

Research Article

Breakdown Mechanism of Different Sulphur Hexafluoride Gas Mixtures

E. Onal 

Electrical Engineering Department, Istanbul Technical University (ITU), Istanbul 34469, Turkey

Correspondence should be addressed to E. Onal; eonal@itu.edu.tr

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Sulphur hexafluoride (SF_6) gas and SF_6 gas mixtures are widely used in gas-insulated systems (GIS) because they have good dielectric and thermal properties. Among the various gas mixtures investigated so far, SF_6 -air, SF_6 - CO_2 , and SF_6 - N_2 are most used gas mixtures. Also, these mixtures have much technical superiority in GIS. These are nontoxic and nonflammable gases, and they have less sensitivity to nonuniformities and higher liquefaction temperature at high pressure. GIS, switchgears, circuit breakers, and substations are systems that work with alternating current and have nonuniform electric fields. For this reason, in this study the breakdown mechanisms of 0.125, 0.5, 1, and 20% SF_6 gas mixtures with rod-plane configuration under AC voltage are investigated and explained breakdown mechanism.

1. Introduction

Sulphur hexafluoride (SF_6) is the most popular insulating gas in the electric power systems such as switchgears, gas circuit breakers, and gas-insulated stations because of having good electrical, thermal, and chemical properties. However, the dielectric strength of SF_6 at nonuniform electric field falls drastically to very low values because SF_6 is very much sensitive to nonuniformities like impurities and electrode configuration. Since the molecule of SF_6 is large and it has small free pathways besides the electrons that are easily attached to SF_6 molecules, it has a high dielectric strength. SF_6 is a very strong greenhouse gas; for this reason, its global use is restricted on the world. Some greenhouse gases, such as CO_2 , are naturally found in nature. Some of them are industrial gases like CO, CH₄, CFCs, SF_6 , and HCFC-22. Greenhouse gases hold longwave radiation while they allow shortwave radiation to pass to earth. This case causes Earth to warm up. This is an undesirable situation. Today, voluntary programs work to reduce the emission of SF_6 into the atmosphere. These programs encourage us to work efficiently at power systems by using less SF_6 . Our study supports this scientific mission. Besides, SF_6 is more expensive than other insulating gases. Thus, it is essential to

improve the different dielectric gas or gas mixtures having more appropriate insulating properties, inexpensive, and without greenhouse effect. So, SF_6 gas and its mixtures with such as air, nitrogen (N_2), and carbon dioxide (CO_2) have been extensively studied [1–6]. The aim of this study is to investigate SF_6 mixtures in terms of their electrical strength and to clarify the mechanisms of breakdown. Breakdown properties of SF_6 gas mixtures in uniform and quasi-uniform electric field are nearly similar, but their breakdown characteristics in nonuniform electric field depend on various factors such as gas pressure, gas temperature, electrode gap spacing, and gas ratios in the mixture and electrode configuration. The breakdown properties of SF_6 gas mixtures in uniform field under impulse and direct voltage have been studied in earlier researches [7–9], but the examination of the characteristics in nonuniform fields is open to research.

Earlier studies have shown that the breakdown voltage of mixtures of SF_6 - N_2 with below containing 30% SF_6 are less than that of pure SF_6 at the pressure of 5 bar. At the same pressure and negative polarity, 0.1% SF_6 - N_2 mixture has half dielectric strength compared with that of 100% SF_6 . The breakdown voltage of SF_6 - CO_2 mixtures is higher than that of SF_6 - N_2 mixtures at the pressure of approximately 4–5 bar,

while the dielectric strengths of two mixtures are the same at low pressures at negative and positive polarities for direct voltage. However, the strength of negative polarity is always higher than that of positive polarity as in all nonuniform fields. The breakdown voltage of SF₆-CO₂ mixtures is higher than that of pure SF₆ at some pressures for impulse voltages. As an example at above the pressure of 3 bar, the strengths of 1% SF₆-CO₂ mixtures are slightly higher than those of pure CO₂ at negative impulse voltage [10].

2. Test Setup

In the experimental study, rod-plane electrode configuration is used to simulate the nonuniform fields in practical systems (Figure 1) because rod-plane electrode system represents the best nonuniformities. The rod electrode with tip radius of 1 mm and the plane electrode with diameter of 75 mm are used.

All experiments are performed in the pressure range from 1 bar to 5 bar and at 25 mm fixed gap spacing. The electrodes are located in a pressure tube as test vessel that has 120 mm diameter and 600 mm length. In rod-plane electrode configuration, high voltage is applied to the rod electrode while the plane electrode is earthed (Figure 1). The test vessel is firstly evacuated and then filled with the gas mixtures to the pressure of 5 bar. For the 50 Hz AC tests, 100 kVrms, and 5 kVA, a high-voltage test transformer is used. A capacitive divider and voltmeter are used to measure the applied high voltage. Experiments were carried out in Istanbul Technical University (ITU) High Voltage Laboratory (Figure 2).

