching time of the spark gap at currents less than $10^4$ A does not depend on the current value and decreases with an increase in the electric field strength and the pressure of the gas being filled [4]. This property of a spark to shorten the time of channel conductivity growth with an increase in gas pressure is widely used in the technique of generating powerful nanosecond pulses, X-ray sources, and powerful pulse generators of ultrashort electromagnetic pulses, for solving problems of ultra-wideband radio communication, radar, and problems of electromagnetic compatibility and radio interference [5].

3. Response times of spark gap-sharpeners of the RO-49 series

The magnitude of the time of development of a high-pressure discharge is determined by a few electrophysical factors. These include both an increase in the conductivity of the gap itself, and the transient process itself in the electrical circuit. It is extremely difficult to isolate the influence of each of these factors at voltages up to 400 kV. Therefore, the time during which the current in the discharge circuit or the voltage at the load under study varies in magnitude from 10 to 90% was taken as the characteristic time of the development of the discharge in the high-pressure spark gap-sharpener.

In order to experimentally determine the characteristic switching times, the electrical circuit shown in figure 5 is used. The measuring complex consists of a cylindrical aluminum body (1), a spark gap (2), a resistive load (3) in the form of a set of low-inductive resistors of the TVO-60 type with a total nominal value from 3 to 30 Ohms, a current measuring resistive shunt (4) with a total resistance of 0.01 Ohms.

In the upper part of the cylindrical casing (1), where the spark gap (2) (RO-49) is located, an additional cylindrical electrode (5) is built-in (figure 5 (b)). It is isolated from the cylindrical casing (1) by a very thin layer of capacitor paper (6). The shading between the spark gap (2) and the casing (1) reflects the area of the high-voltage structural capacitor $C_{CAP}$, the value of which, depending on the size of the gap between the outer shell and the additional cylindrical electrode, and is in the range of 40-70 pF. The structure "spark gap (2) - additional electrode (5) - cylindrical casing (1)" forms a coaxial constructive capacitive voltage divider with a division coefficient $k \approx 1:1000$. The signal from this divider is fed through the high-frequency connector (7) to an additional resistive divider. Structurally, this divider is installed in a protective housing and is located directly at the input of the oscilloscope.

A high-voltage pulse of the required amplitude with a rise time of 1-2 microseconds from a high-voltage pulse transformer is fed to the spark gap's external output (8). The constructive capacitance formed by the spark gap and the cylindrical body is charged to the breakdown voltage of the spark gap.
and the energy stored after that in the constructive capacitance is very quickly transferred to the load resistor along the circuit with minimal inductance. The current flowing through this circuit is recorded using a sequentially installed resistive current shunt. The voltage measured on this resistor allows to determine the parameters of the current pulse. By the measured duration of the first front of the current pulse, the response time of the spark gap can be determined.

The high-voltage pulse generator, which charged the constructive capacitance between the body of the spark-gap and the cylindrical body of the measuring path, was formed by an open-type pulse transformer, a storage capacitor (a set of capacitors of the PKGI or K15-10 type), and a commutator (a hydrogen thyratron of the TGI-1000/25 type). It was completely mounted in a monolithic steel tank, the inner surfaces of which were covered with copper foil. The high-frequency cables were covered with additional copper braids and had a tight contact with the protective foil inside the tank. The tank, along with all the generator elements, was completely filled with transformer oil. High-frequency cables connected to a voltage divider and a resistive current shunt were output through a technological window in the upper lid of the tank. The registration of voltage pulses on the load and the discharge current was carried out on oscilloscopes of the types C1-75 (Δf = 250 MHz) and C7-8 (Δf > 4 GHz). Observations of the shape of voltage and current pulses during commissioning were carried out on a digital oscilloscope of the AKIP-4115/4115/3A brand. To reduce the level of electromagnetic interference generated by spark gap during switching, special measures were applied to organize the grounding of individual units of the measuring stand [6, 7].

The measurements carried out showed that the characteristic rise times of the current in the discharge circuit shown in figure 5 have values of the order of 2-5 nanoseconds.

4. Conclusion

The results of the work carried out can be summarized as follows:

1. A compact design of a spark gap has been developed that can withstand the pressure of the working gas up to 150 Atm, in which a ceramic insulator for a voltage of up to 400 kV is installed in such a way that it experiences only a compressive force.

2. The optimal geometry of parts and assemblies is determined, which provides the necessary distribution of electric fields inside the spark gap casing, which ensures its electrical strength at electrode voltages up to 500 kV.

3. The industrial production of spark gaps for an operating voltage of 100-400 kV with switching energy of up to 10 J has been mastered.

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