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Analysis of nanosecond spark switches applied to high-voltage electrical pulse rock breaking

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Abstract: In order to better apply the designed switch to electric pulse rock breaking, an experimental platform of gas spark switch was built, and the self-breakdown voltage of the switch under different pressure nitrogen was measured. The breakdown stability of the switch was measured by the relative range of the self-breakdown voltage, and it was found that the breakdown stability of the switch was the best under 0.15mpa nitrogen. Then, the breakdown delay of the switch under different working voltages in nitrogen environment with different pressure was measured, and the influence of gas pressure and working voltage on the breakdown delay of the switch was analyzed to test whether it meets the condition that the voltage rise time of rock crushing by direct discharge is less than 500ns.

Keywords: Nanosecond spark switches; High-voltage electrical pulse rock breaking.

1. Introduction

With the deepening of resource exploitation, the geological conditions to be faced are becoming increasingly complex. During the exploration and development process, rock breaking technology is particularly important. The rock in deep formations has high hardness and poor drillability. How to improve drilling efficiency and reduce energy consumption is a key issue for the efficient development of oil and gas resources [1]. High voltage electric pulse rock breaking is a new application of pulse power technology in the field of rock breaking. This technology was proposed by the former Soviet Union in the 1960s[2]. It uses a pulse power device to form a plasma channel inside the rock, which rapidly expands inside the rock, leading to rock breaking [3]. This technology has the advantages of high efficiency, environmental protection, and low cost, and is suitable for use as an auxiliary means of crushing high hard rock to reduce bit loss, improve drilling efficiency, and reduce drilling costs. Currently, high-voltage electric pulse rock breaking is still in the laboratory research stage, and the rock breaking effect depends on the organizational structure of the rock and the voltage parameters output by the pulse power device [4]. Therefore, the pulse power device used for electric pulse rock breaking is an important foundation for in-depth understanding, evaluating, and analyzing the practicality and feasibility of electric pulse rock breaking [5].

Switching module is one of the key components of pulsed power devices, and its performance directly determines the core capabilities of pulsed power systems for high power output, fast pulse discharge, and compact applications in small devices [6]. The pulse power device applied to electric pulse rock breaking has higher pulse amplitude and shorter rise time compared to ordinary pulse power devices, and the shorter the rise time of voltage, the higher the rock breaking efficiency, which puts forward high requirements for the stability of the switch [7]. Therefore, starting from the mechanical structure of the switch, this paper optimizes the electric field distribution between the switch electrodes through theoretical analysis, software simulation, experimental research, and other methods to improve the stability of the switch during breakdown. A nanosecond spark switch that can be applied to electric pulse rock breaking has been designed and fabricated, which has certain reference value for further research on electric pulse rock breaking and high-power pulse switches [8].

2. Physical process of electro-pulse rock breaking

According to different scene conditions in practical applications of pulse power technology, the requirements for the pulse power device itself and its output energy vary[9]. In addition to the magnitude of the pulse power energy, the pulse waveform output by the device is also another very important technical indicator for verifying the effectiveness of pulse power technology. Figure 1 below shows the composition of a typical pulse power system:



Fig. 1 Composition of a typical pulse power system

Compared with traditional rock breaking techniques, high-voltage electric pulse rock breaking has the smallest energy consumption per unit volume in terms of energy consumption; From the perspective of controllability, electrical pulse breaking through rock only requires adjusting the pulse waveform output by the system to achieve the gravel effect; From the perspective of environmental protection, traditional rock breaking methods inevitably generate fugitive dust or toxic gases, while high-voltage electrical pulse rock breaking requires a liquid environment that can inhibit the splashing of rock debris[10].

3. Design of gas spark switch

The charging module provides primary energy for the energy storage module after rectifying 220V AC voltage doubling; The protection module works in three ways: first, to reliably ground the charging module and the energy storage module; second, to protect the system against backspikes during discharge; and third, to release the remaining energy in the capacitor after the test is completed; In addition to releasing energy from the system to rocks, the discharge module also needs to steep the rising edge of the output

voltage to less than 500 ns[11].