In this study, the breakdown voltages of CO₂, N₂, air, SF₆, and the mixtures of SF₆-CO₂, SF₆-N₂, and SF₆-air with 20, 1, 0.5, and 0.125% of SF₆ are measured from 1 bar to 5 bar with 1 bar steps at rod-plane electrode configuration.

3. Experimental Results

SF₆ gas mixtures are lot in nature and cheap. These gas mixtures are selected as air, N₂, and CO₂. The breakdown voltages of these gas mixtures depending on pressure are shown in Figures 3–5, respectively. Since the decompositions of these gas mixtures under pressure are important, air, N₂, and CO₂ gases are selected in this study.

As seen in Figures 3–5, a little bit addition of SF₆ to these gases has significantly increased the breakdown voltage values. The high breakdown of voltage means that high electrical strength is very important in insulation technique in power systems. As can be seen from the above discussion, dielectric strength of only N₂, CO₂, and air increases linearly with increasing pressure, whereas the breakdown voltages of SF₆ mixtures are approximately the same at a pressure of higher than 4 bar. The mixture having the lowest dielectric strength among the three mixtures is the mixture of SF₆-N₂. The effect of N₂ on breakdown strength is less than that of air and CO₂. The reason for this is electron mobility and ionization energy. The gas additive to SF₆ affects the charge density and the width of streamer between the electrodes. Besides, electron mobility affects the delay of leader streamer

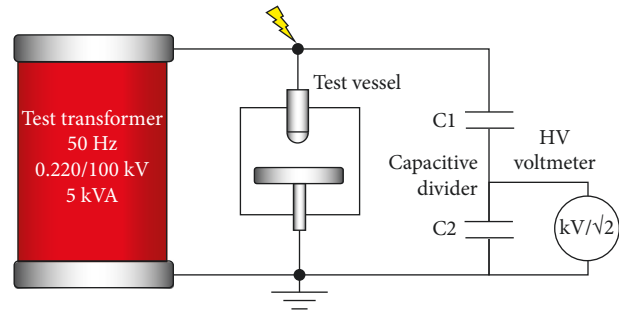


FIGURE 1: Test setup.



FIGURE 2: Test setup at high voltage laboratory of ITU. (1) Test transformer; (2) current limiting resistor; (3) capacitive divider; (4) test vessel; (5) vacuum pump.

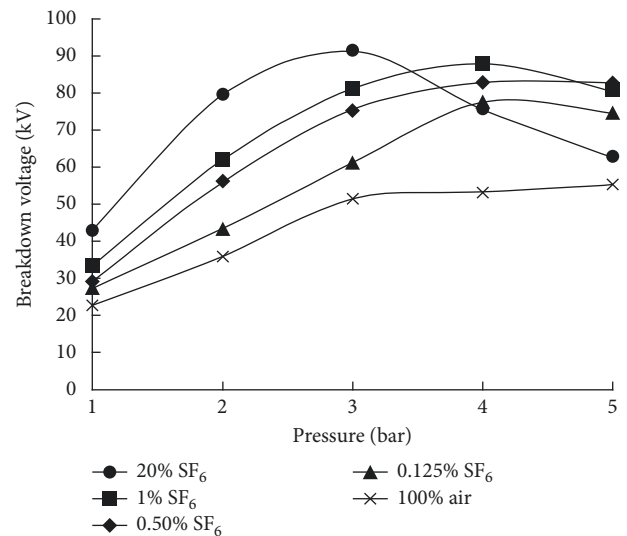


FIGURE 3: Changing of breakdown voltage with gas pressure for SF₆-air mixtures.

in gas mixtures. For this reason, the breakdown mechanisms of SF₆ gas mixtures are different from each other. It is known that the breakdown mechanism of SF₆ is streamer and stepped leader breakdowns. As the SF₆ ratio increases, the stepped leader mechanism is valid. The leader step time is the interval time between two consecutive leader steps and is

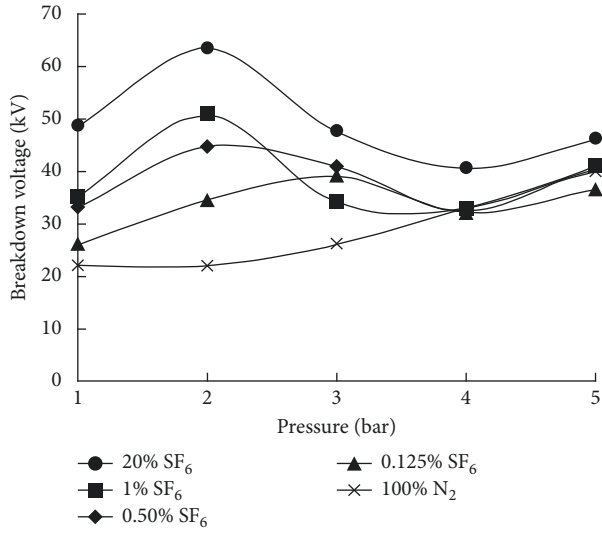


FIGURE 4: Changing of breakdown voltage with gas pressure for SF₆-N₂ mixtures.

