Chapter 35
Impulse Breakdown Characteristics of CF_3I–CO_2 at Various Gas Pressure and CF_3I Content

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Abstract Sulphur hexafluoride (SF_6) is currently the preferred dielectric gas used in medium and high voltage power equipment. However, due to the extremely greenhouse effect by SF_6, the search for alternative gas comprising a fluoro-organic gas with low environmental concern mixed with a buffer gas (N_2, CO_2 and O_2) have received considerable attention from the power industry. Trifluoroiodomethane (CF_3I) is identified to have an excellent insulation performance with a very low GWP can replace SF_6. This paper presents the basic lightning impulse performance of CF_3I mixed with CO_2 as an alternative to SF_6 insulation gas. The 50% breakdown voltage (U_{50}) under both positive and negative polarities were measured at various gas pressure and mixing ratio of CF_3I–CO_2. The results show that U_{50} of CF_3I–CO_2 gas mixtures increases linearly with the pressure, and the difference increases with gap length. Furthermore, an increment of CF_3I content in the mixtures increases the insulation strength. It was also found that U_{50} with negative polarity is much higher than that with positive polarity under the needle-plane electrode and vice versa under the plane-plane configuration. The *V-t* characteristics for CF_3I–CO_2 were also analysed under these two different electric fields. The *V-t* characteristics for plane-plane electrode are more distributed along the wavetail of the lightning impulse under both U_{50} polarities. As opposed to the *V-t* waveforms under needle-plane electrode, the instantaneous breakdowns tend to happen earlier. Overall, the results provide a basis for considering the application of CF_3I–CO_2 as an insulating gas in high voltage apparatus.

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A. B. Mustapha et al. (eds.), *Proceedings of the 7th International Conference on the Applications of Science and Mathematics 2021*, Springer Proceedings in Physics 273, https://doi.org/10.1007/978-981-16-8903-1_35

35.1 Introduction

Sulphur hexafluoride (SF_6) is widely recognised as the best insulation gas in high voltage apparatus due to its outstanding insulation strength and arc quenching properties. But, the longtime excessive usage of SF_6 may increase the percentage of its global warming potential (GWP) and have an extremely long atmospheric lifetime [1, 2]. For these reasons, limiting the application of SF_6, or eventually replaced it by using alternative gases is necessary for the developed countries such as EU, US and China [3].

Much research in recent years has focused on gases or mixed gas, especially the fluorocarbons with halogenated gases or fluorinated compounds, which have similar or better dielectric strength to that of SF_6. Although some perfluorocarbons (PFCs) and hydrofluorocarbons (HFCs) offer an excellent breakdown strength, their GWP remains high, typically in the range of 5000–12,000 [4, 5]. Their lifetime is also relatively higher than SF_6, thus limiting them from consideration. One of the most promising low GWP alternatives is trifluoroiodomethane (CF_3I). Its GWP is less than 5, and the insulation strength of CF_3I is 1.2 times higher than that of SF_6 [6, 7].

CF_3I is colorless, odorless and non-flammable have considered being an environmentally friendly insulation gas [8, 9]. Due to the high liquefaction temperature, CF_3I needs to be mixed with buffer gases (N_2 or CO_2) that have relatively low boiling point [10, 11]. Thus, the problem of high liquefaction temperature of CF_3I can be avoided and the mixtures could possess identical features like economical cost, good dielectric performance and provide less environmental concerns.

In this paper, the fundamental lightning impulse withstand of CF_3I–CO_2 gas mixtures are measured at a pressure range of 1.0 bar to 2.0 bar. In addition, the effect of various mixture ratios on the insulation performance of CF_3I–CO_2 gas mixtures was also analysed. From this study, as the CF_3I content increased, the dielectric strength is more significant in the plane-plane electrode. Meanwhile, in the needle-plane electrode, the increment in the dielectric properties is noticed only in the small gap length.

35.2 Experimental Arrangement and Method

Figure 35.1 shows the complete block diagram of the test setup. The specific details of the lightning impulse generation, structural of pressure vessel, as well as electrode geometry are described in this section.

