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Research paper

Characteristics investigation of R407C in high voltage applications as an alternative to SF_6

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ABSTRACT

The concept of life without electrical power is not possible. All the industrial, domestic zones etc., requires power to operate, which is transmitted by means of overhead high voltage transmission lines from generating stations to sub-stations. In recent, the equipment for handling HV (high voltage) in GIS (gas-insulated switchgear) and GIL (gas-insulated transmission lines) use SF_6 gas with a good dielectric strength, as a medium for equipment isolation and arc cooling/quenching purposes. But SF_6 possess high value of Global warming potential (22,800) and high atmospheric life, in short it's a greenhouse gas which has a direct impact on the environment. However, due to its usage in power industries like china where 70 % emission of SF_6 occurs from industries, therefore, regarding the mentioned drawbacks, R407C with different pressure and mixture ratio of buffer gases like air and CO_2 is analyzed experimentally under high voltage AC and DC breakdown in order to replace SF_6 gas due to less environmental impacts. The Paschen's curve, self-recoverability is given, insulation characteristics and synergistic effect is also calculated in this research work. There is 93.28 % GWP decrease in R407C and atmospheric lifetime is 99.51 % less as compared SF_6.

1. Introduction

Human academic life is not imaginable without electricity. A large part of the population still resides in urban and remote areas, where the gas-insulated systems are widely used for availability of electricity through a high voltage electricity transmission and distribution network. The most excellent gas to be considered for electrical equipment as an insulating and arc quenching medium is Sulfur-hexafluoride (SF_6), which has led to the isolation of gas since its inception thanks to its excellent properties, availability everywhere, low cost, stability and excellent performance [1–4].

But SF_6 has a great capacity to absorb infrared radiation and a long atmospheric life of 3200 years due to which when it is exposed in the atmosphere the infrared radiation towards the earth is reflected back [5]. The reason for several centuries of atmospheric life is due to its resistive nature to photochemical and chemical degradation [6].

According to the fifth assessment report of IPCC WGI, the atmospheric percentage of SF_6 increases gradually. An international agreement, the Kyoto protocol intended to reduce the emissions of CO_2 and greenhouse gases in the atmosphere. In 1977, the protocol declared that SF_6 is one of the major greenhouse gases [7]

SF_6 gas has good properties, such as high dielectric rigidity and the arc cooling capacity due these properties it is considered an ideal gas as insulating medium. It is widely used by the energy producing industry in the GIS gas distribution and transmission network for general circuit protection, arc cooling and circuit interruption. In GIS, general equipment such as circuit breakers, switches, disconnectors and contactors used in the distribution network use SF_6 gas to isolate the equipment or stop the arc. SF_6 gas was also used to isolate high-voltage transmission lines in gas-insulated transmission lines (GIL) [8,9]. SF_6 has a high resistance to decomposition, since it is more electronegative gas. The range is around 800 kV in use, as currently there are no alternatives with the same properties as SF_6 [10,11]. The insulation capability of SF_6 is 3times of air approximately so, SF_6 insulated-equipment size is much smaller than air insulated-equipment's [5].

