# Surface Creepage of High-Voltage Self-Breakdown Gas Switch

Xin-Bing Cheng, Jin-Liang Liu, Shao-Ping Zhou, Zhen Chen, and Bao-Liang Qian

***Abstract*—In this paper, the surface creepage of high-voltage self-breakdown switch which is used in 500-kV pulse modulator is analyzed in theory by employing the method of distributed element equivalent recurrent circuit. Moreover, the field distortion of the connecting ring of the switch is simulated by using software. According to the theoretical analysis, several methods to avoid surface creepage are obtained: 1) the outer housing of the switch should have high surface resistivity; 2) when the surface breakdown electric field is a constant, it is better to decrease the diameter of the electrode and to increase outer diameter and thickness of the outer housing; 3) in order to avoid field distortion, it is recommended, as far as possible, not to use metal connecting ring on the outer housing of the switch; and 4) there should be a clean environment for switch to work.**

***Index Terms*—Gas switch, surface creepage, surface insulation, surface resistivity.**

## I. Introduction

ONE OF THE most active research areas in the field of pulsed power is the development of high-voltage high-peak power-pulse generators. Very high pulse voltages and currents are generated by modular energy-storage circuits connected in parallels or in series. For fast-rising pulses, the waveform is not only determined by the pulse-forming elements but also by firing characteristics of the spark-gap switch. Therefore, high-voltage and high-power switches are widely investigated by other researchers [1]–[4] and are employed in high-power-pulse modulator [5], [6] for high-voltage switch. If the flashover voltage of the outer housing insulator is not high enough, the high pulse voltage will flash along the surface of the insulator, which will influence the characteristics of the switch and reduce the lifetime of the switch. To increase the flashover voltage of the outer housing insulator, the switch is usually immersed in the insulating medium, such as $SF_6$ or transformer oil. However, the insulating gas or transformer oil is usually not so clean, particularly for transformer oil, it will generate electrodeposits on the insulator in long time running which decreases the flashover voltage. Simultaneously, there is electric field distortion around the connecting ring which is usually made of stainless steel and is used to fixate the electrode holder, so it may form electric arc and influence the characteristics of the switch. In this paper, the characteristics of surface creepage of outer housing insulator of a high-voltage switch which is used in 500-kV pulse modulator [7] is analyzed in theory, and some of the factors which affect the surface creepage of the outer surface of the switch is presented. According to the theoretical analysis, several methods to avoid surface creepage are obtained: 1) the outer housing of the switch should have high surface resistivity; 2) when the surface breakdown electric field is a constant, it is better to decrease the diameter of the electrode and to increase outer diameter and thickness of the outer housing; 3) in order to avoid field distortion, it is recommended, as far as possible, not to use metal connecting ring on the outer housing of the switch; and 4) there should be a clean environment for switch to work. Finally, the field distortion of the connecting ring of switch is also simulated by using software.

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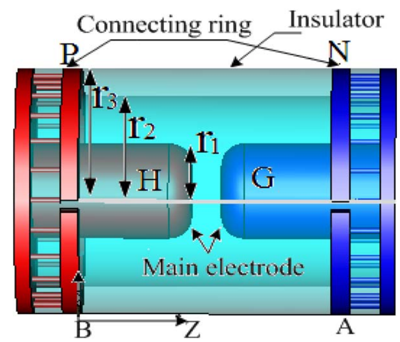


Fig. 1. Schematic diagram of the high-voltage switch.

## II. Theoretical Analysis

### A. Construction of the High-Voltage Switch

The high-voltage switch analyzed in this paper consists of two main electrodes, high-voltage electrode and earth electrode, which are 35 mm in radius and have a rounded edge to minimize electric field enhancement. The main gap can be varied by adding suitable spacers to the electrode. To fixate the electrode holder, two connecting rings which are made of stainless steel are used (Fig. 1). The outer housing of the switch is made of nylon. The switch is a kind of self-breakdown switch, and the working voltage can be varied by changing the gas pressure. For the pulse modulator, the working voltage is 500 kV and peak current is 30 kA, with duration of 60 ns.

### B. Physical Mechanism of Surface Creepage

In Fig. 1, the electrode H and connecting ring P are at high voltage, electrode G and connecting ring N are grounded.