3.1. Charging module

The primary side of the power supply is input with a power frequency of 220V AC, and then boosted by a step-up transformer. The amplitude of the AC boost is adjusted by the control unit [12]. The resulting high voltage is rectified by voltage doubling and then supplied to the energy storage module. The voltage doubling rectifier circuit is shown in Figure 2:

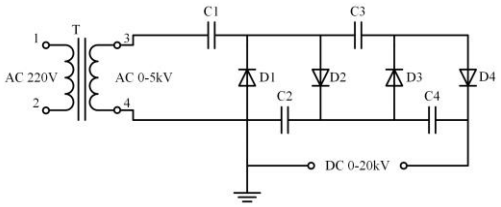


Fig. 2 Circuit diagram of voltage doubling rectifier

Within the negative half cycle of the voltage, the potential at point 3 in Figure 3 is negative, and the potential at point 4 is positive. Diodes D1 and D3 are turned on, and D2 and D4 are turned off [13]. On the one hand, the power supply will charge capacitor C1 through diode D1; On the other hand, it will be superimposed with the voltage on C2, and the capacitor C3 and C1 will be charged through D3. The charging voltage on C3 is twice that on C1. The negative half cycle current path and capacitor polarity are shown in Figure 3:

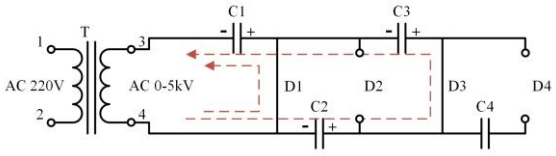


Fig. 3 Negative half cycle current path and capacitor polarity

Within the positive half cycle of the voltage, the potential at point 3 in Figure 4 is positive, and the potential at point 4 is negative. Diodes D2 and D4 are turned on, and D1 and D3 are turned off[14]. On the one hand, the power supply will be added to the voltage on C1, and capacitor C2 will be charged by D2, resulting in a voltage that is twice the charging voltage of capacitor C1; On the other hand, it will be superimposed with the voltages on C1 and C3, and the capacitors C4 and C2 will be charged through D4. The voltage charged on C4 is twice the voltage on capacitor C1. The positive half cycle current path and capacitor polarity are shown in Figure 4:

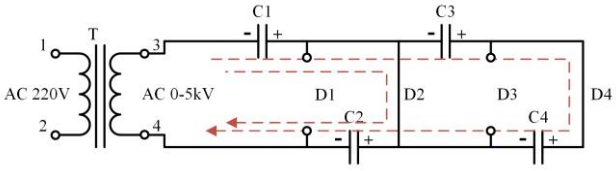


Fig. 4 Positive half cycle current path and capacitor polarity

3.2. Protection module

Backpeak voltage is one of the most common causes of damage when high-voltage DC power supplies are used as energy storage capacitor chargers. High voltage power supplies typically have a unipolar output. In the fields of capacitor charging and power pulses, the RLC resonant circuit is commonly used in the discharge process of energy storage capacitors. The voltage waveform on the capacitor is similar to a sine wave that constantly attenuates with damping oscillations. The voltage at the negative half cycle is opposite to the initial charging voltage of the capacitor, and the voltage at this time is called the back-peak voltage. The duration of the voltage below 0 is referred to as the duration of the back-peak voltage. This section will discuss the generation of back peak voltage and its countermeasures in conjunction with the discharge circuit. Use Pspice to simulate the discharge process of the energy storage capacitor. First, establish the RLC simulation circuit during discharge, as shown in Figure 5:

