Dengming Xiao

肖登明 编著

Gas Discharge and Gas Insulation

气体放电与气体绝缘（英文版）

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内 容 提 要

气体绝缘具有占用空间小(特别是在拥挤的城市中)、对污染敏感度较低、运行维护成本低等优点。绝缘气体不但应具有高的耐电强度和灭弧性能,还要有良好的理化特性,以及环境友好的低 GWP 值(全球变暖潜值)。本书围绕气体绝缘,共分 10 章,主要内容包括:气体放电基础、汤逊放电基础理论、流注及先导放电的基础理论、气体放电发展的理论研究方法、空气的介电性质、六氟化硫(SF_6)气体的绝缘特性、SF_6 混合气体的绝缘特性、潜在 SF_6 替代气体的绝缘特性、气体绝缘的发展前景等。

本书主要用作高电压与绝缘技术专业研究生教材,也可供高电压技术专业和相近专业(应用物理专业、气体激光、等离子体技术等专业)的研究人员和研究生参考,以及国家电力部门、电器制造厂家的工作技术人员参考。

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Preface

Over a century, the study of gas discharge is very active, and the production and development of modern science and technology have greatly contributed to the in-depth study of various types of discharge. Meanwhile, the research progress of gas discharge has played a huge role in promoting the further production and development of science and technology.

Both now and in the future, the insulation gas must be environmentally acceptable. Therefore, the best solution to the global warming problem affected by insulation gases may be to prevent releasing harmful insulation gases into the atmosphere. However, from the point of view of the dependence on industrial gas and the social value of insulation gas, it is hard to imagine what would be happening when completely removing the use of insulation gas. So the solution should emphasize the need to find a kind of environmentally friendly insulation gas, and it is also necessary to study the high-voltage insulation technology on substitute for SF_6 gas.

With increasing concentrations of SF_6 in the atmosphere, which results in essentially irreversible effects on global warming, it is significant to carry out studies of searching for possible alternatives to pure SF_6 with lower environmental impact as the insulating medium. In order to promote research on the new environmentally friendly insulating gas, a professional book concerned with gas dielectrics, involving SF_6 and its mixtures, as well as the possible alternative gases, is needed urgently.

The project team composed by the authors followed the international pace in the past two decades; then carried out a large amount of research on calculating and experimenting of SF_6, SF_6 gas mixtures, and environmentally insulation gases; and achieved lots of results as well. Authors compile their two decades of research into a monograph "gas discharge and gas insulation," which has high academic significance. For international research and development of new environmentally friendly insulation gas, this book also has an important value on guiding application.

This book consists of ten chapters. The first chapter introduces the development history and research progress of gas discharge, and the research and application of gas insulation. Chapter 2 presents the fundamentals of gas discharge and describes the movement and collision interactions of charged particles in gas. In Chap. 3, the fundamental theory of Townsend discharge is specified. Chapter 4 clarifies the fundamental theory of streamer and leader discharge in gas discharge. Then Chap. 5 presents the theoretical analysis methods for simulating gas discharge, mainly including Monte Carlo simulation and Boltzmann equation method. Chapters 6, 7, and 8 present the discharge characteristics, insulation strength, and applications of atmosphere air, pure SF_6 gas, and SF_6 gas mixtures, respectively. Chapter 9 specifies the insulation characteristics of potential alternatives to pure SF_6 gas. In the last chapter, research progression and development prospect of environmentally friendly insulation gas is presented.

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Finally, I appreciate the continuous supports from my wife and son.

Shanghai, China Dengming Xiao

Contents

Chapter 1
Introduction

Abstract The development history and research process of gas discharge are introduced in this chapter where the classification and application of gas discharge are analyzed as well. The features of gas insulation, and also the research status and development prospects of environmentally friendly insulation gases, are expounded in this chapter. Special attention is paid to the development and application of SF_6.

Keywords Gas discharge • SF_6 • Environmentally friendly gases • Gas insulation

1.1 Definition and Content of Gas Discharge

Gas discharge is the various forms of current circulated in the gas atmosphere.