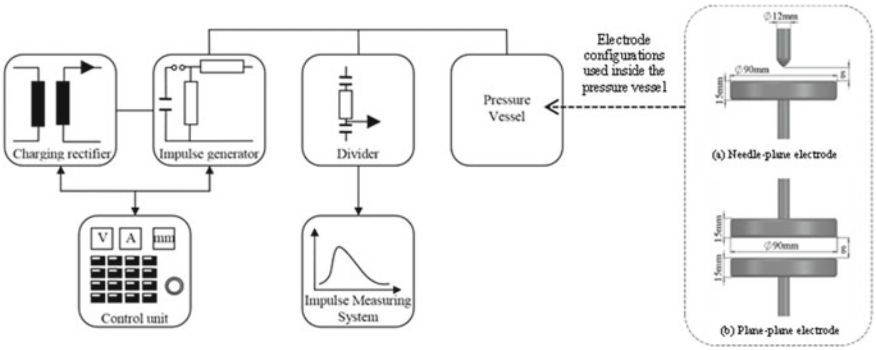


Fig. 35.1 Block diagram of the test setup

35.2.1 Lightning Impulse Test

The impulse voltages were generated by a four (4) stage Marx impulse generator. The maximum output voltage level is 400 kV, delivering 100 kV per stage [12]. The impulse voltage was then measured by a 50 ns rise time capacitive voltage divider and recorded using a digital oscilloscope. The up-and-down method was used to obtain the 50% breakdown voltage (U_{50}) with at least 20 impulse shots for each test condition.

35.2.2 Pressurized Vessel

The cylindrical-shaped pressure vessel was built with a height of 500 mm, having a radius of 250 mm, and a thickness of 10 mm, giving a volume around 0.0982 m^3, or 98.2 L. The main constituent material of the vessel is mild steel, a non-alloy structural steel that can withstand specific high pressure and high voltage stresses. Meanwhile, the vessel window is made of polycarbonate, in which able to observe the experimental phenomena easily.

35.2.3 Electrode Configuration

A needle-plane and plane-plane electrode were used in this study. The diameter of the needle electrode is 12 mm, having a tip curvature diameter of 1 mm, while the diameter of the plane electrode is 90 mm, the thickness is 15 mm, and the chamfer radius is 5 mm. All electrodes are made from brass. The electrodes surface was mirror finished to ensure no effect from protrusion, compromising the test results.

35.3 Result and Discussion

This section focuses on both positive and negative lightning impulse breakdown testing. The effect of various gas pressure and different mixture ratios on the impulse breakdown characteristics of CF_3I–CO_2 were briefly discussed.

35.3.1 *Breakdown Performance of CF_3I–CO_2 Mixture Under Different Pressures*

Figure 35.2 shows the impulse breakdown voltage-pressure relationship of 30%CF_3I–70%CO_2 gas mixture under positive and negative polarity at different gas pressures and various electrode gap distances. The U_{50} of CF_3I mixture increase with the increasing pressure range between 1.0 bar and 2.0 bar (abs). It is noted that the saturation value is approached more gradually at a higher pressure, especially in 5 cm gap under both U_{50} polarities.

The *V-t* characteristics in Fig. 35.3 indicate the positive lightning impulse breakdown properties of CF_3I–CO_2 gas mixtures at the respective pressure range studied. In the case of positive impulse polarity under a non-uniform (needle-plane electrode) configuration, most of the breakdowns appeared around the wavefront duration corresponding to the peak value, less than 8 μs. A closer examination of the results in Fig. 35.3a reveals that the duration of the breakdown voltage at 1 cm gap length under 1.0 bar pressure occurs near the peak value in the region of 1–2 μs. When the gas pressure is changed to 1.5 bar and 2.0 bar, the breakdown voltages are more dispersed throughout the time scale, reach to 6 μs, as shown in Fig. 35.3b, c, respectively. At a pressure of 2.0 bar, shown in Fig. 35.3c, the *V-t* plots for a 4 cm gap is almost similar to that for a 5 cm gap with only 2 kV difference. This behaviour shows the saturation phenomenon under positive lightning impulse at higher pressure and gap length.