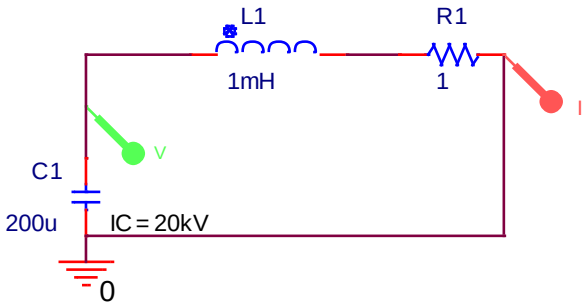


Fig. 5 Inverse peak simulation circuit diagram

The output of the power supply is a positive voltage, which means that the electric charge is output from the negative electrode to the positive electrode inside the power supply. The secondary (secondary) side of a high-voltage power supply allows charge to flow from the negative electrode to the positive electrode within the power supply. During the peak inversion process, due to the voltage at the output end of the high-voltage power supply being lower than 0V, the rectifier diode inside the power supply is turned on, and the uncontrolled flow of charge from the ground to the output end causes damage to the secondary (secondary) rectifier diode.

In order to prevent excessive current in the freewheeling diode from causing damage to the freewheeling diode, a series anti peak inductor is connected in the charging circuit, and a simulation circuit is established to analyze its anti-peak principle. The simulation circuit is shown in Figure 6:

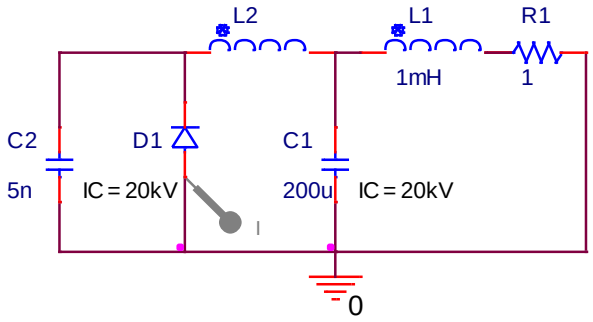


Fig. 6 Anti peak inductance simulation circuit

In Figure 6, C2 is the internal energy storage capacitor of the high-voltage power supply, D1 is the freewheeling diode, L2 is the anti-peak inductance, C1 is the energy storage capacitor, L1 and R1 are the simulated loads, and the initial voltages of C1 and C2 before discharge are 20kV. Due to the existence of the freewheeling diode, there will be no reverse peak voltage, so the magnitude of the peak current flowing through the freewheeling diode becomes the key. The smaller the peak current, the more obvious the protection effect. Set

L2 to 0, 1 mH, 2 mH, and 4 mH, respectively, and measure the current flowing through the freewheeling diode during the transient state of 0-10 ms. The simulation results are shown in Figure 7:

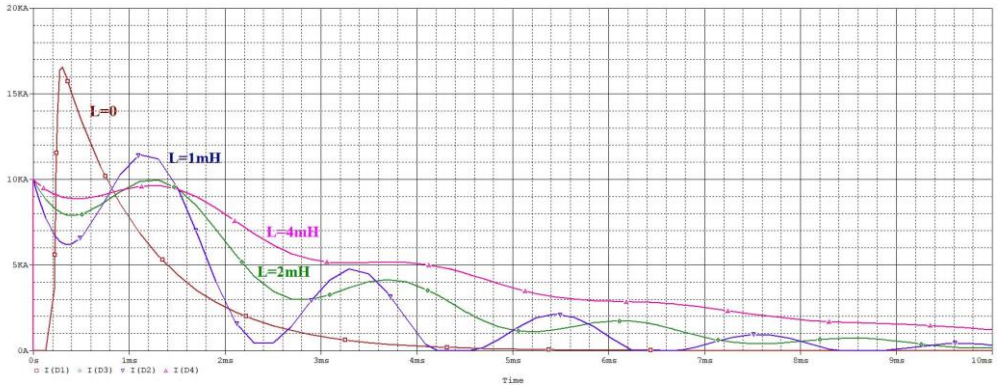


Fig. 7 Anti peak inductance simulation results

It can be seen that when a reverse peak occurs, the inductance has a restraining effect on the current, and the larger the inductance, the smaller the current flowing through the freewheeling diode. However, as the inductance increases to a certain value, the restraining effect on the reverse peak will not increase significantly.