Under normal state, gas that is isolated from a variety of external ionization is not conductive. But, in fact, due to ultraviolet radiation, cosmic rays and radiation from the interior of the earth, there is always a small amount of charged particles in the air. For example there are about 1,000 positive and negative ions per cubic centimeter in the atmosphere (the ion is the charged molecule, according to the electrical property correspondingly called cation or anion). Under the effect of an electric field, these charged particles moving along the direction of the electric field form a conduction current, so a gas usually is not the ideal insulating medium. But when the electric field is weak, given little charged particles and because the conductivity of gas is extremely small, gas is still an excellent insulating medium.

When the voltage on the gas gap reaches a certain value, current will sudden surge and the gas will lose insulating properties. The process of the insulating state mutated to the conductive state is called breakdown. When the breakdown process occurs at the interface between the gas and liquid or the gas and solid, it is known as flashover. When breakdown and flashover occur, the conductance increases obviously, but usually accompanied by light and sound. The minimum critical breakdown or flashover voltage is called the breakdown voltage U_b or flashover voltage U_f. Breakdown and flashover are sometimes referred to as discharge in general; the breakdown voltage or flashover voltage is also sometimes referred to as the discharge voltage in general. In a uniform electric field the ratio of the breakdown voltage and gap distance is called the breakdown strength E_b; it reflects the

D. Xiao, *Gas Discharge and Gas Insulation*, Energy and Environment Research in China

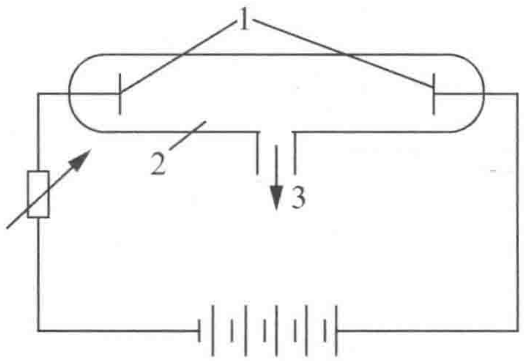

Fig. 1.1 Schematic diagram of the gas discharge tube: 1—electrodes; 2—discharge tube; 3—connection to the vacuum pump

resistance of electric capacity, namely the dielectric strength of the gas. In a non-uniform electric field the ratio of the breakdown voltage and gap distance is called the average breakdown strength; this is related to the electric field distribution and depends on the quantity of the concrete structure, and can be used to measure the degree of the gas insulating ability utilized.

Depending on the gas pressure, electrical power, electrode shape and other factors, after a breakdown of the gas discharge there can be a variety of different forms. Figure 1.1 shows the use of a gas discharge tube to observe the change of discharge [1].

When the gas pressure is low and electrical power is very small (access to a large impedance in the discharge circuit), after the applied voltage increases to a certain value, the loop current suddenly increases significantly; between the whole space of the cathode and the anode tube, a luminous phenomenon suddenly appears. This is called glow discharge. The current density of discharge is small, and the discharge area usually occupies the entire space between the electrodes. As the outer loop impedance decreases, the current increases. When the current increases to a certain value, the discharge channel becomes small and increasingly bright, then the terminal voltage of the tube decreases, indicating that the channel conductance is increased. This form is called arc discharge.

Because electrical equipment often uses air as an insulating medium, we are more concerned about discharge under atmospheric conditions. Corona discharge, brush discharge, spark discharge, arc discharge and other forms of discharge may occur at this time. Gas will lose its insulating ability after breakdown, so we focus on the breakdown of gas, and the various forms of gas discharge (except corona discharge) do not form the focus of too much research.

1.2 History of Electrical Discharge Research

Since the observation of thunder and lightning, humans have gradually explored the mysteries of gas discharge, and the study of gas discharge also has a history of more than 100 years. At present, there are still a lot of people around the world researching gas discharge from different aspects; advanced technology has also added a new vitality to the subject. The study of gas discharge has had two main periods of rapid development in the recent 100 years [2].

