Corona pre-ionized gas switches with an increased lifetime for Marx generator of the lightning test complex

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Abstract. A new design of triggered spark gas switches with an increased operation life and stable dynamic performances for 2.4 MV, 4 MJ Marx generator of the lightning test complex is developed. An operation mode of switches in the test complex is the following: the total voltage – up to 80 kV, the discharge current – up to 50 kA, the charge flowing – up to 3.5 C/pulse, the working gas – dry air at an atmospheric pressure. An increased operating life is achieved by using the torus-shaped electrodes with an increased working area and by the application of a thick disk with a hole, as a trigger electrode, installed between the two torus-shaped electrodes. A short breakdown time delay and a high stability of the breakdown voltage under dynamic conditions are provided by gas pre-ionization in the spark gap by UV-radiation of an additional corona discharge in the axial region of the switch.

1. Introduction
A mobile lightning test complex constructed at Joint Institute for High Temperatures RAS (Moscow) in collaboration with TRINITI (Troitsk) is intended for tests of lightning protection systems, measurements of the conductivity of soil and grounding elements at current levels of 50 kA and pulse duration up to 150 μsec [1].

A pulsed power generator of the test complex consists of two discharged in series Marx generators providing the total peak voltage up to 2.4 MV. The full stored in Marx capacitors energy is as high as 4.2 MJ.

Each Marx generator includes 15 stages of bipolar charging up to ±40 kV capacitors switched by 16 air insulated gas switches. Seven of them are three-electrode triggered switches and others are two-electrode switches closed by overvoltage. All switches have the same semi-spherical (R=46 mm) main electrodes of 78 mm diameter. They are installed radially in sections of a plastic (polyethylene) tube of 250mm inner diameter assembled together, to form columns of UV-coupled switches. The triggered switches of a “field distortion” type have the third electrodes in the form of a thin disk with a central hole of 50 mm diameter installed at the mid-plane between the main electrodes. The chosen spark gap of 50 mm between the electrodes of all switches corresponds to the self-breakdown voltage of about 115 kV, which is ≈1.5 times higher than the maximal voltage of 80 kV appeared by the end of the capacitor charging to ±40 kV.

The experience of the full-scale lightning tests showed that a stable synchronous operation of two Marx generators is limited by a degradation of characteristics of triggered switches. High flowing
currents and the high charge – up to 3.5 C/pulse lead to melting and local thermal deformation of sharp edges of the thin disc electrodes, which in its turn results in increasing the switching time delay and its deviation. To solve this problem, a new design of triggered switch with stable dynamic characteristics during a long time was developed. It is based on the design of the developed earlier long life time switches with toroidal main electrodes and a thick trigger disc in a combination with parallel corona discharge in the axial region of the electrode system [2]. Gas pre-ionization in the spark gap by UV-radiation of the corona discharge provides a short time delay of the switch closing and a high stability of the pulsed breakdown voltage. The design of the new electrode system is compatible with the construction of the original switches

2. Design and main characteristics of new switch

2.1. Switch electrode system

The electrode system chosen for a new triggered switch combines two discharge gaps working in parallel. First of them, the main high-current spark gap, is formed by two torus shaped main electrodes and a thick trigger disc electrode installed between them. The second is an additional corona discharge gap. It is formed by a corona needle installed in the cavity of one (negative) main electrode and the other electrodes positively charged relative to a negative corona needle. A correct design of this electrode system is able to provide the following consequence of the discharges. The first is that the corona discharge sets up at some critical voltage $U_{cr}$, which is lower than the breakdown voltage $U_{br}$ of the main high-current gap. Then, when the applied voltage reaches the level of $U_{br}$, a fast breakdown of the main gap takes place. The short time delay of the main gap closing is provided by the appearance of free electrons, as a result of gas photoionization by the ultraviolet (UV) radiation from the corona discharge localized in an axis region. At these conditions, the breakdown time delay is determined mainly by the time of plasma channel formation [3].

The new electrode system of the triggered switch was developed on the basis of the outlined requirements. The size of the electrodes was chosen for a maximal compatibility with an original switch construction.