Ecofriendly SF_6 alternative gases have been extensively studied and

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hypothetical substitutes such as carbon dioxide (CO_2), hydrogen (H2), rare gases (He-Elio, Ar-Argon), nitrogen (N2), oxygen (O2), air, have been selected and their mixtures. The analysis of CO2, air and N2 clarifies that its breakdown voltage was very low compared to SF6 and that a significant increase in the size of the equipment was found. To reduce the environmental impacts and maximize the capability of arc quenching and dielectric strength, mixtures of carbon dioxide (CO_2) or nitrogen (N2) and CF3I were studied and it was concluded that they are toxic to reproduction and have a high liquefaction temperature [2]. The Novec 4710 fluid has been studied in [2], but it is toxic and has a high liquefaction temperature. HFO1234ZEE was studied in place of SF6 and found it toxic [12]. In [13,14] mixtures of carbon dioxide (CO_2) or air were analyzed with C5F10O and C6F12O and their work shows that the liquefaction temperature of these gases is very high and are not suitable as alternatives for SF_6. The alternative [15] has a high liquefaction temperature compared to SF_6. R12 gas and air mixture in a pressure band for the interruption voltage, but the analysis was not detailed. In [16], the author performed an experimental analysis of the R12 gas and the air / N2 mixture and suggested an alternative to SF_6 gas. The R12 molecules contain fluorine, carbon and chlorine, which are highly stable and contribute to the destruction of the ozone layer. In [17] the only disadvantage of R134a was high boiling points. R407C is a mixture of R-22 (23 %), R-125 (25 %) and R-134a (52 %) [18]. R407C is non-toxic, non-flammable and has a boiling point of −43.6 °C. It has a global warming potential (GWP) 1530, an atmospheric life span of 15.65 years and a potential for zero ozone reduction (ODP), its safety classification is A1 according to ASHRAE standard 34 [19].

2. Experimental arrangement

The equipment used in experimental arrangement based on TERCO setup, for AC and DC breakdown of R407C and its mixture with Air/ CO_2 as shown in Figs. 4b and 5b includes control desk, High voltage transformer, Sphere electrodes with diameter of 20 mm, vacuum and pressure vessel, earthing rod, connecting rod, connecting cup. The standard of the procedure followed in experiments is based on IEC60270 [20] (Fig. 1).

2.1. Control desk (HV9103)

The To control and operate the AC/DC high voltage equipment used in experiments performed control desk is used. In this unit all the elements are assembled such as signal and operating components for safety and warning purposes. The measuring instruments displays the AC/DC voltages through peak, DC voltmeters mounted on the control desk. The peak voltmeter measurer up to a range from 100–1000 kV. The input of the desk is 220/230 V, fed to the primary winding of the high voltage transformer. The description of the buttons are given in Table 1.

Fig. 1. Control desk.

Table 1
Button description.

S. No.	Description
1	Main switch
2	Control switch
3	ON secondary
4	OFF secondary
5	ON primary
6	OFF primary
7	Sphere gap Measuring
8	Voltage Regulation

2.2. Test transformer (hv9105)

To The transformer measures from 0–100 kV AC and 0–140 kV DC. The primary winding of the transformer is connected to control Desk, transformer oil (high grade) is used as insulation medium for windings (Fig. 2).

2.3. Vacuum and pressure vessel

The vessel is used to determine the flashover Voltage between the electrodes during the breakdown of the gas. The lower part of the vessel consists of vacuum and pressure gauges, inlet/outlet valve and is at ground potential, the upper part is for high voltage. Plexiglass is the central part of the vessel. The electrodes with diameter of 20 mm were used for the experiments as shown in Fig. 3.

HV9111 is silicon rectifier with a resistance of 100 kV used to rectifier DC voltage and impulse voltage generation, HV9112 is used as a smoothing capacitor for generating DC voltage, measuring high voltage resistor (HV9113) is used for DC measurement, earth switch (HV9114) is for automatic safety earthing purpose.

3. Results and discussion

A detailed discussion for experimental results of AC, DC breakdown voltages, synergistic effects of base gas, CO_2 and Air with different mixing ratios and pressures are included in this section and also self-insulation recovery of base gas.

Before performing the experiments, pressure and gas vessel along with the electrodes were cleaned with wet silk cloth dipped in alcohol and dried-up. After that to prevent the gas to be injected through the inlet valve from leakage the top of the vessel was fixed tightly by means

Fig. 2. Test transformer.

Fig. 3. Vacuum and pressure vessel.

of cylinder key and raised the pressure to the required value to check the breakdown strength the of the base gas and its mixture with Air/ CO_2. The process was repeated for every breakdown but before that the gas was ejected by means of outlet valve.