In the first period in the early nineteenth century to the twentieth century, people focused on the nature of various gas discharges in theory analysis and research. Sufficiently powerful electric barriers were developed at the beginning of the nineteenth century to allow the discovery of arc discharge. V.V. Petrov, who worked in the Saint Petersburg Medical Academy in Russia, reported the discovery in 1803. The arc was obtained by bringing two carbon electrodes connected to battery terminals into contact and then separating them. In 1831–1835, Faraday discovered and studied glow discharge. Faraday worked with tubes with evacuated pressure to 1 Torr and applied voltage up to 1,000 V. The history of the physics of gas discharge in the late nineteenth and early twentieth centuries is inseparable from that of atomic physics. In 1891, N. Tesla found radio frequency discharge. After William Crookes's cathode ray experiments and J.J. Thomson's measurements of the e/m ratio, it became clear that the current in gases is mostly carried by electrons. A great deal of information on elementary processes was obtained by studying phenomena in gas discharge tubes. Beginning in 1900, J.S.E. Townsend, a student of J.J. Thomson, discovered the laws governing ionization and gaseous discharge in a uniform electric field. Numerous experimental results were gradually accumulated on cross sections of various electron-atom collisions, drift velocities of electrons and ions, their recombination coefficients, etc. This work built the foundations of the current reference sources, without which no research in discharge physics would be possible. The concept of plasma was introduced by I. Langmuir.

The second period of rapid development was in 1950, when people saw that the use of a gas discharge plasma could yield cheap atomic bomb raw materials, which could be extracted from seawater inexhaustibly. They started studying controlled thermonuclear reactions. Around 1950, people pursuing research into radiofrequency discharge began to systematically study microwave discharge, and on that basis developed radar technology. The discovery of lasers encouraged people to begin studying discharges in optical frequency. In the 1970s, the development of photovoltaic technology quickly attracted people's attention. So far, the depth of research into microwave discharge and photoelectric technology has generally matched the depth of reseavch into discharge in uniform electric field in the recent one hundred years. Under the development of photovoltaic technology, glow discharge, as one of the oldest and most studied fields, has been revitalized in the past 15–20 years, showing a lot of new features. In addition, the use of the low temperature plasma generator in metallurgy, plasma chemistry and plasma welding and cutting has also promoted deeper research into arc discharge plasma in all frequency ranges, pressures under 1 atm (1 atm=$1.013{,}25\times10^5$ Pa), and temperatures below 10^4 K.

For decades, the study of gas discharge has been very active; the development of modern science and technology has greatly contributed to the in-depth study of various discharges; at the same time, gas discharge advances in turn have played a huge role in further development of science and technology. Especially in the last 20 years, gas discharge plasma has been shifting from the study of space plasma research towards materials and microelectronics research. It has now become an important issue with global implications, having a huge impact on the development of the high-tech economy and the transformation of traditional industries.

1.3 Classification of the Discharge

Depending on the gas pressure, electrical power, electrode shape and other factors, after gas breakdown the discharge will show a variety of different forms; the discharge phenomenon can be observed through the discharge tube.

When the gas pressure is low and electrical power is very small (access to a large impedance in the discharge circuit), after the applied voltage increases to a certain value, the loop current suddenly increases significantly, between the whole space of the cathode and the anode tube suddenly appears a luminous phenomenon. This is called glow discharge. It has a small discharge of current density; the discharge region generally occupies the entire space between the electrodes. The neon tube discharge is an example of it. The emitting light colors are dependent on the filling gases in the tube. The current increases as the impedance decreases. When the current increases to a certain value, the discharge channel becomes small and increasingly bright. The terminal voltage of the tube decreases, indicating that the channel conductance increases. This form is called a arc discharge.

When increasing the pressure of the discharge tube, the plasma channel is gradually smaller and the discharge no longer fills the entire space between the electrodes. When the outer loop impedance greatly limits the discharge current, the thin bright spark between the electrodes will appear, which is called the spark discharge. The reason for the intermittent spark discharge is that the form of the spark gap makes the current suddenly increase, resulting in the impedance voltage of the external circuit being increased as well, so the gap voltage is reduced at the same time. The spark cannot be maintained and extinguished. This makes the circuit impedance voltage drop again, so the gap will form a spark breakdown again. This makes the formation of the intermittent spark discharge. If the outer loop impedance is small, that is, the power supply is large enough, arc discharge can be transferred immediately after the gap breakdown, forming the bright discharge channel with high conductance. The temperatures of the arc channel and the electrode are both high with great current density. The circuit has short circuit characteristics.