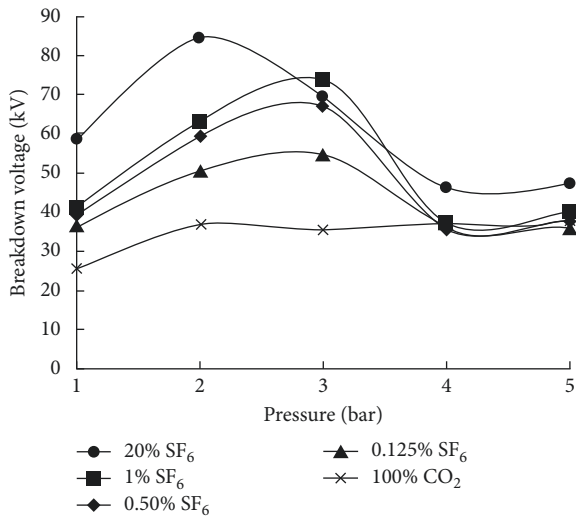


FIGURE 5: Changing of breakdown voltage with gas pressure for SF₆-CO₂ mixtures.

an important parameter in SF₆ gas mixtures. It is a decisive factor in the development of breakdown and streamer. It depends on the SF₆ gas mixture ratio, pressure, and voltage and is represented by

$$t_s = \frac{K}{(pU)}, \quad (1)$$

where p is the gas pressure, U is the voltage applied between the electrodes, and K is the constant depending on the SF₆ gas mixtures ratio. For SF₆-N₂ mixtures, K is smaller than that for SF₆-CO₂ and SF₆-air mixtures [11]. These mixtures have many superiorities compared to pure SF₆. The addition of relatively small amount of SF₆ to nitrogen, carbon dioxide, and air causes a significant increase in dielectric strength. As an example, breakdown voltage of 0.125% of SF₆-air is 1.5 times higher than that of pure air at the pressure of 4 bar.

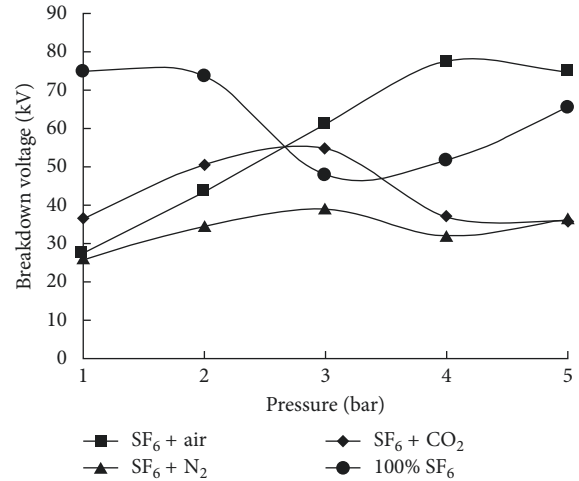


FIGURE 6: Changing of breakdown voltage with gas pressure for 100% SF₆ and 0.125% SF₆ mixture.

Figure 6 gives the variation of breakdown voltage of pure SF₆ and 0.125% SF₆ mixtures depending on gas pressure.

As seen in Figure 6, for 25 mm rod-plane gap, breakdown voltage of pure SF₆ is about 3 times higher than that of air, N₂, and CO₂ at pressure of 1 bar. However, as the gas pressure is increased to about 3.5 bar, breakdown voltage of SF₆ is 20% less than that of air. At the pressure of 5 bar, pure SF₆ is 20% higher than that of air. The breakdown voltages of CO₂ and N₂ are lower than that of SF₆. As seen in Figures 3–5, the breakdown voltages of pure N₂, CO₂, and air are increased approximately linear with pressure; however, pure SF₆ has a maximum-minimum breakdown characteristic. The experiments have shown that addition of relatively small amount of SF₆ to air, N₂, and CO₂ causes important increase in dielectric strength. As an example, the breakdown voltage of 0.125 SF₆-air is approximately twice than that of pure SF₆ at pressure of 3.5 bar. Breakdown strength of SF₆-CO₂ is higher than that of other mixtures at the pressure range of 1–3 bar, but SF₆-air mixtures are better at higher pressures. From experimental results, SF₆-air mixtures show less degree of saturation at higher pressure when compared to SF₆-N₂ and SF₆-CO₂ mixtures. Since breakdown phenomena occur in the positive polarity, the breakdown mechanism explanations about AC voltage are related to the mechanism of positive impulse and direct voltage. It is needed to mention the breakdown mechanism to explain the abnormal case. In this study, the electrode gap is of 25 mm. The breaker contact spacings used in practice are in these ranges, and most of them have nonuniform fields. The best model to simulate these nonuniformities is the rod-plane electrode configuration. The contact ranges of the switch-gears vary between 1 and 10 cm according to the nominal voltage and current. However, for GIS, these gaps may be 25–30 cm, but the investigations show that they have the same breakdown mechanism. As is known, there are two types of breakdown mechanisms in gas mixtures. These are Townsend theory and streamer theory. Townsend breakdown mechanism is valid for smaller product of the gas pressure (mmHg) and the electrode gap (cm) of 500 mmHg·cm.