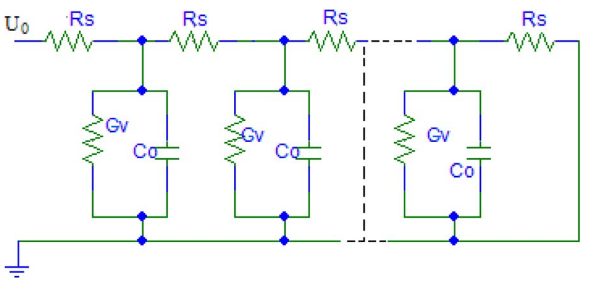


Fig. 2. Distributed element equivalent recurrent circuit of the high-voltage switch.

Therefore, the voltage distribution on the surface of the insulator is supposedly described by the distributed element equivalent recurrent circuit [8], which is shown in Fig. 2.

Moreover, in Fig. 2, $C_0$ is the capacitance between the unit area of outer surfaces of the outer housing and the electrode G which is low voltage

$$C_0 = \frac{\varepsilon_{rn} \cdot \varepsilon_{rg}}{36\pi \cdot 10^{11} \cdot \varepsilon_{rg} \cdot r_3 \ln \frac{r_3}{r_2} + 36\pi \cdot 10^{11} \cdot \varepsilon_{rn} \cdot r_2 \ln \frac{r_2}{r_1}} \mathrm{F/cm^2} \tag{1}$$

where $\varepsilon_{rn}$ is the relative permittivity of the nylon and $\varepsilon_{rg}$ is the relative permittivity of the insulation gas in the switch; $r_3$, $r_2$, and $r_1$ are out radius of the outer housing, inside radius of the outer housing, and the radius of the electrode G, respectively. Moreover, $r_3 = 90$ mm, $r_2 = 70$ mm, $r_1 = 35$ mm.

$G_v$ is volume conductance of the unit insulator and insulation gas, and $R_s$ is the surface resistance of unit insulator, respectively

$$G_v = \frac{1}{\rho_{vn} r_3 \ln \frac{r_3}{r_2} + \rho_{vg} r_2 \ln \frac{r_2}{r_1}} \tag{2}$$

$$R_s = \rho_s (\Omega) \tag{3}$$

$\rho_{vn}$ is volume resistivity (in ohms centimeters) of the nylon, $\rho_{vg}$ is volume resistivity of the insulation gas in the switch, and $\rho_s$ is surface resistivity (in ohms).

Moreover, from Fig. 2, according to the distributed element equivalent recurrent circuit of the switch, the equivalent equations can be obtained as follows:

$$\begin{cases} -\frac{d\vec{I}}{dz} = (G_v + j\omega C_0)\vec{U} \\ -\frac{d\vec{U}}{dz} = R_s \vec{I} \end{cases} \tag{4}$$

where $\vec{U}$ and $\vec{I}$ are phasors of angle frequency $\omega$ and $z$ is the distance between the surface of the insulator and the high-voltage electrode; $\omega = 2\pi \times f$, where $f$ is the frequency of the voltage.

To obtain the distribution of the voltage along the outer surface of the insulator, the boundary condition $(z = 0, U = U_0, z = L, U = 0)$ should be taken into account. From (4) and boundary condition, we have

$$U = \frac{sh(L-z)\gamma}{shL\gamma} U_0 \tag{5}$$


Fig. 3. Photograph of the metal connecting ring.

where $\gamma = \sqrt{\rho_s (G_v + j\omega C_0)}$, so we have the distribution of electric field along the outer surface of the insulator

$$E_z = -\frac{dU}{dz} = \frac{ch(L-z)\gamma}{shL\gamma} \gamma U_0. \tag{6}$$

From (6), we can obtain that the electric field along the surface of insulator is nonuniform, and the position of the maximum electric field is $z = 0$, $E_0 = cth(L\gamma)\gamma U_0$, if the $E_0$ is electric field where there is corona (filamentous) discharge; therefore, the voltage on the connecting ring is the critical flashover voltage

$$U_0 = \frac{th(L\gamma)}{\gamma} E_0. \tag{7}$$

In the switch, $G_v = \omega C_0$; therefore, $\gamma = \sqrt{j\rho_s \omega C_0}$. When $th(L\gamma) \approx 1$, (7) can be simplified as follows:

$$U_0 = \frac{E_0}{\sqrt{\rho_s \omega C_0}} \tag{8}$$

From the analyzed earlier, we can obtain several conclusions as follows:

1) From (8), the higher the $\omega$, which means that the voltage change fast, the lower the critical flashover voltage, so it is easier to occur surface creepage; this shows that the surface creepage should be taken into account in the condition of high frequency, and in the direct-current (dc) condition, the surface creepage does not happen.
2) Formulas (1) and (8) show that when $r_3$ is constant, $C_0$ increases with the $r_2$, and when $r_2$ is constant, $C_0$ increases with the $r_1$. Moreover, we know that the bigger the $C_0$, the smaller the $U_0$; it is much easier for surface creepage to occur. Therefore, in order to avoid surface creepage, it is better to decreases the radius of the electrode and increase the thickness of the insulator.

