Erosion Pits Distribution Characteristics of Nanosecond Pulse Gas Spark Switches at Different Repetition Rates

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Abstract. Gas spark switches are widely used in the field of nanosecond pulses. Lifetime is one of the key parameters of a gas spark switch, which is closely related to the distribution of erosion pits. A repetition rate nanosecond pulsed discharge experimental platform is set up to investigate the distribution characteristics of erosion pits on the electrodes of nanosecond pulsed gas spark switch under different repetition rates. The distribution of erosion pits on the electrodes at different repetition rates has been analyzed statistically through a metallographic microscope. The results indicate that the range of erosion pits on the surface of electrodes is linearly related to the repetition rate. As the switch repetition rate increases, the range of erosion pits expands. The range of erosion pits on the cathode surface is slightly larger than that on the anode. When the repetition frequency increases from 1 Hz to 100 Hz, the radius of the anode pit range increases from 7.27 mm to 9.2 mm, and the cathode pit range increases from 8 mm to 9.73 mm. The density of erosion pits is related to the normalized electric field intensity in power function. With the increase in repetition rate, the tendency for erosion pits to concentrate at the geometric center of the electrode weakens. This research is of significant importance for the design of long-life gas spark switches.

Keywords: pulsed power technology; gas spark switch; nanosecond pulse; repetition rate; electrode erosion.

1. Introduction

Pulsed power technology has been widely used in various fields such as inertial confinement fusion, high-power particle beam generation, medical device sterilization, and waste gas treatment [1-6]. The switch is one of the key components in pulsed power devices, and its characteristics directly determine the performance of the entire pulse device, making it a key factor influencing the development of pulsed power technology [7-12]. Gas spark switch, due to its advantages of high current, simple structure, and easy maintenance, is widely researched and applied in the field of pulsed power, especially in the field of nanosecond pulses [13-19]. However, during the discharge of the gas spark switch, the electric arc will cause phase changes and removal of the electrode material, forming erosion pits on the electrode surface, which directly reduces the reliability and stability of the pulsed power system [20-24]. For high-power nanosecond pulsed power devices operating at repetition rates, the impact of electrode erosion will be particularly significant. Therefore, researches on the erosion of electrodes in repetition rate nanosecond pulsed gas spark switches can not only provide a basis for the design of erosion-resistant gas spark switches, but also improve the reliability, and stability of the pulsed power system, which has significant practical value.

In order to enhance the erosion resistance of electrodes, scholars have conducted extensive research on electrode erosion. Donaldson systematically summarized the phenomenon of electrode erosion, pointing out that it involves two processes: heat transfer and material desorption [25]. Although the physical process of erosion is clear, the characteristics of erosion vary for different gas spark switches [26]. Wang Hu studied the characteristics of electrode erosion under different
discharge conditions and found that when the current waveform is the same, the pit depth and erosion volume basically show a monotonically increasing trend with the increase of transferred charge and peak current [27]. Zeng Han's research shows that the erosion resistance of different electrode materials is different. The erosion resistance of common electrode materials is ranked from high to low as follows: tungsten, molybdenum, graphite, platinum, copper, gold, silver, iron, titanium, aluminum [8]. Different electrode structures have different erosion characteristics. Zhang Yongmin studied the performance of spherical, flat spherical, Chang, and Bruce electrode surfaces, and found that the erosion of Bruce electrodes is more uniform and covers a larger area [28]. Current research mainly reduces the impact of erosion by selecting erosion-resistant electrode materials and expanding the distribution range of erosion pits [26]. However, in practical engineering applications, the distribution of erosion pits on the surface of the electrodes of repetition rate nanosecond pulsed gas spark switches is not only related to the shape of the electrodes but is also affected by discharge parameters such as the repetition rate of switch. Conclusions drawn under single discharge conditions are difficult to provide a reliable basis for optimizing the shape and structure of the electrodes.

In this study, a repetition rate nanosecond pulsed discharge experimental platform is set up to investigate the distribution characteristics of erosion pits on the electrodes of nanosecond pulsed gas spark switch under different repetition rates. It is found that the range of erosion pits is linearly related to the switch repetition rate. As the switch repetition rate increases, the range of erosion pits expands. The density of erosion pits is related to the normalized electric field intensity in a power function relationship. As the switch repetition rate rises, the range of erosion pits expands, and the tendency for erosion pits to concentrate at the geometric center of the electrode weakens.

2. Experimental Setup

In order to study the erosion pit distribution characteristics of repetition rate nanosecond pulse gas spark switches, a nanosecond pulse discharge experimental platform is set up. The platform consists of a gas spark switch and a pulse power source. The gas spark switch adopts a dual electrode structure, and the switch electrodes are simple hemispherical electrodes, which are widely used. The electrode material is 316L stainless steel, and the electrode gap distance can be adjusted within the range of 0-50 mm. The sealed cavity of the gas switch is filled with nitrogen, with a pressure range of 0.1-0.8 MPa. The distribution of erosion pits on the electrode surface is observed and statistically analyzed through a metallographic microscope.

