

Investigation on Post-arc Recovery Characteristics of SF₆/N₂ Mixed Gas Medium



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Abstract SF₆ is a strong greenhouse gas with high liquefaction temperature, which limits its application in gas insulation equipment to a large extent. Therefore, the search for a replaceable gas has become a hot topic in electrical field. Although scholars have carried out a lot of research work on SF₆ replacement gas, they have not yet found a gas that can completely replace SF₆. At present, the most cost-effective way is to use SF₆ gas mixture. Therefore, this paper mainly studies the recovery of insulation strength of SF₆/N₂ gas mixture with different proportions after a certain arc-burning time. In this experiment, the RC circuit is used to simulate the arc-burning condition. After the arc current transfer, the high-voltage pulse generator is used to apply pulse to the contact gap, so as to obtain the back-arc recovery characteristic curve of the gas medium, which provides data support for the research and development of the circuit breaker replacing SF₆ gas, and also has important significance for the study of the breakdown problem of the replacement gas circuit breaker.

Keywords SF₆ gas mixture · Post-arc recovery characteristic · Arc

1 Introduction

In the last half century, with the rapid development of the power industry, the voltage level in the process of transmission and distribution is getting higher and higher, which puts forward higher requirements for the electrical equipment in the power system. SF₆ due to its high chemical reliability generally does not produce chemical reactions with other substances; it is not easy to burn and can effectively perform the specified function. Moreover, SF₆ gas has strong arc-extinguishing ability and insulation ability [1, 2]. Therefore, for more than half a century, the power equipment with SF₆ as the insulating medium and arc-extinguishing medium has occupied a

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dominant position in medium- and high-voltage power grids [3, 4]. About half of the SF₆ produced in industry is used in the power sector, with about four-fifths in the high-voltage sector. With the development of the power industry in recent years, a large amount of SF₆ is directly leaked or discharged into the atmospheric environment without treatment [5]. However, SF₆ gas also has some defects, among which the most critical is its greenhouse effect. SF₆ gas is a kind of strong greenhouse gas, which has great harm to the atmospheric environment. Its Global Warming Potential (GWP) is about 23,900 times of CO₂ gas. Moreover, SF₆ gas has an extremely long atmospheric life, with a life span of 3400 years [6, 7]. At the third Conference of the Parties to the United Nations Framework Convention on Climate Change held in Tokyo, Japan, in 1997, 149 countries and regions signed the Kyoto Protocol, which listed SF₆ gas as one of the six greenhouse gases with limited emission [8, 9]. Compared with western countries, our country's SF₆ gas emission increases by a large amount every year, and our country's population has a large-scale, vast territory; the demand for electric power is large; therefore, SF₆ gas usage is large, which causes the problem of SF₆ greenhouse gas to be particularly prominent in our country. Moreover, the liquefaction temperature of SF₆ gas is higher, in the north and cold region in our country, and the winter temperature can reach -30 to -40 °C. In such an environment, most of the existing SF₆ electrical equipment cannot work normally [10].

In order to solve the problem that SF₆ gas has high greenhouse effect and is easy to liquefy in cold environment, finding alternative gas has always been a hot research topic in the field of electrical. As a replacement gas for SF₆, it should meet the following requirements: First, it should have a low enough greenhouse effect, non-toxic, and do no harm to the environment; secondly, it needs to meet the most basic technical performance requirements, such as low liquefaction temperature, high insulation strength, strong heat dissipation capacity and good arc-extinguishing performance [11]. The current solution is mainly divided into two directions: One is to mix SF₆ gas with some conventional gas of liquefaction temperature to reduce the usage of SF₆ gas; the second is the use of new insulating gas medium, completely replacing SF₆ gas. Scholars have carried out a lot of research work to find SF₆ alternative gases. At present, although there are some new insulating gases, which have the potential to replace SF₆ gas in some aspects, they all have certain defects. The liquefaction temperature of these new gases is low, so they need to be mixed with other buffer gases to reduce the liquefaction temperature [12].