### *C. Electric Field Distortion Around the Tip of the Connecting Ring*

In the switch, the connecting ring is usually made of stainless steel and is used to fixate the electrode holder (Fig. 1). Moreover, the connecting ring consists of two semicircles (Fig. 3), so there is a small gap between the junction points of the two semicircles, and owing to the effect of point, it leads to electric field distortion around the junction point. Usually, electric field of the tip of the connecting ring is enhanced, and the point J is

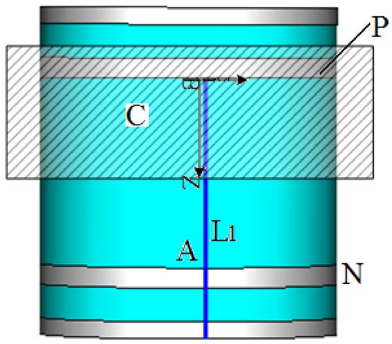


Fig. 4. Simulation model of the gas switch with no gap in the junction point of the connecting ring.

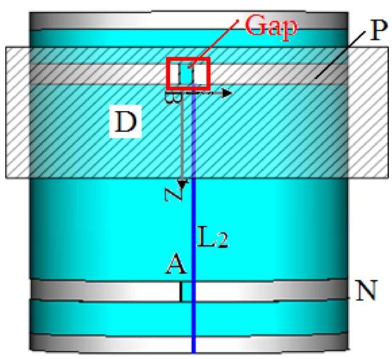


Fig. 5. Simulation model of the gas switch with gap in the junction point of the connecting ring.

the point which the electric field is enhanced, as shown in Fig. 3. Obviously, the point J is also the triple junction of the gas, metal connecting ring, and insulator, so the surface creepage usually starts at this point. This field enhancement is also shown by the simulation of software as follows.

## D. Electric Field Simulation With Software

Through the analyzed earlier, we have drawn a conclusion that the electric field will be enhanced in the junction point of the connecting ring, and the surface creepage starts at this point; therefore, it is very important to design the metal connecting ring to decrease the electric field distortion. In designing the metal connecting ring, the electric field and potential distribution of junction point of the metal connecting ring are carried out by employing electromagnetic simulation software of CST EM STUDIO, which is based on the finite-element method.

Fig. 4 shows the simulation model of the gas switch with no gap in the junction point of the ring (ideal model), and the electric field of region C is taken into account. Fig. 5 shows the simulation model of the gas switch with gap in the junction point of the ring (switch model); the gap is caused by the two connecting rings, and the electric field of region D is taken into account. For the region D, it is tangent to the outer housing of the switch at line $L_2$.

During the simulation, the electrode H and connecting ring P are at 500 kV; the electrode G and connecting N are grounded. Fig. 6 shows the distribution of potential at the region C; the potential distribution shows that the electric field is uniform. Fig. 7 shows the distribution of potential on the cross section of the surface with gap in the junction point of the ring; the potential distribution shows that the electric field is distorted on the edge of the junction point of the connecting ring. It also clearly shows that the distorted point of the electric field is also the triple point, so the surface creepage usually starts at the gap in the junction point of the connecting ring.

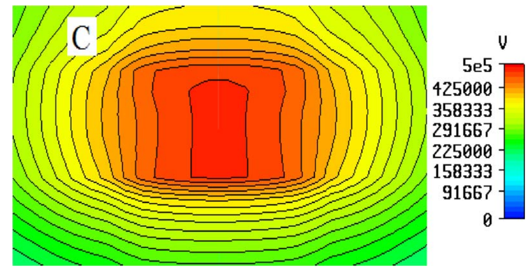


Fig. 6. Distribution of potential on the cross section of the surface with no gap (region C).

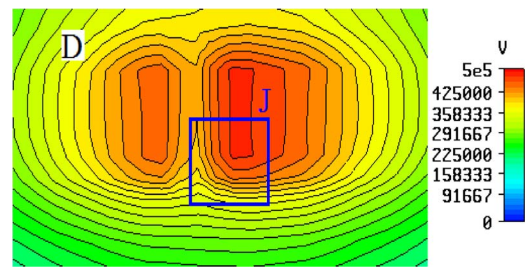


Fig. 7. Distribution of potential on the cross section of the surface with gap in the junction point of the ring.