Figure 35.4 shows the corresponding *V-t* waveforms of CF_3I–CO_2 mixtures under negative polarity in needle-plane electrode configuration. As observed in Fig. 35.2,

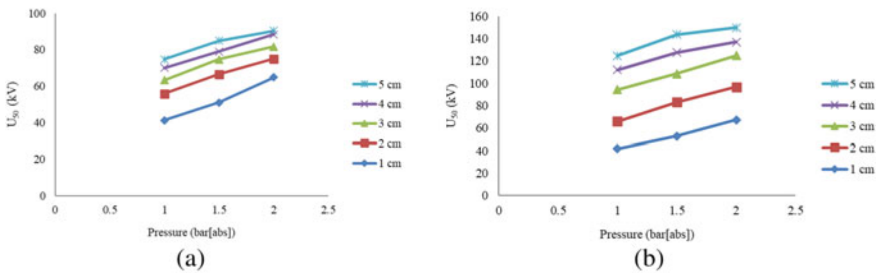


Fig. 35.2 Effects of CF_3I–CO_2 pressures on (**a**) positive, and (**b**) negative breakdown voltages, U_{50}

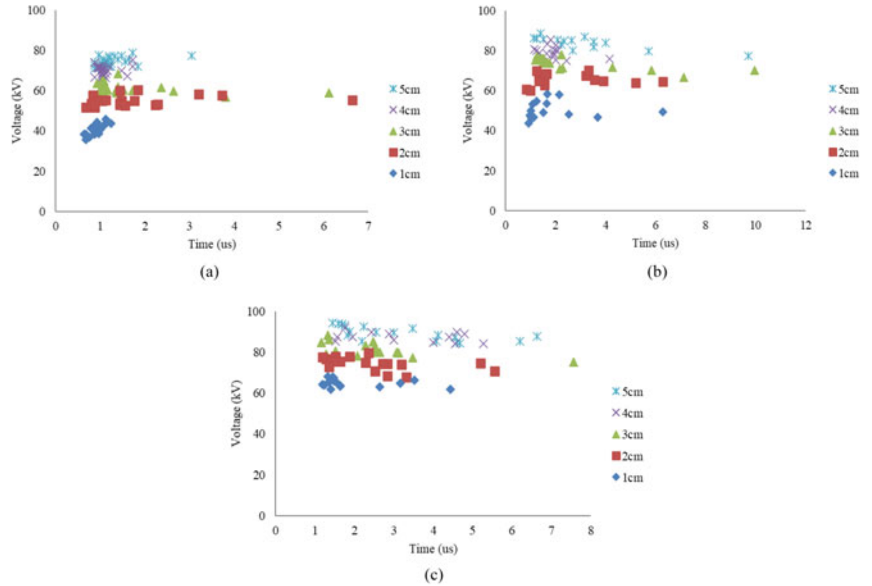


Fig. 35.3 *V-t* characteristics for 30%CF_3I–70%CO_2 under positive impulse at (**a**) 1.0 **bar**, (**b**) 1.5 **bar**, and (**c**) 2.0 bar

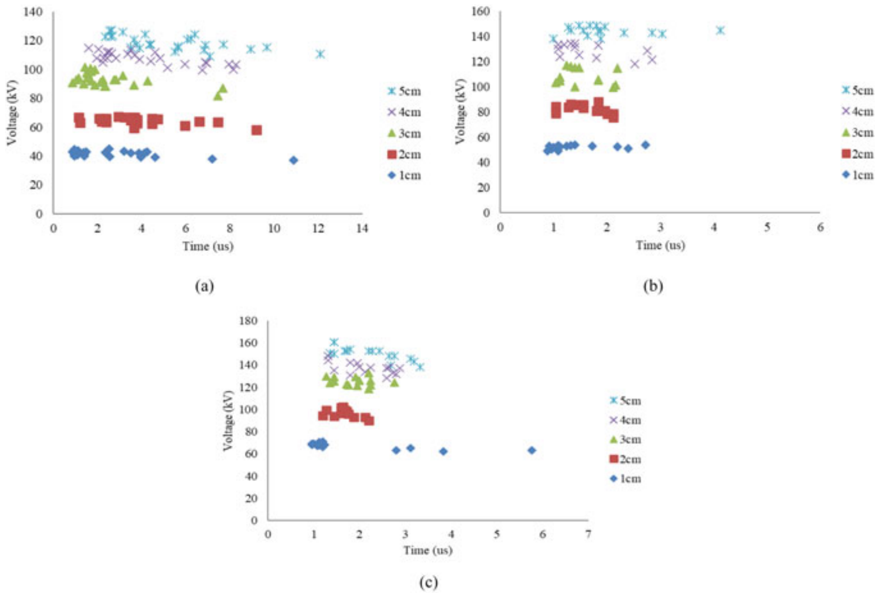


Fig. 35.4 *V-t* characteristics for 30%CF_3I–70%CO_2 under negative impulse at **a** 1.0 bar, **b** 1.5 bar, and **c** 2.0 bar

50% breakdown voltages under negative lightning impulse are significantly higher than those under positive impulses in an expanded range of pressures. The differences in U_{50} increase as the gap increase. Furthermore, the increase rate of U_{50} is more significant over the gap distance between electrodes at all pressures. The increasing trend can be noticed in Fig. 35.4 when compared to Fig. 35.3. A relatively significant time lag was observed at lower pressure of 1.0 bar in the negative impulse under the non-uniform field. However, the *V-t* waveforms at higher pressure are concentrated near the peak value with a duration of less than 6 μs.

