Corona-stabilized gas spark gap switch for a double forming line with 300 kV working voltage

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Abstract. A high-current self-breakdown gas switch stabilized by corona preionization was developed for closing of 300 kV repetitively operated at 10 pps water insulated double-forming line (Blumlein) of a nanosecond electron accelerator. The switch is installed at the end of the Blumlein and is used for closing of outer of two coaxial lines. High stability of the self-breakdown voltage (within ±1%) at fast charging of Blumlein (during ≈1.4 μs) is achieved by gas preionization in the spark-gap by additional pulsed corona discharge. The spark-gap electrode system includes two main toroidal electrodes and an additional corona needle that is located in the cavity of one of them (negative during the operation). It combines two parallel gas discharge gaps – the main spark gap and an additional corona discharge gap. Separating the functions of the spark and corona gaps makes it possible to optimize the geometry of the electrodes of each gap and provide both the ability to switch high currents and high dynamic characteristics for a long operating time. Dried air is used as a working gas at pressure of 3-4 atm (abs.). Gas blowing system includes 4 gas inlets located at outer flange supporting the high voltage insulator (water-gas interface) and one outlet in the cavity of the grounded main electrode. This scheme of gas flow protects the insulator from deposition of electrode erosion products and minimizes gas flow (∼20 l/min) for stable operation of the switch by removing of the hot gas throw the cavity of the grounded electrode. The design of the switch together with the main results of the working tests will be presented and discussed.

1. Introduction

Gas spark gap switches are the main type of pulse forming line (PFL) switches in generators of high-voltage nanosecond pulses operating in a repetitively pulsed mode. The range of their operating voltage extends to over 1 MV, and the pulse repetition rate can exceed 100 Hz in intensive gas purging [1, 2].

Self-triggered two-electrode switches are widely used [1, 3]. They are simple in design and do not require complex high-voltage synchronization systems. One of the advantages of self-triggered switches is long lifetime, which is largely due to no ignition electrodes used to initiate discharge under trigger pulse action since thin electrode edges are not erosion-resistant and damage-sensitive.

The main disadvantage of self-triggered spark gap switch is instability of the breakdown voltage in charging of the pulse forming line within short time. For high power lines with water insulation it does
not exceed 1-2 μs. The breakdown instability during rapid voltage rise is caused by the spread in its delay time, one of the main components of which is the statistical waiting time for the "effective electron" that initiates discharge development [4, 5].

Different methods of gas preionization of the discharge gap are used to minimize the time spread and operating voltage of self-breakdown switches. One of the main methods is ultraviolet (UV) illumination using an auxiliary discharge gap [1, 2]. In the repetitively pulsed mode, the preceding discharge can perform the role of a preionizer to produce initiating electrons under certain conditions of the pulse repetition rate and the purging rate of the spark gap switch [3].

The structure and characteristics of the self-breakdown spark gap switch of double forming line (DFL) with water insulation at voltage of 300 kV and a pulse repetition rate of up to 10 Hz are described below. Spark gap switch breakdown voltage is stabilized by gas preionization (air dried under pressure) with UV radiation of an additional corona discharge.

DFL, together with the spark gap switch, is part of the system for forming high-voltage nanosecond pulses of a high-current electron accelerator, which is constructed according to the scheme with an output induction voltage doubler in the form of a single-coil coaxial transformer similar to that considered in [6]. The transformer provides accelerating voltage pulses with amplitude of up to 500 kV at DFL charging voltage $\leq$300 kV.

The spark gap switch design is based on a binary electrode system that combines two parallel gas-discharge gaps – the main discharge gap and additional corona discharge gap. According to the scheme proposed in [7], the main discharge gap is formed by two hollow toroidal electrodes, and the additional discharge gap is formed by the corona needle located along the axis in the cavity of one of the toroidal electrodes and the second hollow electrode. The electrode dimensions and corona needle position meet the requirements of a sequential ignition of the corona discharge (in the additional gap) followed by spark discharge (in the main gap). The pulsed mode of the corona discharge ignition with air as a working gas prevents the transition of corona into spark before main gap breakdown.

2. **DFL spark gap switch design**

The design of the gas spark switch of coaxial DFL with water insulation is shown in figure 1. The switch located at the end of DFL to commutate the external line formed by grounded case 1 and high-voltage intermediate electrode 2 (the elements of the DFL internal line are not shown to simplify the drawing). The case internal diameter is 320 mm, the high-voltage electrode outer diameter is 168 mm, and the forming line impedance is $Z$=4.3 Ohm. If the charging voltage amplitude $U_{\text{max}}$=300 kV and the switch breakdown at $U$=0.9$U_{\text{max}}$=270 kV, the amplitude of current passing through the spark gap reaches $\approx$60 kA.