If the ratio between the curvature radius of the electrode and the electrode distance is large, that means the electric field is uniform; when the voltage rises to a certain value, the entire gap will break down suddenly. Conversely, if the ratio between the curvature radius of the electrode and the electrode distance is small, that means the electric field is non-uniform; when the voltage rises to a certain

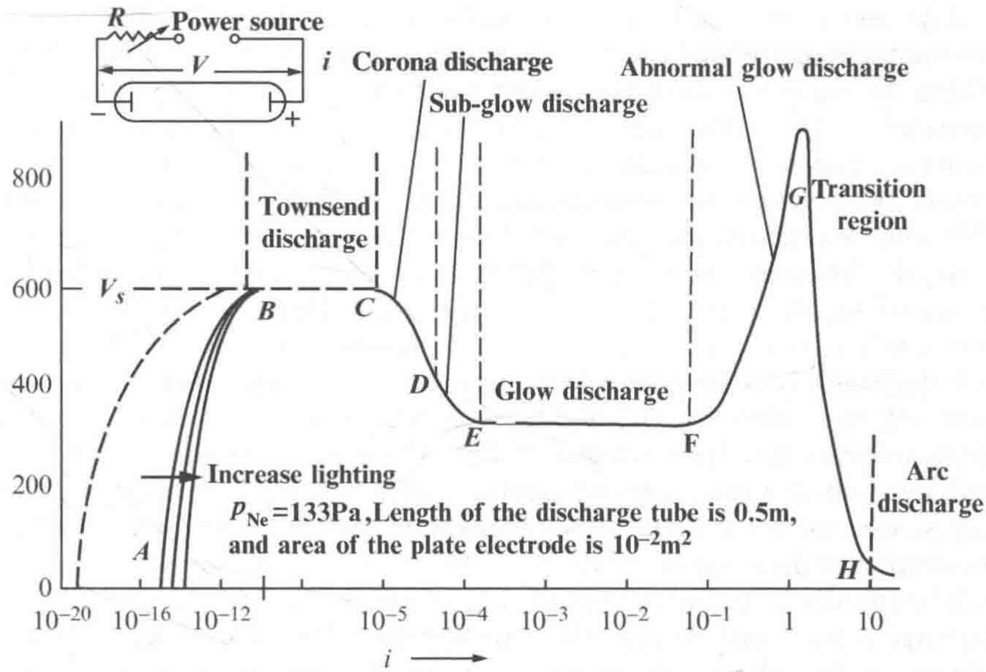

Fig. 1.2 Volt-ampere curves of gas discharge

value, at first the electrode surface appears as a light-emitting layer, and the circuit current can be detected with general instruments. As the voltage increases, the light-emitting layer expands and the discharge current also increases gradually. This discharge is called corona discharge. When corona discharge occurs, most parts of the gas gap have not yet lost insulation performance; the discharge current is very small and the gap still has insulating proprieties. As the voltage continues to rise, a number of relatively bright thin corona discharge channels occur from the electrode, and this is called brush discharge. When the voltage keeps rising, the whole gap will break down finally, it will become a spark discharge or arc discharge according to the supply power.

In order to better illustrate the classification of gas discharge, the different discharge phenomena can be described in gas discharge volt-ampere curves, namely the electrode discharge current with a voltage change curve [3]. Because the dominant basic physical process is different, the gas discharges have different volt-ampere curves, as shown in Fig. 1.2.

As shown in Fig. 1.2, when the outer voltage between the electrodes increases, the sensitive galvanometer can detect the weak electric current which flows through the electrode, and the minimum detectable current is about 10^{-16} A; this is a random impulse current. If we add some electronic source between the electrodes, the characteristic curve will move to the right. With the increase of electrode voltage, the space charge can completely move on the electrode, and the current can be up to 10^{-14} A.

With the continued increase in the discharge voltage, due to secondary ionization the discharge current increases slowly at first, butby exponential increase later. Within this range the discharge current can be increased 10^8 times, while the discharge voltage is almost not increased. The transition of the paroxysm is called electrical breakdown, and the corresponding voltage is called the breakdown voltage. When gas breakdown occurs, the increasing discharge current has nothing to do with the external ionization source; the discharge can maintain itself. In other words, the discharge converts from the original non-self-sustaining discharge to a self-sustaining discharge. This part of the region belongs to the Townsend discharge.