35.3.2 Breakdown Performance of CF_3I–CO_2 Mixture Under Different Pressures

Further impulse breakdown tests were carried out for three (3) different mixture ratios, which are 20%–80%, 30%–70% and 40%–60% of CF_3I–CO_2 at a pressure of 1.0 bar. The tests involved two (2) different electrode arrangements, including the needle-plane and the plane-plane configuration.

Effects of CF_3I Content in Needle-Plane Configuration. The breakdown voltage (U_{50}) at different CF_3I–CO_2 gas mixing ratios for various gap distance is plotted in Fig. 35.5. It is noted that the increment of U_{50} is nearly linear with the increasing electrode gap under positive impulse voltage and gradually increase for negative impulse voltage. However, as expected in a needle-plane electrode, U_{50} under the negative impulse is probable to be higher than those under positive polarity. This phenomenon shows that the electron emission from the cathode surface was remarkable at the higher electric field under a non-uniform configuration. Therefore, U_{50} would have the maximum value to initiate a complete breakdown.

The growth trend of U_{50} curves is obvious under negative impulse polarity with the increase of CF_3I content. The comparison can be made between the highest and the lowest concentration of CF_3I in CF_3I–CO_2 gas mixtures. The U_{50} of 40%CF_3I–60%CO_2 mixture is about 21% higher than that of 20%CF_3I–80%CO_2 at a 1 cm gap distance. For the 3 cm and 5 cm gap, U_{50} of the highest CF_3I content is 12 and

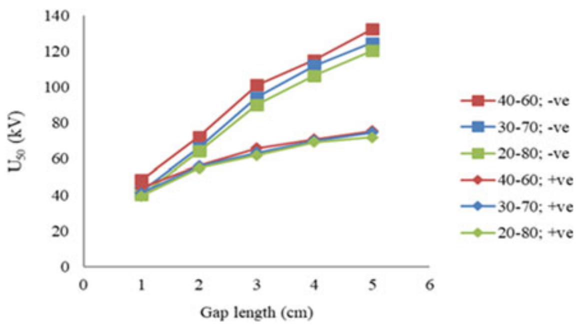


Fig. 35.5 Breakdown voltages at various gap length for different CF_3I–CO_2 mixture ratios in needle-plane electrode

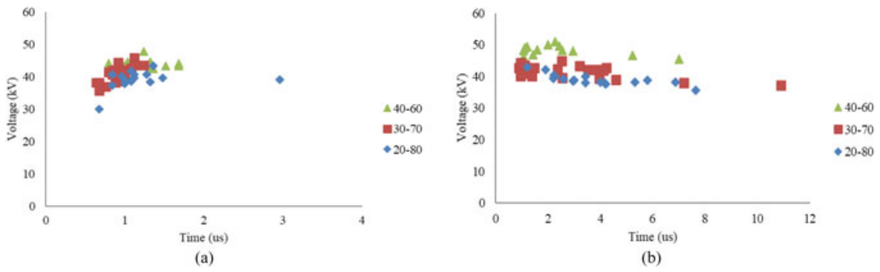


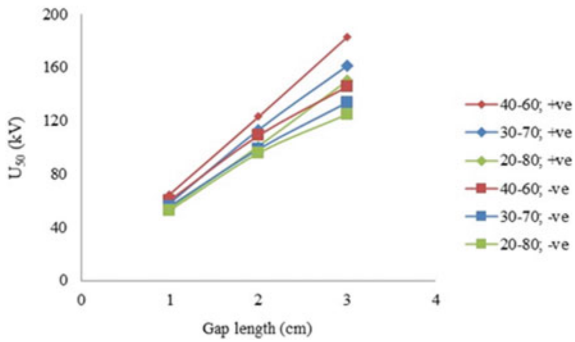
Fig. 35.6 *V-t* characteristics for different $CF_3I–CO_2$ mixture ratios under **a** positive and **b** negative U_{50} in the needle-plane configuration

10% higher. While a slight effect on the positive impulse breakdown voltages can be seen when changing the proportion of CF_3I electronegative gas from 20 to 40% in $CF_3I–CO_2$ mixtures. There is only 11% increase of U_{50} at 1 cm gap, 6% at 3 cm gap, and 5% at 5 cm gap distance. From the result, the effect of CF_3I content in the $CF_3I–CO_2$ mixtures was noted on smaller gaps under both polarities.

