Rail-type gas switch with preionization by an additional corona discharge

O S Belozerov and E G Krastelev

Joint Institute for High Temperatures, Russian Academy of Sciences, st. Izhorskaya 13/19, Moscow, 125412 Russia

E-mail: ekrastelev@yandex.ru

Abstract. Results of an experimental research of a rail-type gas switch with preionization by an additional negative corona discharge are presented. The most of measurements were performed for an air insulated two-electrode switch assembled of cylindrical electrodes of 22 mm diameter and 100 mm length, arranged parallel to each other, with a spark gap between them varying from 6 to 15 mm. A set of 1 to 5 needles connected to a negative cylindrical electrode and located aside of them were used for corona discharges. The needle positions, allowing an efficient stabilization of the pulsed breakdown voltage and preventing the a transition of the corona discharge in a spark form, were found. It was shown that the gas preionization by the UV-radiation of the parallel corona discharge provides a stable operation of the switch with low variations of the pulsed breakdown voltage, not exceeding 1% for a given voltage rise-time tested within the range from 40 ns to 5 µs.

1. Introduction
A long-term stable operation of high-voltage pulsed power generators is mainly determined by a lifetime and stability of the parameters of switching devices involved in their operation. This primarily concerns the spark gas switches, which are used most often in designing the high-voltage generators, in particular, in almost all types of Marx generators and others [1].

Traditionally, an increase of the lifetime of switches is achieved by increasing a working surface of the electrodes and by excluding the sharp edge electrodes with high electric field gradients and a short time delay of discharge, which quickly fail due to erosion. The deterioration of the dynamic characteristics of gas switches with thick and smooth electrodes may be compensated by pre-ionization of the insulating gas. The method, which is used most frequently in practice, is based on the photoionization by the ultraviolet (UV) radiation of spark sources [1,2].

Below, there are the results of a study of characteristics of an experimental rail-type switch with long linear electrodes, in which an additional corona discharge is used as a source of the UV-radiation for pre-ionization. The corona discharge is ignited by a set of needle electrodes, electrically connected to the negative main electrode. Together with the second positive rail electrode, the needles form a corona discharge gap, which works in parallel to the main spark gap of the switch. Two separate discharge gaps - the main spark gap between the rail electrodes and the corona discharge gap - provide an opportunity to optimize the electrodes for a long-term high-current operation with a stable dynamic performance. This method was successfully tested in a design of coaxial switches [3].
2. The design of the experimental switch
The main spark gap is formed by two parallel cylindrical electrodes of 22 mm diameter and 100 mm length of the working cylindrical part ended by semi-spherical edges. The electrodes are bolted to the insulating plates made of Plexiglas, which are adjusted parallel to each other with the help of 4 long bolts at the corners of the plates. During the experiments, the spark gap between the electrodes was changed within the range from 6 mm to 15 mm, using the sets of spacers of an appropriate length installed at corner bolts.

To produce a highly divergent field, the corona discharge needles are located aside from the negative cylindrical electrode. They are fixed to a movable metal plate, which is connected directly or through a current viewing resistor to the negative cylindrical electrode. Steel sewing needles and segments of wires of 0.5 mm diameter, made of W, Cu and Fe, were used as the corona needles.

The photo of the assembled switch and a sketch of the cross section of its electrode system are shown in Figure 1. The designation of dimensions used in the next sections of this paper and the calculated plot of the equipotential lines characterizing the electric field distribution in the main and the corona gaps are shown on the sketch in Figure 1(b).

![Figure 1](image)

Figure 1. Photo (a) and calculated pattern of equipotential lines in a cross section (b) switch. Step equipotential lines is 0.1 $U$, where $U$ voltage between the electrodes.

The equipotential lines in the gap between the main electrodes are distributed nearly uniformly. They are concentrated near the top of the corona needle indicating a highly divergent electric field in this region. According to three-dimensional calculations, the electric field at the top of the needle is approximately an order of magnitude higher than the field in the gap.

Three-dimensional calculations of the electric field distribution were carried out by a finite element method. The results were used for the calculations of a static breakdown voltage $U_{br}$ and for the estimations of the field at corona needles, depending on their position – the distance from the plane of symmetry of the switch $d_1$ and the elevation above the top of located near cylindrical electrode $h$.

3. The switch characteristics in the static mode

3.1. Breakdown of the main spark gap.
Being measured without corona needles, the static breakdown voltage $U_{br}$ increases almost linearly when the gap between the electrodes increases from $\approx 19$ kV at $d=6$ mm to $\approx 44$ kV at $d=15$ mm. A difference between the measured values $U_{br}$ and those obtained by calculation does not exceed 5% for the entire range of the spark gap variations.