The high-voltage positively charged DFL electrode and electrode of spark gap switch 6 connected to it are fixed on insulator 3, which serves as the interface separating the DFL volume filled with deionized water from the gas filled volume of the switch. The isolator is located in the cavity on the DFL case and fixed with an intermediate flange through the ring rubber seals. Flange 4 of conical spark gap switch case 5 is fastened to it on the other side. At the end of the conical case, the second, grounded spark gap switch electrode 7 is mounted. Corona needle 8 is placed into the cavity of this electrode. It is fixed in the holder with threaded fastener to the bottom of the toroidal electrode. At the bottom, there are through-holes 9 for gas discharge through the thread fittings of hose coupling, pressure gauge connection and protection valve mounting. The design of the spark gap switch allows for quick removal and mounting of the spark gap switch electrodes without its disassembling and leakage in the DFL water-filled volume.

The dimensions of the electrodes and the case of the spark gap switch, and the profile of the insulator section are chosen based on the results of simulation of the electric field distribution with due regard to the DFL design features, the required electric strength, and the limitations per the switch circuit inductance value.

The simulated distribution of the equipotential lines in the diametrical cross section, plotted with a step of 4% of the voltage between DFL electrodes and a 25 mm spark gap is shown in figure 2.
Figure 1. Design of the DFL spark gap switch 1) DFL case, 2) high-voltage DFL electrode, 3) insulator, 4) case flange with gas inlet channels, 5) conical shell, 6) high-voltage electrode, 7) ground electrode, 8) corona electrode (corona needle), 9) gas outlet channels.

Figure 2. Simulated distribution of the equipotential lines in the spark gap switch cross section with a step of 4% of the voltage between DFL electrodes. Spark gap between the tops of toroidal electrodes is 25 mm.

2.1. Spark gap switch insulator
Insulator is made of plexiglas. Its configuration was chosen to primarily provide voltage distribution close to uniform both across the surface in water and in gas medium, and to eliminate the electric field strength near the triple points at the points of electrode contacts. For the simulated distribution shown in figure 2, the average value of the tangential component of the electric field along the gas insulator surface at voltage of 300 kV attains 25 kV/cm. The maximum value of electric field strength near the fastening points of the high-voltage electrode of the spark gap switch and insulator in the case do not exceed 36 kV/cm and 24 kV/cm, respectively. The high-voltage electrode contacts with the insulator through a thin (0.5-1 mm) rubber gasket. It provides uniform distribution of the clamping forces and reduces the field strength near the contact with the metal.

2.2. The main discharge gap
The main discharge gap is formed by two hollow electrodes (6 and 7 in figure 1) with toroidal working surface. The electrode outer diameter is 118 mm, the inner cavity diameter is 58 mm, and the small toroidal surface radius is 15 mm. The electrodes are made of stainless steel. The bearing surfaces of the electrodes have narrow ring protrusions, which ensure reliable electrical contact along the entire perimeter, when the electrodes are clamped with fastening elements, thus eliminating sparking during high current.

The electric field distribution in the spark gap is slightly non-uniform. For the calculated interelectrode gap \( d=25 \) mm (between the tops of electrodes), the non-uniformity coefficient is \( k=E_{\text{max}}/E\approx 1.35 \), where \( E_{\text{max}} \) is the maximum and \( E=U/d \) is the average field strength in the gap. The maximum voltage is reached near the high-voltage electrode (in the zone with a radial coordinate 4 mm greater than the radial position of its top). It insignificantly (\( \leq 15\% \)) exceeds the maximum field at the top of the ground electrode, which exhibits an elongated cylindrical form to ensure electric field strength equalization.

The breakdown voltage of the main discharge gap was calculated according to the method described in [8]. The values of the non-uniformity coefficient \( k \) obtained in simulation and the
effective distance \( d_{\text{eff}} \), the distance from the electrode surface at which the field strength decreases to 0.82\( E_{\text{max}} \), were taken into account when calculating the voltage. The empirical ratio \( E_{\text{br}}[\text{kV/cm}]=24.5p+6.7(p/d_{\text{eff}})^{1/2} \), where \( p \) is the atmospheric air pressure, was used to calculate the breakdown voltage on the electrode surface. The corresponding value of the static breakdown voltage is \( U_{\text{br}}=E_{\text{br}}/k \).

The calculated relation of the static breakdown voltage of the gap at the air pressure is presented in figure 3.

\[ U, \text{kV} \]
\[ 0 \quad 1 \quad 2 \quad 3 \quad 4 \]
\[ p, \text{atm} \]

The calculated relation shows the lower limit of the breakdown voltage. During charging of DFL, the dynamic breakdown voltage exceeds the calculated values by the magnitude of the voltage increase within the time of spark discharge formation.