In recent years, some new environmentally friendly gases have attracted much attention, such as *c*-C₄F₈, C₄F₇N, C₆F₁₂O, C₅F₁₀O and CF₃I. The greenhouse effect of these gases is much lower than SF₆, and they have good environmental protection and insulation properties. The insulation properties and GWP values of different gases are shown in Table 1. However, as mentioned above, these gases have a high liquefaction temperature and cannot be used as insulating gases alone. They must be mixed with some buffer gases to meet the ambient temperature requirements of power equipment. At present, the buffer gases mainly include CO₂, N₂ or dry air

[13]. However, at present, the decomposition mechanism of this kind of gas is not clear, and the phenomenon of solid precipitation exists, so the safety of engineering application needs to be further studied [12].

The current research on SF₆ gas mixture mainly focuses on SF₆ mixed with CO₂, N₂, CF₄ and inert gas. The research shows that adding a certain proportion of buffer gas to SF₆ gas can achieve good insulation and arc-extinguishing effect and meet the basic electrical performance requirements of power equipment [14, 15]. In addition, the addition of buffer gas can help to reduce the liquefaction temperature of gas medium, reduce the cost, reduce the impact of SF₆ gas on the environment and improve the greenhouse effect brought by SF₆ gas, which can provide strong support for the realization of the current goal of “carbon peak and carbon neutrality [16].”

Among the above-mentioned buffer gases, N₂ and CO₂ have high content in the air and are the main components of the air, which are relatively easy to obtain. Therefore, these two mixed gases become the preferred targets of alternative gases. Compared with CO₂, N₂ has a lower price and less impact on the environment, so it has become the main research object [17]. At present, circuit breakers with SF₆/N₂ as gas medium have been put into use. In the 1980s, about 160 SF₆ gas-mixed circuit breakers were put into use in Canada. This batch of circuit breakers adopted SF₆/N₂ gas-mixed aeration pressure of 0.5 MPa, of which SF₆ accounted for 40% [18].

SF₆ gas mixture is mainly used as the insulating medium in gas circuit breaker, which plays the role of arc extinguishing and insulation, and is mainly used in medium- and high-voltage circuit breakers. At present, researches on SF₆ gas mixture are in-depth in the aspects of insulation strength and cold breakdown [19], while most researches on insulation strength recovery after arc extinguishing tend to be on the simulation level. In particular, there is a lack of comparative studies on the recovery rate of SF₆ gas mixtures with different mixing ratios after arc ignition. Circuit breaker is an important protection device in power system, and its success affects the normal operation of the whole power system. When gas circuit breaker is normally broken off, it is bound to produce arc. After the arc is extinguished, when it enters the medium recovery stage, whether the gas medium is broken down is the key factor to judge whether the breaking is successful [20].

In this experiment, the RC discharge circuit is used to provide current and simulate arc-burning conditions. After the arc is extinguished for a period of time, the high-voltage pulse device is used to apply pulse voltage between the contacts. By measuring the breakdown voltage in the recovery stage of the gas medium between the contacts after extinguishing the arc, the recovery characteristic curve of the gas medium is obtained. In this paper, the post-arc recovery characteristic curves of

Table 1 Comparison of key characteristics of environmental gases

Characteristic	SF ₆	c-C ₄ F ₈	C ₄ F ₇ N	C ₆ F ₁₂ O	C ₅ F ₁₀ O	CF ₃ I
GWP	23,500	8700	2100	~ 1	~ 1	0.45
Liquefaction temperature (°C)	- 64	- 8	- 4.7	49	27	- 22.5
Dielectric strength	1.00	1.30	2.00	2.50	1.20	1.20

different proportions of SF₆/N₂ gas mixture are compared, and from the perspective of post-arc medium recovery, which proportion of gas mixture has more potential to replace SF₆ gas.

2 Experimental Setup

The power supply used in this experiment is a high-power capacitor with a stable output voltage of 500 V. The main circuit switch is a three-phase vacuum AC contactor whose action can be controlled by controlling the electrical signal output to the control terminal of the main circuit switch. The current-limiting resistance is a high-power load with adjustable resistance value, which controls the current in the loop by adjusting the resistance value. The high-power diode in the loop is used to protect the equipment in the loop from the influence of the reverse voltage; thyristors VT₁ and VT₂ are controlled by the TTL signal generator. When the main loop switch is closed, the TTL sends an electrical signal to the VT₂ to control its on-off. The function of thyristor VT₂ is transfer current. When VT₂ is switched on, the current flowing through the experimental chamber will be transferred from the branch of VT₂. The arc-burning time is controlled by controlling the time difference between VT₁ and VT₂. The function of high-speed camera is to shoot arc image to observe the shape of arc. There is a set of electromagnetic mechanism inside the experimental chamber. The contact mechanism is closed by controlling the current of the closing coil inside the electromagnetic mechanism. The thyristor VT₁ is switched on after the contact mechanism is closed, thus generating current in the loop. Then by controlling the electromagnetic mechanism part of the gate coil current to control the opening of the contact mechanism, generate arc. Trigger signals of thyristor, electromagnetic mechanism and high-speed camera in experimental device are uniformly controlled by TTL signal generator.