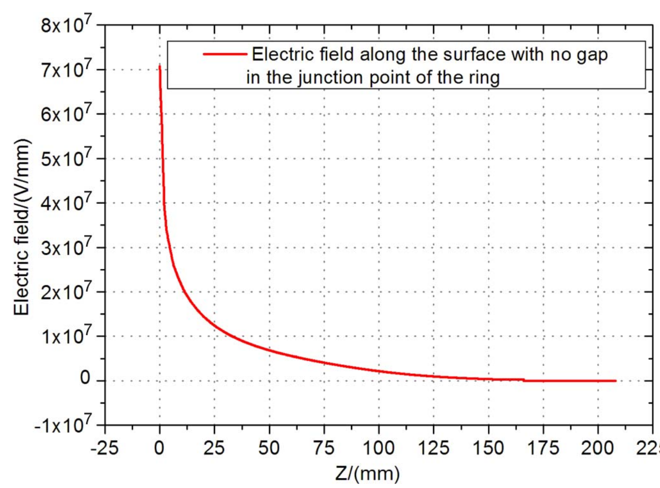


Fig. 8. Electric field along the line $L_1$ with no gap in the junction point of the ring.

In addition, the electric field along the line $L_1$ shown in Fig. 4 and line $L_2$ shown in Fig. 5 can be obtained from the simulation; Figs. 8 and 9 show the value of the electric field along the two lines. It obviously shows that the electric field of the ideal model is smaller than the switch model. Therefore, in order to avoid for the surface creepage to start at the junction point of the connecting ring, we should try our best to decrease the electric field distortion on the junction point of the connecting ring.

Of course, according to the electromagnetic field theory, it is a good idea to machine the junction point with a large

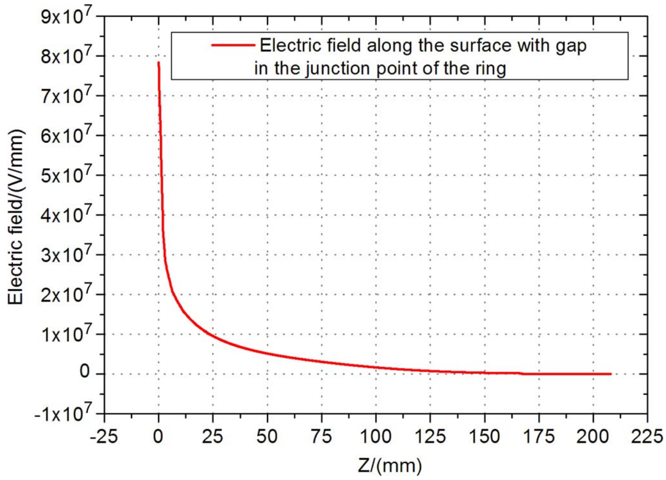


Fig. 9. Electric field along the line $L_2$ with gap in the junction point of the ring.

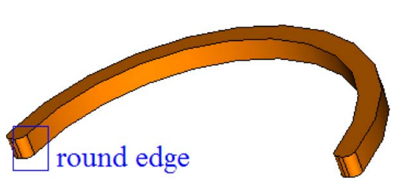


Fig. 10. Structure of the optimized connecting ring.

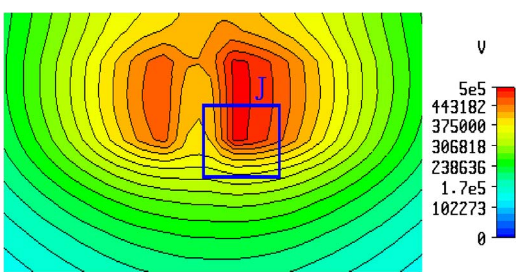


Fig. 11. Distribution of potential on the cross section of the surface with gap in the junction point of the optimized ring.

radius. This can decrease the electric distortion and avoid the electric field enhancement, simultaneously avoiding the surface creepage from happening at the junction point of the connecting ring. Fig. 10 shows the optimized structure of the connecting ring, and the junction points of the connecting have a rounded edge with a radius of 3 mm.

If the optimized connecting ring shown in Fig. 10 is used, instead of the connecting ring shown in Fig. 5, then the simulation is redid in the same condition. The distribution of potential at the region D is shown in Fig. 11; the value of the electric field along the $L_2$ is shown in Fig. 12.