Especially at large electrode gap spacing, Townsend theory is insufficient to explain the discharge mechanism. Streamers in short gaps develop with the increase of the applied voltage until spark takes place. Physical and chemical interpretations can be made about some of the characteristic cases. Maximum-minimum behaviour due to gas pressures is indicated as abnormal discharges in the literature. The reason why breakdown voltage has maximum-minimum characteristics according to the pressure is related to the following situations: nonuniform field, SF₆ gas, positive polarity voltage, or AC voltage. The breakdown voltage increases with the increasing pressure. This is a very normal situation. If the ambient has nonuniform field, SF₆ gas and AC voltage as in our system, variation of breakdown voltage has the maximum-minimum characteristic. Earlier research has shown that the rise time duration of the test voltage increases when the possibility of effective corona stabilization raises. This behaviour is significant for gas pressures of 1 and 2 bar. Also for longer rise time duration and higher gas pressure of 3 bar, the effect of corona stabilization is weak. This means with high gas pressure and the low leader inception voltage, the breakdown strength reduces. This period is the diffusion time of a thermic wave. This wave starts from the high-field electrode system and spreads the whole gap. The temperature rises to as high as 900°K under AC voltages in the ionization region. So it is important to reduce the temperature at this region. The electrical strength rises at point and the spark becomes easily. This theory is investigated as “a narrow jet model” at dc voltage by R. S. Sigmond. As a result, the diffusion and heat convection in the pressure range of 2-3 bar decrease, and the thermal ionization brought by the electron avalanche plays an important role. In this case, breakdown follows the shortest ionized path. The reason of this abnormal breakdown is the opposite effect of ionization and diffusion phenomena related to breakdown voltage. Diffusion is reduced by the pressure increase; this case leads to increase of space charge and electrical strength. This phenomenon causes the breakdown voltage to decrease. Ionization effect is active at positive polarity since heavy positive ions cannot reach the opposite electrode easily, and the positive ions are collected at the tip of the rod electrode, so they shorten the space gap. Diffusion also causes the thermal convection, and the breakdown follows the shortest way between the electrodes. As seen in Figures 3–5, the maximum point shifts to the right as the SF₆ ratio decreases [12]. This is also an abnormal condition in SF₆ gas mixtures for nonuniform fields. Small SF₆ mixtures may fall to a minimum at higher pressures. Ionization and diffusion events are also effective here.

4. Conclusion

The test results show that SF₆ mixtures have an important electrical strength at the pressure range of 1–4 bar according to electrical strengths of pure air, N₂, and CO₂. SF₆ has disadvantage properties particularly between the pressure of 2-3 bar, which is the range of use of electrical devices, but SF₆ gas mixtures have many superiorities compared to pure SF₆. These mixtures are technically and economically attractive

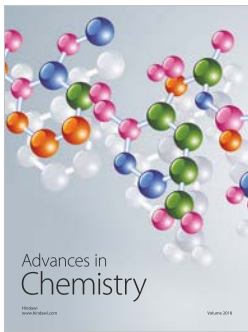
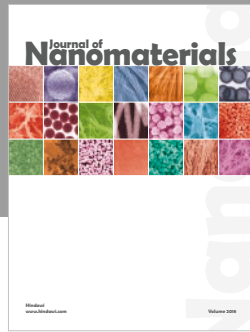
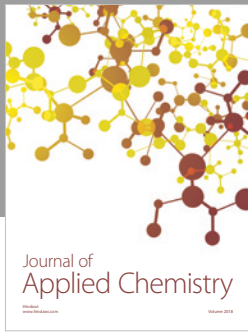
alternatives. These mixtures are cheaper and more environmentally friendly than pure SF₆. It is important to check the chemical decomposition of SF₆ mixture under electrical stress at various mixture ratios. Further studies will focus on decomposition of SF₆ mixtures under pressure at ambient with water vapour and oxygen because at this case decomposition of SF₆ forms as solid state.

Conflicts of Interest

The author declares that he has no conflicts of interest.

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