Figure 1 shows the cross-section of the new electrode system installed in the plastic tube section of the original switch. The electric field distribution is illustrated by the calculated plot of equipotential lines shown in figure 1. This pattern of equipotential lines corresponds to the initial state of the switch before closing with a zero potential at the middle trigger electrode and the equal in magnitude voltages $U$ of opposite polarity applied to the main electrodes. The step of equipotential lines is 0.1U.

![Figure 1. Cross-section sketch of the new triggered switch electrode system with calculated plot of the equipotential lines. Electrodes and their mounting parts are colored.](image-url)
2.2. *The main spark gaps*

The main spark gaps are formed by two electrodes of the external diameter of 78 mm with the toroidal working surface of \( r = 12 \) mm and the trigger electrode in form of disc of 10 mm thick with the central hole of 54 mm diameter with rounded edges located midway between them. The outer diameter of electrodes is equal to the outer diameter of the electrode holders of the original switches. It provides the possibility of reusing the existing holders after little mechanical improvement. The minor radius of the tor \( r = 12 \) mm was found as optimal for achieving approximately the same voltage, as for original switch breakdown, for the same gap \( d = 25 \) mm between the top of the toroidal electrode and the trigger disc. This result of the breakdown voltage calculations was supported by direct measurements of the breakdown voltage for two sets of electrodes – an original semispherical and a new toroidal one.

Figure 2 shows the plots of measured self-breakdown voltages \( U_{br} \) vs the gap distance \( d \) for the semispherical (1) and for the toroidal (2) electrodes with the optimized minor radius \( r = 12 \) mm.

![Figure 2. Breakdown voltage vs the gap distance: 1 – for original semispherical electrodes, 2 – for toroidal electrodes with minor radius \( r = 12 \) mm](image)

As you can see, the new toroidal electrodes provide approximately the same static breakdown voltages as measured for the original electrodes for the same gap distances. The difference of the measured and calculated breakdown voltages is lower than 5%.

2.3. *Characteristics of corona discharge*

The corona needle electrode is made of a tungsten wire with a diameter of 0.5 mm. The needle is installed in the cavity of the main toroidal electrode (negative during the work). The tip of the needle is located at the same axial position as the top of the tor or slightly outside. As it was shown during the dynamic test of the switch, the outside position of the needle tip of \( h \approx 1 \) mm, relative to the top of the tor, increases the efficiency of the pre-ionization and provides a lower spread of the pulsed breakdown voltage. It is supposed, that the UV-illumination of the working surface of the main electrode may be more efficient, because of the lower work function for metals, compared to the ionization potential of the gas.

The volt-ampere characteristics of the stationary corona discharge for two spark gaps \( d = 20 \) and \( d = 25 \) mm are shown in Figure 3. The discharge current was measured by an analog (integrating the Trichel pulses) microampere meter connected in series with the negative high voltage electrode with the corona needle. The positive voltage of the same magnitude was applied to the second main electrode, and the trigger disc electrode was grounded via the resistor of 1 kOhm.
Figure 3. The volt-ampere characteristics of corona discharge for two gap distances: 1 – \( d = 20 \) mm and 2 – \( d = 25 \) mm. The needle tip is outside of the tor for \( h \approx 1 \) mm.

The presented characteristics show that the corona set up critical voltage \( U_{cr} \) is in a range 10÷12 kV and much lower than the breakdown voltage for the both gaps. Measured characteristics are in a good agreement with the shown by solid lines approximations by a quadratic function: \( I \sim kU(U - U_{cr}) \), where \( U_{cr} \) – the critical voltage.

It is important to note that the second microampere meter connected in series with the positive main electrode showed approximately the same currents and the readings of the microampere meter in the circuit of the trigger electrode were close to zero up to 25÷30 kV, when they reached several microamperes. It means that the most of the electrons from the corona discharge and formed in air negative oxygen ions move in the axis region and do not fall in the gaps. The main reason for the appearance of free electrons in the spark gaps is the gas photoionization by the corona UV-radiation.