3.2. Characteristics of corona discharge
A high electric field at the corona needles provides an ignition of the corona discharge at the voltage levels, which are lower than those of the spark gap breakdown. Throughout the range of changes, the needle height $h$ was from -3 mm to +3 mm (relative the top of a cylindrical electrode, see Fig.1) and the distance $d_1$ was up to 35 mm. Measured in this ranges values of the threshold voltage $U_{cr}$, which is necessary for an ignition of the corona discharge for different needles, varied from 6-8 kV to 12-13 kV. A comparison of the experimental and the calculated data shows that the variation of the threshold voltage correlates with the corresponding variations of the calculated electric field strength near the tip of needles.

Figure 2 shows the volt-ampere characteristics of the corona discharge for two positions of a single corona needle: $d_1=26$ mm and $d_1=21$ mm for the fixed gap $d=10$ mm and the needle elevation $h=+1$ mm.

![Figure 2](image-url)

Figure 2. The volt-ampere characteristics of corona discharge for two positions of the corona needle $d_1$ for the main gap $d=10$ mm and needle height $h=+1$ mm.

Measured characteristics are in a good agreement with the those shown in the same figure approximations by a quadratic function: $I \sim kU(U - U_{cr})$, where $U_{cr}$ – a critical voltage.

The principal difference between the two shown volt-ampere characteristics is as follows. The first of them, corresponding to the distance $d_1=26$ mm, is completed by the spark breakdown of the main gap at $U=30$ kV. In the second case, ($d_1=21$ mm) at $U \approx 27$ kV voltage, the corona transfers to a spark form prior to the breakdown of the main gap.

Figure 3 shows the dependences of the main gap breakdown voltage and the voltage for a transition of the corona discharge to the spark form for the distance $d_1$ of the needle location. Experimental data are shown for two main gaps: $d=10$ mm and $d=13$ mm, and for a fixed elevation of the corona needle $h=1$ mm. In this figure, light symbols correspond to the main gap breakdown, and black symbols – to the transition of the corona discharge to the spark form.
Figure 3. Dependence of the sparking voltage on the corona needle location $d_1$ for two main gaps: $d=10$ mm and $d=13$ mm. Light symbols – main gap sparking, blacked symbols – corona gap sparking.

It is seen that for a far-located needle, the gap between the main cylindrical electrodes is sparking first and the breakdown voltage does not depend on the distance of needle location $d_1$ remaining the same as the static breakdown voltage $U_{br}$, shown in the picture by the dotted lines. For a closer located needle, starting from some critical position, the spark breakdown takes place in the corona gap. This breakdown voltage depends on the position of the corona needle and it is limited by a critical value of an average field in the corona gap, which determines the transition of the corona discharge to the spark [1, 4]. An analysis of the data obtained for the conditions of the experiments show that for an air of an atmospheric pressure, it corresponds to the average field $E \approx 14$ kV/cm in the corona gap. The calculated voltages for $E=14$ kV/cm, for two given spark gaps are shown in Figure 3 by solid lines.

Similar dependencies obtained for various values of the spark gap, needles number, and their positions showed that the average field in the gap between the tip of the corona needles and the positive cylindrical electrode is a crucial condition for the transition of the negative corona discharge to the spark.

Taking $E=14$ kV/cm as the average field limit for an air insulated gap, the positions of the needles, excluding a possible transition of the corona discharge to the spark form, may be calculated. For example, for the main gap $d=10$ mm, the condition $E < 14$ kV/cm is satisfied by moving the corona needles to the distance $d_1 \geq 26$ mm. These requirements are important for a normal switch operation in a static mode, or for the DC pre-stressed, or the slowly-varied voltage switches. For the pulsed mode of the switch operation, significantly higher fields are allowed due to a qualitatively different dynamics of the corona discharge.

4. The switch characteristics in the pulsed mode

The dynamic characteristics of the switch were studied by applying single pulses with a voltage rise time from 40 ns to 5 µs and a voltage amplitude up to 60 kV.

Without corona needles, the variations of the pulsed breakdown voltage exceeds 20%. An installation of one or several corona needles qualitatively changes the picture by a strong stabilization of the breakdown voltage. Simultaneous measurements of the applied to the switch pulsed voltage and the corona discharge current show that a short pulse of the corona current precedes to the breakdown of the main gap. This corona current pulse, so called Trichel pulse, appears when the rising voltage exceeds the critical voltage $U_{cr}$ defined as a threshold voltage for a corona ignition under the static mode.