Figure 35.6 shows the *V-t* plots of $CF_3I–CO_2$ under non-uniform field electrode at 1 cm gap for both positive and negative standard lightning impulse. As mentioned in previous discussion, the breakdown voltages under a positive polarity tend to happen earlier, near the peak value in the range of 1–2 μs under 1.0 bar gas pressure. This occurrence can be seen for all $CF_3I–CO_2$ mixing ratios shown in Fig. 35.6a, caused by the developing speed of discharge under a non-uniform electrode configuration. Under the negative polarity, the duration of the instantaneous voltages is longer and more scattered along the negative U_{50} wavetail shown in Fig. 35.6b. Among the three mixture ratios of $CF_3I–CO_2$, the *V-t*-plot for $40\%CF_3I–60\%CO_2$ gas mixture is the highest under both impulse polarities.

Effects of CF_3I Content in Plane-Plane Configuration. The effect of CF_3I content in $CF_3I–CO_2$ mixtures was further observed under a more uniform electric field, which represents by the plane-plane electrode configuration. The tests involved gap lengths between 1 and 3 cm. Based on the data demonstrated in Fig. 35.7, the standard

Fig. 35.7 Breakdown voltages at various gap length for different $CF_3I–CO_2$ mixture ratios in plane-plane electrode



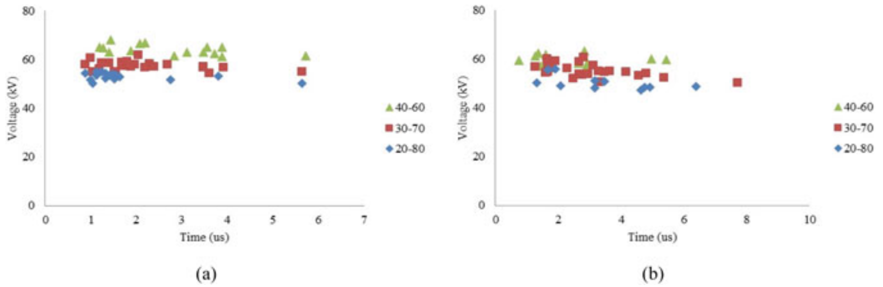


Fig. 35.8 *V-t* characteristics for different CF_3I–CO_2 mixture ratios under **a** positive and **b** negative U_{50} in the plane-plane configuration

impulse breakdown voltages (U_{50}) under a uniform electrode contrast from those under a non-uniform electrode, which means the U_{50} with positive standard lightning impulse is higher. In all mixtures, U_{50} values increase linearly with increasing the gap distance between electrodes.

Furthermore, it is noted that a slight increment in U_{50} between positive and negative impulse polarity when CF_3I content was increased. Under positive polarity, the relationship between U_{50} and the gap length at different mixing ratios of CF_3I–CO_2 is almost linear. An increase from 20 to 40% of CF_3I in the mixture shows significantly less changes for the slope of the U_{50}. About 20% increase of U_{50} at 1 cm gap, 22% at 2 cm gap, and 22% at 3 cm gap distance. A smaller percentage difference in U_{50} also can be found under negative polarity while varying the proportion of CF_3I content in the mixture. The U_{50} of 40%CF_3I–60%CO_2 mixture is higher than 20%CF_3I–80%CO_2 about 15% at a 1 cm gap, 12% and 10% at a corresponding 3 cm and 5 cm gap.

Figure 35.8 shows the *V-t* waveforms at 1 *cm* plane-plane electrode gap for both lightning impulse polarities. In contrast to the non-uniform electrode arrangement, the instantaneous breakdowns in a more uniform field electrode are more distributed along the wavetail time duration under both positive and negative polarity. Among all mixture ratios, the *V-t* characteristic for CF_3I–CO_2 at 40%–60% remains highest similar to the *V-t* plots in the needle-plane electrode.