2.4. Switch dynamic test

Dynamic characteristics of the switch were measured at a test stand by applying the static voltage of charged to ±U capacitors to the main electrodes and the fast rising pulse to the disc trigger electrode. The measurements were performed for the static voltages within ± 30 kV limited by the capability of the test stand. To satisfy these conditions, the spark gap distance of the experimental switch was reduced to 13÷15 mm. The pulsed voltage at the trigger electrode was measured by a high voltage probe Tektronix 6015, and the capacitors charging voltage was measured by the electrostatic kilovolt meter C1-35. The resulting voltage at the gaps was defined as a sum of the readings of the kilovolt meter and the recorded voltage pulse at the trigger electrode.

Figure 4 shows the traces of the voltage at the trigger electrode recorded for the applied trigger pulse of a positive polarity for two levels of a static voltage at the main electrodes (the capacitors charging voltage). The gap distance for these measurements is \( d = 13 \) mm, which corresponds to the self-breakdown voltage of 38 ± 0,5 kV, the critical voltage for the corona discharge set up is \( U_{cr} \approx 9 \) kV. The trace marked as 1 was recorded for the charging voltage \( U = \pm 20.5 \) kV and the trace 2 – for \( U = \pm 22 \) kV. These charging voltages correspond to 0.54 and 0.6 of the levels of self-breakdown voltage, respectively. The dotted lines in figure 4, marked as \( U_1 \) and \( U_2 \), show the levels of the total voltage equal to the sum of charging and pulsed trigger voltages corresponding to the static breakdown for the given gap \( d = 13 \) mm.
Figure 4. Voltage traces at trigger electrode for static charging voltages: 1 – $U=\pm 20.5$ kV and 2 – $U=\pm 22$ kV, dotted lines – levels of total voltage corresponding to static breakdown for the given gap $d=13$ mm.

As you can see, the closing of the first gap takes place shortly after the total voltage, charging plus triggering, reaches the level of the breakdown voltage shown by a dotted line.

For the charging voltage of $U=\pm 20.5$ kV (the trace 1), the breakdown of the first gap occurs at the peak trigger voltage of 19.4 kV, when the total voltage at the gap reaches 39.9 kV which exceeds the static self-breakdown voltage by 1.9 kV or lower than by 5%. The time delay, measured from moment of reaching the level of the breakdown voltage until the gap closing, is about 108 ns. After that, the doubled charging voltage of 41 kV is applied to the second gap. For this voltage, the breakdown of the second gap takes about 85 ns.

An increase of the charging voltage to $U=\pm 22$ kV (trace 2) leads to the lowering of the trigger voltage level, at the moment of breakdown in the first gap, and to the shortening of the closing time of both gaps. So, the time delay of the second gap breakdown for the increased to $2U=44$ kV total voltage is reduced to $\approx 70$ ns. All measured time delays are consistent with the estimations of a time needed for the plasma channel formation [4].

A long time tests show that the scattering of the pulsed breakdown voltage amplitude for the first gap does not exceed 0.5 kV or is not higher than 1.5% of the self-breakdown voltage. For comparison, the dynamic tests of previously used original switch under the same conditions, with the decreased to 11 mm gaps, show a much longer time delay, up to 1 ms, and the breakdown voltage spread is higher than 5 kV.

2.5. Switch design

The developed design of the new electrode system is compatible with the construction and all electrical connections of the original switches. The chosen sizes of the electrodes provide re-using of the existing elements in the new switches: the unchanged tube sections of switch housing, the mounting elements, the outer connectors and the holders of the trigger electrode. Newly manufactured are the toroidal and trigger electrodes, the mounting elements for the corona needle. All mentioned parts for the new switch are made of stainless steel.

Figure 5 shows the photos the new (a) and the original (b) switches installed in the same plastic tube sections.
3. Conclusion

The new high-current, high-coulomb triggered air insulated switch was developed for the Marx generator of the lightning test complex. The increasing of the life time is achieved by using the torus-shaped main electrodes with an increased working area and by the application of the thick disc trigger electrode installed at a mid-plane between the main electrodes. The low breakdown time delay and the high stability of the breakdown voltage under dynamic conditions are provided by the gas pre-ionization by UV-radiation of the additional corona discharge in the axial region of the switch. The design of the new electrode system is compatible with the construction of the used now original switches.

References

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