The pulse power source is a solid-state repetition rate pulse generator based on a Semiconductor Opening Switch (SOS), with typical output characteristics of 300 kV voltage, 2 kA current, 35 ns pulse width, and a maximum repetition rate of up to 100 Hz. As shown in Fig 1, it mainly includes a primary charging unit and a high voltage pulse compression unit. In the primary charging unit, the DC source charges the primary energy storage capacitor $C_0$ to 960 V through the silicon stack $S_0$ and current limiting resistor $R_0$. The trigger controller outputs pulse signals at different repetition rates to control the fast thyristor $S_1$. When $S_1$ conducts, the energy in $C_0$ is input to the high voltage pulse compression unit through the magnetic saturation pulse transformer PT. The intermediate storage capacitors $C_1$ and $C_2$ in the high voltage pulse compression unit is connected to PT. When the energy in $C_0$ is transmitted to $C_1$ and $C_2$ through PT, the secondary side of PT, $C_1$, $C_2$, and the magnetic switch MS1 form a voltage multiplying circuit to further increase the voltage amplitude. After MS1 saturates, $C_1$ and $C_2$ charge the high voltage capacitor $C_3$, while forward pumping the SOS. After MS2 saturates, $C_3$ discharges in reverse, reverse pumping the SOS. When the reverse current approaches its maximum value, the SOS cuts off, forming a high voltage nanosecond pulse to the load.
The pulse power source has two operating modes: single trigger and repetitive trigger. In the repetitive trigger mode, the trigger controller in the primary charging unit controls $S_1$ by outputting square wave signals of different frequencies, thereby deciding the repetition rate of the pulse power source. According to the repetition rate of the trigger controller, the pulse power source can output nanosecond pulse signals at four different repetition rates: 1 Hz, 10 Hz, 50 Hz, and 100 Hz. The output voltage and current are determined by the load impedance. The load impedance is determined by the load resistance $R_{\text{load}}$, the current limiting resistance $R$ and gap parameters which include the electrode gap distance $d$ and the switch pressure $p$. As an example, when $R_{\text{load}}$ is 200 $\Omega$, $R$ is 5 $\Omega$, $d$ is 20 mm, and $p$ is 0.1 MPa, the waveforms of voltage and current output by the pulse power source are as shown in Fig 2. The voltage amplitude is 238.84 kV and the current amplitude is 3.31 kA while the pulse width $t$ is about 25 ns. The outputs of pulse power source remain unchanged at different repetition rates.

During the discharge, the arc plasma which contains a large number of high-temperature particles such as electrons, ions, and neutral molecules, causes rapid heating on the surface of the switch electrode, thereby causing phase change processes such as liquefaction, vaporization or sublimation of the electrode material. At the same time, the arc generates electromagnetic forces on the electrode, removing the phase-changed electrode material from the electrode surface, and erosion pit is formed at the point where the arc strikes. [29]. Before the discharge, the shape of the electrode determines the electric field on the electrode surface, and then determines the position where the arc strikes. After the discharge, the existing pits distort the local electric field on the electrode surface, affecting the position of the next pit. Therefore, the distribution of erosion pits on the electrode surface changes with the number of discharges [30]. For gas spark switches with smaller discharge currents, the erosion pits caused by single erosion on the electrode surface are small and cannot significantly affect the electric field on the electrode surface. Therefore, when the number of discharges is small, it can be approximately considered that the electric field on the electrode surface remains constant.

3. Results and Discussion

3.1 Erosion range at Different Repetition Rates

Using a spherical electrode with a radius of curvature of 80 mm, the gap distance between the
electrodes is set at 20 mm, and 0.1 MPa of nitrogen is filled into the discharge chamber. Discharge is repeated 2000 times at a frequency of 100 Hz. The electrode surface after discharge is observed through a metallographic microscope. As shown in Fig 3, the erosion pits on the anode surface are distributed in a circular area centered on the geometric center of the electrode. Moreover, the distribution of pits on the electrode surface is not uniform.

Fig. 3 Anode surface after 2000 repeated discharges.

Keeping the electrode gap and switch pressure constant, discharge is repeated 1000 times at frequencies of 1 Hz, 10 Hz, and 50 Hz, respectively. The electrode surface is observed through a metallographic microscope, and the distribution range of erosion pits on the electrode surface at different repetition rates is recorded, as shown in Fig 4. The distribution range of erosion pits on the electrode surface increases with the increase of repetition frequency, and the two are basically linearly related. Moreover, the range of erosion pits on the cathode surface is slightly larger than that on the anode. When the repetition frequency increases from 1 Hz to 100 Hz, the radius of the anode pits range increases from 7.27 mm to 9.2 mm, and the cathode pits range increases from 8 mm to 9.73 mm.

Fig. 4 Range of erosion pits on electrode surface at different repetition rates.