3.3. Discharge module

On the one hand, the discharge module releases the energy in the energy storage capacitor onto the rock, and on the other hand, it needs to compress the output pulse voltage on a time scale. The rising edge of the output voltage of the mechanically triggered conducting discharge isolation switch used in the laboratory is only millisecond level. Therefore, this paper designs a nanosecond level spark switch for sharpening the rising edge of the pulse voltage, which is connected in series with the isolation switch in the system to form a discharge module.

Set the initial voltage of C=200pF to 20kV and R=50 Ω. When the values of L are 1nH, 50nH, 100nH, and 150nH, the simulation results are shown in Figure 8:

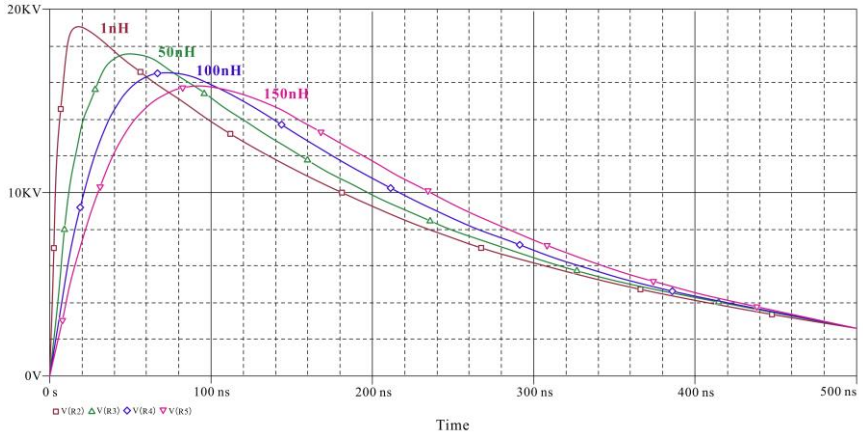


Fig. 8 Change inductance simulation results

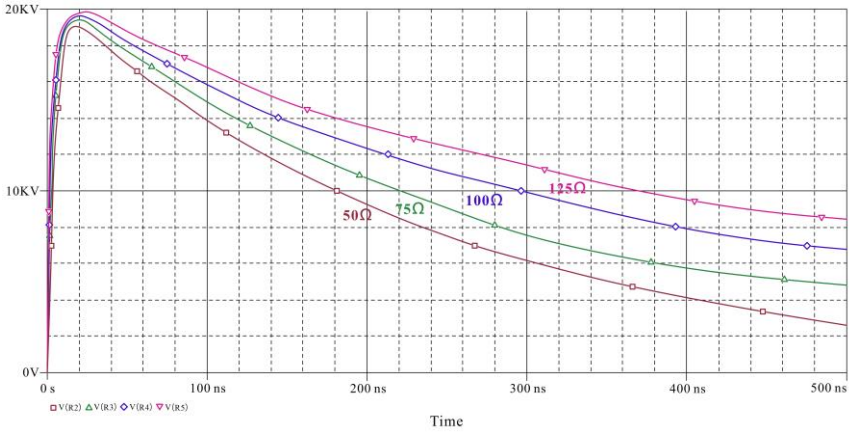


Fig. 9 Change the simulation results of resistance and inductance

As can be seen from Figure 8, as the inductance increases, the peak value of the voltage gradually decreases, and the corresponding rise time of the voltage increases as the inductance increases.

Set the initial voltage of C=200pF to 20kV and L=1nH. When the values of R are 50 Ω, 75 Ω, 100 Ω, and 125 Ω, the simulation results are shown in Figure 9:

As can be seen from Figure 9, as the resistance increases,

the peak value of the voltage gradually decreases and increases, and the corresponding rise time of the voltage increases as the resistance increases.

4. Conclusion

In this paper, a high-voltage electric pulse rock breaking experimental device based on a capacitor parallel structure is designed. Based on this, according to the requirements of high-voltage electric pulse rock breaking for switch stability and output voltage rise time less than 500 ns, a nanosecond spark switch that can be applied to high-voltage electric pulse rock breaking is emphatically studied and designed.

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