If the resistance of the external circuit is changed, and the discharge current is increased, the voltage on the discharge gap will reduce and decline to a certain steady voltage value. There is a process from Thomson discharge, through corona discharge, sub-glow discharge and eventually glow discharge. After the discharge process the current increases exponentially with voltage, this area is called the abnormal glow discharge area.

When the discharge current continue to increase, the discharge convert to an arc discharge region which has negative characteristics. The arc discharge's positive column area is a high energy plasma area; it launches the intense radiation.

From the above gas discharge volt-ampere curves, we can see that each segment of the curves represent different discharge forms. These characteristic curves obviously do not cover all forms of discharges.

Gas discharge has many forms; there are also many kinds of classification methods. For example, according to whether the discharge needs sustaining by an outside ionization source, it can be divided into a non-self-sustaining and self-sustaining discharge. According to whether the discharge parameter changes with time, it can be divided into steady discharge and unsteady discharge. According to the working method of the cathode, it can be divided into cold cathode discharge and hot cathode discharge, etc.

1.4 Application of the Discharge

We do not want gas breakdown in transmission lines and electrical equipment, but in many other areas, the gas discharge has been widely applied, such as energy, metals processing, xerography, environmental protection, etc. They all gradually show great economic benefits as well as profound research prospects.

The MHD generator is now widely studied. It is an example of the discharge used in the new energy conversion devices. Fully ionized gas at high temperature is known as plasma; when plasma gas transits through a magnetic field that is perpendicular to the direction of the gas flow with high speed, an electromotive force will be generated in the direction which perpendicular to both the plasma flow and the magnetic field. The current can be drawn through electrodes and the electrical energy can be obtained directly, so heat convert into electrical energy directly. This kind of power generation is expected to increase the overall efficiency of power plants to 60 %, but at the moment, continued high temperature and high temperature plasma gas are still difficult, and many issues need further research.

In industry, dust particles are often removed through electrical methods, called electrical dust collection. In an electric field the charged particles will go to the opposite polarity of the electrode by electric force. With the above principle the floating particles in gas can be removed.

Electrostatic painting is widely used in automobile manufacturing. When painting, the corona electrode connects with negative high voltage, and objects that will be sprayed connect with the ground. Atomized paint (or other coatings) pass through the corona electrode and will be charged, so that the coating will be evenly distributed on the object.

Xerography is made from a thermoplastic copolymer powder and uses an ordinary transparent record paper method. It has been widely used in modern society. The xerographic principle with photoconductive material cartridges is the use of selenium (Se) on the photographic film. The photographic film has photoconductivity. When the photosensitive film is charged by a corona, it can make the lighted part disappear (the photosensitive film's conductivity increases) and produce electrostatic latent images. Images after development are transferred to plain paper and the images will be fixed on the paper.

Electric erosion processing is an application of electrical discharge in the field of machining. It is the direct use of electrical energy through spark discharge to form the size of the metal parts. The time of spark discharge is very short (10^{-7}–10^{-2} s) and the discharge region is very small. However the discharge current density is large, so the anode produces a high temperature. The work piece to be machined may melt or even vaporize under such high temperature. The high pressure generated by the spark discharge will scatter the melted or vaporized material from the work piece to the working fluid, so a part of the work piece material is etched away, only leaving a small pocket. Each discharge erosion can remove part of the material; the accumulation will make the work piece similar to the shape of the electrode cavity. But the ablation of the tool electrode itself is very small. Electrical sparks can also do some parts (such as molding) for surface hardening, grinding and cutting; for example, accelerated ion swarm adopted from discharge can be used to punch tiny hole in the manufacture of semiconductors and modification of insulating materials.

The impact current in liquid has an electrohydraulic effect. It can generate a powerful impact wave which can form sheets and tubes. In metallurgy, mining, cement and other places, the great impact pressure produced by the electrohydraulic effect can be used to crush ore. By using the reflection of the elliptical shaped device, the pressure wave produced by the electrohydraulic effect can be transmitted to the human body to crush stones (kidney stones, bladder stones, etc.) and has achieved good clinical results.