From Figs. 7 and 11, it clearly show that the distribution of potential on the cross section of the surface with gap in the junction point of the optimized ring is more uniform. Moreover, the maximum of the electric field of the line $L_2$ shown in Fig. 12 is much less than the electric field shown in Fig. 9; these simulation results show that machining the junction point with a large radius can decrease the electric distortion and avoid the electric field enhancement.

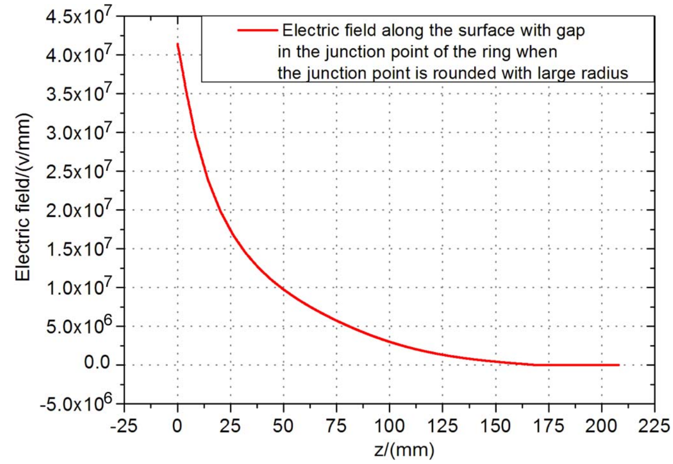


Fig. 12. Electric field along the line $L_2$ with gap in the junction point of the optimized ring.

Fig. 13. Photograph of the surface creepage of the switch.

## III. Experimental Result and Discussion

Fig. 13 shows a photograph of surface creepage of a high-voltage switch which is immersed in the transformer oil and is used as main switch of an electron-beam accelerator. The working voltage is 500 kV. It clearly shows that surface creepage starts at the junction point of the connecting ring, and the discharge is filamentous. The switch works as main switch about half year, so this picture is formed by many time discharges.

We observe the surface of the switch. It is clear to see electrodeposits on the surface of the switch; this shows that the main reason for surface creepage to happen is the pollution of the insulator. Because the surface resistivity of the insulator decreases when the electrodeposits are adsorbed on the surface of the insulator and when the voltage on the surface is surge voltage with 1.2/50 $\mu$s, the experimental results show that the typical flashover electric field of the pollution surface is [9]

$$E = 7.76 + 300S - 0.1D - 3.6 \log G \text{ (kV/cm)} \quad (9)$$

where $S$ (in millimeters) is the thickness of the electrodeposits, $D$ (in millimeters) is the circumference of the outer housing of the switch, and $G$ (in microsiemens) is the conductance. Formula (9) shows that the bigger the conductivity, the smaller the flashover electric field. In addition, if $S$ and $D$ are constant, then, substituting (9) into (8), the conclusion can be drawn that the bigger the conductivity, the smaller the flashover voltage.

Therefore, when the switch works for a long time, if we do not clean the surface of the insulator, and the conductivity becomes bigger, so the surface creepage of the switch would happen.

## IV. Conclusion

Through the analyzed earlier, in order to avoid the surface creepage of high-voltage switch, we must optimize the structure of the switch and adopt the appropriate insulator. Moreover, according to the theoretical analysis earlier, several methods for avoiding surface creepage can be obtained.

1) For insulator of the switch, it must adopt the insulating medium with high resistivity to increase the flashover voltage.
2) When the surface breakdown electric field is a constant, it is better to decrease the diameter of the electrode and to increase outer diameter and thickness of the outer housing.
3) In order to avoid field distortion, it is recommended, as far as possible, not to use metal connecting ring on the outer housing of the switch, which can increase the size of the surface and avoid electric field distortion. Of course, if the connecting ring is inevitable to use, the junction point should be machined with a large radius to avoid electric field distortion.
4) When the switch is immersed in the air, particularly in damp air, the surface creepage is much easier to happen; therefore, the switch is usually immersed in insulating medium, such as $SF_6$ or transformer oil. In order to increase the flashover voltage and the life of the high-voltage switch, the insulating medium should be clean; it is better to renew the insulating medium and to clean the surface of the switch at definite time.

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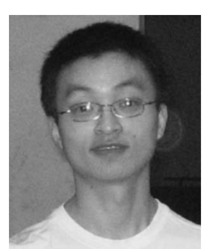

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