Figure 4 shows 10 superimposed traces of the switch voltage and a signal from a current viewing resistor of 75 Ohm in series with the corona needle. Traces are recorded using the probe Tektronix 6015 (bandwidth 60 MHz) for the switch with one needle installed at $d_1=23$ mm and $h=+1$ mm. The dotted line shows the static breakdown voltage $U_{br}$ for the given gap of $d=10$ mm.
Figure 4. Traces of switch voltage (1) and the signal from current viewing resistor of 75 Ohm in series with the corona needle (2).

As we can see, the switch breakdown occurs in a short time after reaching the level of the static breakdown voltage \( U_{br} \) and is preceded by a short pulse of the corona discharge at the voltages of 10-11 kV (\( U_{cr} \), for the given switch parameters, is about 8.5 kV).

The breakdown is reproduced with very high stability, both of a time and an amplitude of the pulsed breakdown voltage. The scatter of the breakdown voltage is about 1%.

The traces of the corona discharge shown in figure 4 don't reflect a real shape and a real amplitude of the corona current since a long oscilloscope sweeping is needed for an observation of the entire voltage pulse. In this case, they serve only as a time indicator of a corona discharge. A trace podium is due to the presence of a capacitive coupling between the corona needle and the high-voltage positive electrode. Together with the current viewing resistor, the stray capacitance forms a differentiating circuit. As a result, the recorded voltage drop across the resistor is proportional to the derivative of the applied pulsed voltage. Using the recorded traces, the stray capacitance for a single needle and a given geometry of the switch was defined as \( \approx 1.5 \text{ pF} \).

Real traces of the pulsed corona current recorded at a faster oscilloscope sweeping show that the duration of the corona current pulse at the half maximum is about 5 ns. The current amplitude reaches 0.35 A, and it is two orders of a magnitude above the measured for Trichel pulses in a static mode.

The corona current traces recorded for two needles connected to the common current viewing resistor looks like one half of an amplitude of one needle current pulse or a pair of separated in time pulses. A similar picture was observed for three or more corona needles. The synchronous flash of the corona discharge of a few needles, which are different in their position and sizes, may be explained in terms of a mutual UV-radiation resulting in the generation of free electrons initiating the discharge.

A consequence of several Trichel pulses was observed as a longer voltage pulses applied to switch and longer gaps between the main electrodes before the breakdown. Note, that the amplitude of the first pulse is greater than that of the subsequent pulses. It is consistent with the results of model calculations, which assume that the first current pulse in the corona is generated in a free space charge gap, and its appearance after the first flash weakens the electric field in the ionization region and reduces the current of the subsequent pulses.

4.1. The stability of pulsed breakdown voltage

The measurements of the breakdown voltage, as the functions of the needles parameters, show that the needle elevation \( h \) has the main influence on a stability of the breakdown voltage and its deviation. It was found, that the breakdown voltage variation was minimal for the corona needle, slightly elevated over the top of the main negative electrode. In particular, for the fixed parameters of measurements, the variation of the corona needle elevation from \( h=-3 \text{ mm} \) to \( h=+1 \text{ mm} \) resulted in a decrease of the
breakdown voltage deviation from ≈1% to ≈0.5%. Further elevation of the corona needle had no effect. This dependence was observed for other experimental conditions.

This dependence may be explained by the UV-radiation of the working surface of the cylindrical electrode resulting in an appearance of additional photoelectrons emitted from the electrode. Since the work function of the metal is lower than the ionization potential of the gas, the photoelectric effect at the surface can have a greater value for the appearance of, the so-called, "effective" electrons, responsible for the beginning of the switch closing. Moreover, the appearance of free electrons at the surface of the negative electrode is most favorable for the development of anode directed avalanches.

4.2. Distribution of discharges along the length of the electrodes
Visual measurements of the spark discharge distribution along the cylindrical electrodes show that for single corona needle, more than 50% of the total number of discharges were localized within ±1 cm from the axial position of the needle. Increasing the number of corona needles extended the length of the discharge area. The discharge distribution, which was close to be uniform throughout the total electrode length of 100 mm, was achieved for five corona needles set with axial step of 2 cm. Note that the delay time and the breakdown voltage does not depend on the number of needles and a position of the discharge zone.

5. Conclusion
The results of the research presented in this paper show that the gas pre-ionization of parallels corona discharge by the UV-radiation provides the stable operation of the rail-type switch with low variations of the pulsed breakdown voltage. The measured variations did not exceed 1% for the given voltage rise-time within the range from 40 ns to 5 µs. The requirements for the corona needles geometry were found, for preventing the transition of the corona discharge to the spark form and for an effective stabilization of the pulsed breakdown voltage.

References
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