3 Experimental Results and Analysis

3.1 Arc Characteristic Analysis

The contact structure is in the shape of “ball-plate,” as shown in Fig. 1a. The anode is the ball contact, and the cathode is the plate contact, which is conducive to providing a stable arc during the process of the contact being pulled apart. The material of the two contacts is CuW₈₀. The current of the experiment is 550 A, the current of arc burning is 500 A, the proportion of SF₆ in the gas mixture is 10, 50 and 90%, and the inflation pressure is 2 atm. The arc image taken is shown in Fig. 1b. It can be seen from the shooting results that when the contact reaches the maximum opening distance, the arc presents a stable “bell shape” structure. Figure 2 shows the voltage

and current waveform of the arc in the arc-burning process, which can be divided into three stages from the beginning of the experiment to the current being transferred away. The first stage is the current conduction stage. At this time, the thyristor is switched on, and the contacts are closed. In the second stage, the contact starts to move, and the gap between the upper and lower electrodes gradually increases until the maximum opening distance is reached. The third stage is stable arc-burning stage. Under the condition of 500A current, the arc is stable arc-burning stage. In this stage, the arc form is stable “bell shape.”

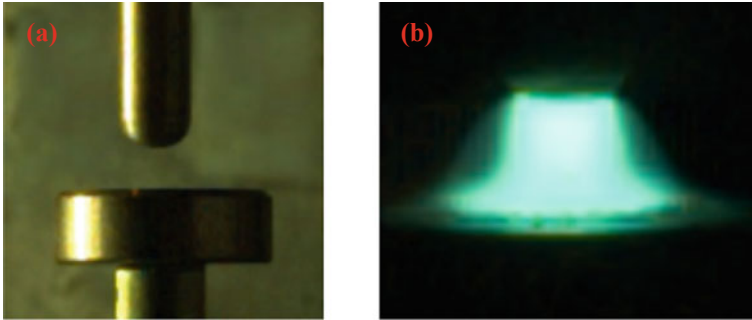


Fig. 1 Electrode shape and arc shape diagram

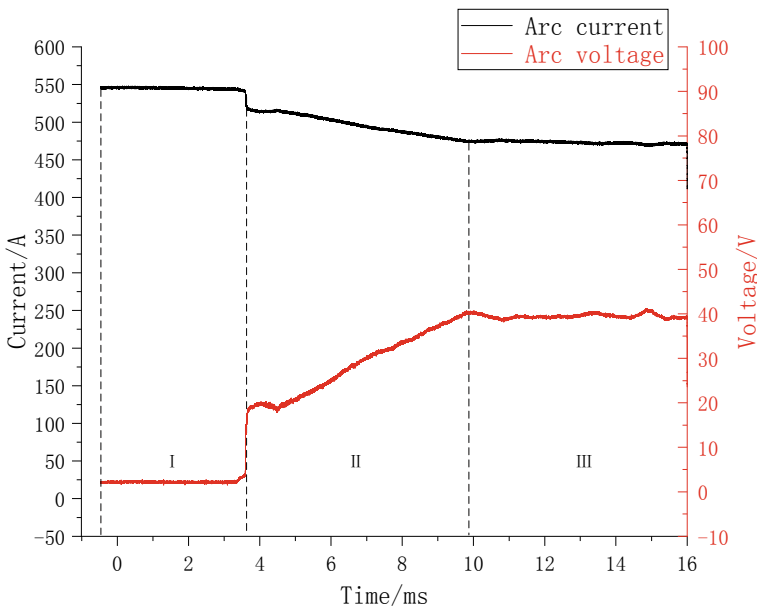


Fig. 2 Arc voltage and current diagram

3.2 *Experiments on Recovery of Back-Arc Medium Under Different Mixing Proportion*