35.4 Conclusion

The dielectric strength of CF_3I–CO_2 mixtures is significant at higher pressures. The 50% breakdown voltages, U_{50} for both lightning impulse polarities increase over the pressure range under the plane-plane and the needle-plane electrode arrangement. When the gap between the electrode is varied, U_{50} of CF_3I–CO_2 mixtures shows the same increment trend as the change in pressure. Furthermore, the increment in CF_3I concentration increase the dielectric strength of CF_3I–CO_2, obviously in the plane-plane configuration compared to the needle-plane configuration. On the other hand, the *V-t* characteristics for $CF_3I–CO_2$ under uniform electric field (plane-plane electrode) are more dispersed along the U_{50} wavetail duration for both impulse polarities. Unlike the *V-t* waveforms under the non-uniform field (needle-plane electrode), the instantaneous voltages tend to occur earlier at the peak value of the wavefront duration. However, in all mixture ratios, *V-t*-characteristic for $CF_3I–CO_2$ at 40%–60% is the highest under both lightning impulse polarities. Overall, the insulation performance of $CF_3I–CO_2$ gas mixtures has been proved and can be considered a possible substitute to SF_6 as a new insulating medium.

Acknowledgements The authors gratefully acknowledge the financial supports from the Ministry of Higher Education Malaysia under the Fundamental Research Grant Scheme Vot No. FRGS/1/2018/TK10/UTHM/02/10 and partially sponsored by Universiti Tun Hussein Onn Malaysia.

References

1. S. Xiao, X. Zhang, J. Tang, S. Liu, A review on SF6 substitute gases and research status of CF_3I gases. Energy Rep. **4**, 486–496 (2018)
2. B. Khan et al., Analysis of the dielectric properties of R410A gas as an alternative to SF for high-voltage applications. High Voltage **4**(1), 41–48 (2019)
3. M.S. Kamarudin et al., CF_3I gas and its mixtures: potential for electrical insulation, in *International Conference on Large High Voltage Electric Systems (CIGRE) Session 45*, 2014
4. X. Li, H. Zhao, A.B. Murphy, SF6-alternative gases for application in gas-insulated switchgear. J. Phys. D: Appl Phys. **51**(15) (2018)
5. H.S. Kharal, M. Kamran, R. Ullah, M.Z. Saleem, M.J. Alvi, Environment-friendly and efficient gaseous insulator as a potential alternative to SF6. Processes **7**, 1–13 (2019)
6. M.S. Kamarudin, M. Albano, P. Coventry, N. Harid, A. Haddad, A survey on the potential of CF_3I gas as an alternative for SF6 in high voltage applications, in *45th International Universities Power Engineering Conference (UPEC)*, 2010
7. X. Zhang, S. Xiao, Y. Han, Q. Dai, Analysis of the feasibility of CF_3I/CO_2 used in C-GIS by partial discharge inception voltages in positive half cycle and breakdown voltages. IEEE Trans. Dielectr. Electr. Insul. **22**(6), 3234–3243 (2015)
8. X. Li, H. Zhao, J. Wu, S. Jia, Analysis of the insulation characteristics of CF_3I mixtures with CF_4, CO_2, N_2, O_2 and air. J. Phys. D: Appl. Phys. **46**(34), 345203 (2013)
9. X. Zhang, S. Xiao, J. Zhou, J. Tang, Experimental analysis of the feasibility of CF_3I/CO_2 substituting SF6 as insulation medium using needle-plate electrodes. IEEE Trans. Dielectr. Electr. Insul. **21**(4), 1895–1900 (2014)
10. S. Zhao, D. Xiao, P. Xue, R. Zhong, Analysis of insulation performance and polar effect of CF_3I/CO_2 mixtures. IEEE Trans. Dielectr. Electr. Insul. **25**(4), 1364–1370 (2018)
11. B. Zhou, D. Tan, J. Xue, F. Cai, D. Xiao, Lighting impulse withstand performance of CF_3I-N_2 gas mixture for 252 kV GIL insulation. IEEE Trans. Dielectr. Electr. Insul. **26**(4), 1190–1196 (2019)
12. T. Wen et al., Discussion on lightning impulse test waveform according to breakdown characteristics of SF6 gas gaps. IEEE Trans. Dielectr. Electr. Insul. **24**(4), 2306–2313 (2017)