When a nanosecond pulse voltage is applied to a gas spark switch, a strong electric field is generated between the electrodes. In the strong electric field area near the center of the electrode, gas molecules are ionized to form free electrons and positive ions, forming an arc channel that causes breakdown of the gap. However, in the weak electric field area far from the electrode center, the degree of gas ionization is low, making it difficult to form a discharge channel. This results in the erosion pits on the electrode surface mainly concentrated in the strong electric field area at the
electrode center. As the discharge progresses, the current in the arc channel begins to decrease. The arc cannot maintain the required temperature and ionization level. The ionized gas molecules begin to recombine. When the current drops to a level that cannot sustain the arc, the arc extinguishes [31]. After the arc extinguishes, the charged particles further diffuse and recombine, and the gas between the electrodes eventually returns to its initial state. As the switch repetition rates increases, the time for gas to recovery decreases. When the next discharge occurs, the charged particles generated by the previous discharge have not completely disappeared. After multiple discharges, due to the accumulation of residual charged particles, the density of charged particles in the gap increases. The strong ionization area that can form a discharge channel expands, eventually leading to an increase in the distribution range of erosion pits.

### 3.2 Distribution of Erosion Pits at Different Repetition Rates

The electrode surface is observed through a metallographic microscope, and the distribution of erosion pits at different repetition rates is analyzed statistically. Taking the geometric center of the electrode as the origin, the position coordinates of each erosion pit is recorded. A two-dimensional frequency analysis is performed on the obtained coordinates, and histograms of the erosion pits distribution on the electrode surface at different repetition rates are obtained, as shown in Fig 5. Erosion pits are dense in the center area of the electrode, and as the radius increases, the erosion pit density decreases. There are significant differences in the distribution characteristics of erosion pits at different repetition rates.

![Histogram of pit distribution on the electrode surface at different repetition frequencies.](image)

(a) $f=100\text{Hz}$  
(b) $f=50\text{Hz}$  
(c) $f=10\text{Hz}$  
(d) $f=1\text{Hz}$  

Fig 5 Histogram of pit distribution on the electrode surface at different repetition frequencies.
The electrode surface is discretized into a series of concentric circular ring areas of equal width. The number of erosion pits in different radius ring areas is counted, and the erosion pits density in different areas is calculated. The electric field intensity on the electrode surface is calculated using COMSOL, as shown in Fig. 6. The electric field intensity on the electrode surface is normalized, and the relationship between the erosion pits density $\rho$ and the normalized electric field intensity $E_r$ is fitted to obtain the erosion pits distribution function at different repetition rates, as shown in Fig. 7. The erosion pits density is approximately a power function of the normalized electric field intensity. As the switch repetition rate increases, the tendency of erosion pits to concentrate in the center of the electrode weakens, and the pits are distributed on the electrode surface more evenly.

![Electric field intensity of the gas spark switch](image1)

**Fig 6 Electric field intensity of the gas spark switch**

![Relationship between erosion pits density and the normalized electric field intensity](image2)

**Fig 7 Relationship between erosion pits density and the normalized electric field intensity**

Gas spark switch conduction, due to the electrode center electric field intensity is large, easy to cause gas ionization and the formation of the arc channel, when the switch repeat frequency is small, the breakdown of the erosion pits is mainly concentrated in the vicinity of the electrode center. When the repetition rate increases, the switch is on, the electrode gap, especially near the arc channel generated by the previous discharge, there are still charged particles that have not faded, so compared with the electrode center, the arc is more likely to be formed in the vicinity of the previous breakdown location. When the arc deviates from the electrode center, subsequent discharges may continue to deviate, which leads to a weakening of the tendency for the concentration of the erosion pit distribution at the electrode center and a relatively uniform distribution of erosion pits on the electrode surface.

It is easier to cause gas ionization and form an arc channel at the geometric center of the electrode due to the higher electric field intensity. Therefore, the erosion pits formed are mainly concentrated near the center of the electrode when the switch repetition rate is low. However, when the repetition rate increases, during the process of the next discharge, there are still unextinguished charged particles formed by the previous discharge in the gap between the electrodes, especially near the previous arc channel. Therefore, compared to the geometric center of the electrode, the arc is more likely to form near the location where the previous arc is. When the arc landing point
deviates from the center of the electrode, subsequent arcs may continue to deviate, which weakens the tendency of erosion pits to concentrate at the geometric center of the electrode, and the erosion pits are distributed on the electrode surface more evenly.

**Conclusion**

This study investigates the characteristics of erosion pits distribution on the electrode surface of a nanosecond pulse gas spark switch at different repetition rates and gap parameters. The following conclusions are obtained:

1. The range of erosion pits expands with the increase in switch repetition rate, showing a linear relationship. The range of erosion pits on the cathode surface is slightly larger than that on the anode. When the repetition frequency increases from 1 Hz to 100 Hz, the radius of the anode pit range increases from 7.27 mm to 9.2 mm, and the cathode pit range increases from 8 mm to 9.73 mm.

2. The erosion pits density and the normalized electric field strength on the electrode surface have a power function relationship. With the increase in repetition rate, the arc deviates from the center of the electrode more easily, which causes the weakening of tendency for erosion pits to concentrate at the geometric center of the electrode.

**References**