After the arc current is transferred, there are still a large number of charged particles in the area where the arc is generated between the contacts, resulting in low insulation strength of the gas medium between the contacts in a short time. When the pulse voltage is applied to the contacts, the breakdown between the contacts will be caused, forming a breakdown channel. With the diffusion of charged particles between the contacts, the insulating strength of the gaseous medium slowly increases. This process is called electrical recovery process. In the arc-burning process, due to the high temperature of the arc, after the arc current is zero, the gas medium also needs a certain time to recover to the initial temperature, and this process is called the thermal recovery process. Compared to the two processes, electrical recovery is faster than thermal recovery. When the gas medium returns to the initial temperature, then its insulation strength is completely restored and the breakdown channel is no longer formed.

The dielectric insulation recovery test loop built was used to conduct insulation recovery test on SF₆/N₂ mixed gas at different mixing ratios under the condition of 2 atm. The experimental results are shown in Fig. 3. As can be seen from the Fig. 3, as the proportion of SF₆ gas increases, the recovery voltage of the gas mixture rises higher and recovers faster. The recovery rate of the gas mixture with 50% SF₆ is 45.45% faster than that with 10% SF₆, and the recovery rate of the gas mixture with 90% SF₆ is 66.67% faster than that with 10% SF₆. The recovery rate of SF₆/N₂ gas mixture is quite different under the conditions that SF₆ accounts for 50% and 90%, which may be due to the synergistic effect of SF₆ and N₂, leading to a higher saturation ratio.

It can be seen from the above conclusions that, although the higher the SF₆ ratio, the faster the recovery rate of the gas mixture, the higher the SF₆ ratio of the gas mixture will increase the liquefaction temperature of the gas mixture and enhance the greenhouse effect, resulting in the limited application environment and greater harm to the environment. Overall consideration, SF₆ in SF₆ gas mixture should not exceed 50%.

4 Conclusion

In this paper, the insulation recovery test loop of gas medium was built to test the insulation recovery test of SF₆/N₂ mixed gas under the condition of 2 atm, providing certain data reference for the engineering application of SF₆ mixed gas. The experimental results show that the recovery rate of gas mixture increases gradually with the

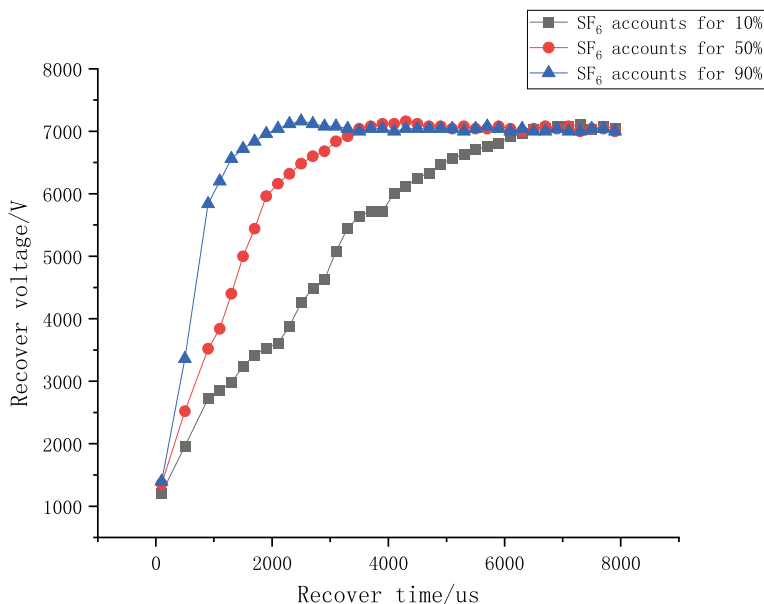


Fig. 3 Post-arc recovery characteristic curve of SF₆/N₂ mixed gas medium

increase of SF₆ proportion. Considering the effects of GWP and liquefaction temperature, SF₆ in the gas mixture should not exceed 50%. Therefore, from the perspective of back-arc recovery, SF₆/N₂ gas mixture with 50% SF₆ has the potential to replace SF₆ gas.

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