2.3. The corona gap
The corona gap is formed by axial corona electrode (8 in figure 1) and the cavity of high-voltage toroidal electrode (6). The corona electrode is tungsten wire of 2 mm in diameter, about 25 mm in length, and with a top pointed on one side. The other end of the wire is fixed in the holder mounted at the bottom of the hollow electrode. The threaded fastener of the holder enables adjustment of the corona electrode top position. The position at which the wire is at the same level as the top of the toroidal surface of the corona electrode is chosen as the working one. This position ensures the early ignition of the corona discharge due to a multiple increase in the electric field strength, as compared to that in the main discharge gap, as well as the UV illumination of the ground (negative) electrode top.

2.4. The spark gap switch purging.
The use of air as a working gas makes it possible to omit recirculation for the given parameters of the switched circuit and to implement the scheme of a constant gas flow and its subsequent release into the atmosphere.

The scheme of the gas flow through the switch is shown in figure 1. The dried pressure air enters the working volume through four radial channels in the flange of the spark gap switch case. The channel angular cuts formed by the flange on the inner conical surface determine the primary flow of the gas supplied towards the insulator. The gas flows along the insulator and through the main discharge gap, and then heated and partially ionized gas enters the cavity of the ground electrode and exits through the channels at its bottom. This purging scheme prevents deposition of the electrode erosion products on the insulator surface and enables minimization of gas consumption due to rapid penetration of partially ionized flow into the ground electrode cavity, which is not affected by the electric field.
3. Experimental results

The spark gap switch characteristics were investigated as part of the system for generating pulses of a high-current accelerator in different operational modes.

In the accelerator operational tests, the spark gap switch breakdown voltage was determined by the oscillograms of DFL charging voltage, which is measured with the high-voltage probe (capacitance divider) mounted in the DFL near the spark gap switch. The output pulses of the accelerating voltage and current of the electron beam in the diode were recorded as well. The measurements were carried out in a repetitively pulsed mode of the accelerator at a pulse repetition rate of 2–10 Hz and in a single pulse mode.

Figure 4 shows the oscillogram of the voltage pulse for the switch (DFL charging voltage) in a single pulse mode. The excess air pressure in the switch \( p = 2 \text{ atm} \), and the charging voltage amplitude (without commutation) is 240 kV. The dashed line in the oscillogram indicates the calculated static breakdown voltage of the spark gap switch at \( d = 25 \text{ mm} \) for the given air pressure \( U_{br} \approx 172 \text{ kV} \).

The spark gap breakdown in the repetitively pulsed mode was found to occur at voltage of \( \approx 190 \text{ kV} \), which exceeds the static breakdown voltage by the magnitude of the charging voltage increase within the discharge delay time.

In the repetitively pulsed mode of the accelerator, the breakdown voltage value averaged over \( \approx 700 \) pulses under similar pressure is \( 187\pm2 \text{ kV} \). The breakdown voltage distribution is illustrated in figure 5.

The data was obtained in the accelerator operation at a pulse repetition rate of 8 Hz and in the switch purging at a rate of 17 l/min. Note that the limited rate of the recorded oscillogram transfer in the oscilloscopes (Tektronix TDS 2024) used in the experiments enabled processing of every fifth pulse only. Accordingly, the total number of pulses to obtain the given relation exceeds the number of pulses indicated in the graphs by a factor of 5.

A similar pattern of the breakdown voltage distribution can be observed for various operating modes of the accelerator. The relative variation of the switch operating voltage \( \Delta U/U \) is about 1%.

Figure 6 shows the photographs of the high voltage and ground electrodes after \( \approx 60 \) thousand pulses.

The absence of melting or destruction of the corona electrode top, as well as erosion marks on the working surface of the main electrodes, indicate the discharges with large switching currents of the DFL in the main discharge gap. At the bottom of the high voltage electrode cavity, single marks without damage to the surface characteristic of high-current discharges can be identified. Their occurrence is likely due to the formation of low currents passing from the corona electrode caused by
the poorly conducting plasma channels that are formed under long-term and large current oscillations, as well as the formation of voltage in the non-matching operating modes of the DFL during the tests.

![Figure 6](image)

**Figure 6.** High voltage anode (a) and ground cathode (b) electrodes of the spark gap switch after ≈60 thousand pulses.

### 4. Conclusion

The developed design of the self-triggered gas spark gap switch with preionization by an additional corona discharge provides a high ($\Delta U/U\approx \pm 1\%$) stability of the voltage at DFL charging within $\approx 1.4$ μs. The spark gap switch design is based employs a binary electrode system that combines two parallel-connected gas-discharge gaps, i.e. main and additional corona discharge gaps. The separation of the functions of two parallel-connected gas-discharge gaps with sequential ignition ensures both high dynamic characteristics of the switch and the possibility of achieving significant operational long lifetime at high switching currents, mainly determined by erosion of the working surface of the main electrodes with large areas. The advantages of the considered spark gap switch include similar efficiency of the breakdown voltage stabilization both in the repetitively pulsed mode and single pulse mode, instantaneous operational readiness, and lack of necessity to provide any additional equipment and synchronization systems.

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