The breakdown voltage increases with increase in distance between the electrodes, it means that breakdown voltage is dependent on electrodes gap as expressed in Eq. (1)

$$\boldsymbol{E} = \boldsymbol{f} \times \frac{\boldsymbol{V}}{\boldsymbol{D}} \quad (1)$$

Where D is the distance of electrodes, V is applied voltage and f is non-uniformity constant. The schematic and experimental circuits for AC and DC breakdown is shown in Figs. 4(a and b) and 5(a and b).

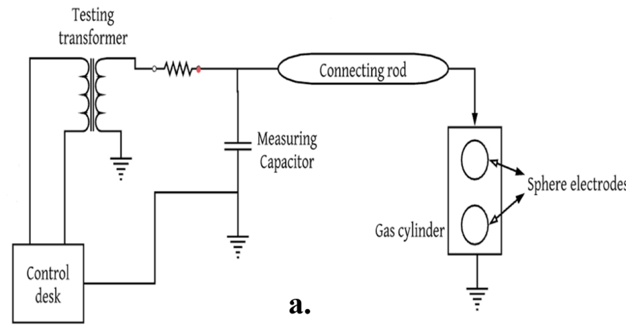
3.1. Breakdown of R407C with air

Generally, gases are considered as perfect insulating medium however by application of electric field ionization process takes place due to gaining of energy by free electrons and free ions. The first ionization coefficient (Townsend's coefficient) termed as α is defined as "the number of production of electrons in the path of a solo electron traveling one centimetre". R407C is an electronegative gas, so negative ions are produced by the attachment of electrons produced to neutral molecule and positive ions are produced by detachment of electrons from molecules. This attachment and detachment is dependent on the field applied. The expression which relates dN, N, α, η and dx is:

$$dN = N\,(\alpha - \eta)dx \quad (2)$$

Whereas, N is the initial number of electrons, dN indicates change initial electrons number, η is coefficient of detachment, dX is variation in distance. The condition for occurring gas breakdown is $\alpha > \eta$.

The AC and DC breakdown characteristics of base gas with Air at different mixing ratios and varying pressure is shown in figures, the mixing ratios in experimental results are (a) 100 % R407C (b) 90 % R407C, 10 % Air (C) 80 % R407C, 20 % Air (d) 70 % R407C, 30 % Air, (e) 60 % R407C, 40 % Air, (f) 50 % R407C, 50 % Air. As shown in Fig. 6. by adding a ratio of base gas to air at any extend, gradually shoots the breakdown strength of air and shows good dielectric properties. The reason behind this breakdown shoot is that R407C gas has high attachment cross section at lower energy levels from 0–0.5 eV. This makes it possible for small amount of R407C to get attached to electrons having low energy, resulting increase in breakdown voltage (Fig. 7).



a.

b.

Fig. 4. AC schematic (a) and experimental (b) circuit.

The comparative analysis on the basis of dielectric strength at different ratios of R407C and air mixture with SF_6 is studied in this section. At 50 psi the breakdown strength of R407C(80 %) and at 40 psi with R407C (90 %) with air(10 %) ratio is 0.87times of SF_6.

At 50 psi and different mixing ratios the DC breakdown strength of R407C (100 %) is 0.86times of SF_6, R407C (80 %/20 %) is 0.87times, R407C (70/30) is 0.813times of SF6. while at ratios of 80/20 % breakdown strength is 1.013times of R407C, 70/30 % is 0.93times of (80/20 %) and at 50/50 % the breakdown strength is 0.83times of 70/30 % ratio.

3.2. Breakdown of R407C with CO_2

The CO_2 is mostly known by ability of good arc quenching properties. It is the most inert and stable gas because of its very low reactivity, its atmospheric presence is 0.04 % and easily available in market, boiling point is −78°C and has unity GWP [21]. The addition of CO_2 to R407C will reduce overall BP and GWP as compared to pure R407C. Experimental analysis shows that by mixing particular ratio of CO_2 with base gas increases the dielectric strength but by adding more ratio breakdown strength slightly changes or approximately remains constant. It is because, at lower energy levels the attachment of electrons is easy and is difficult at higher energy levels and thus the dielectric strength remains constant. According to Fig. 8. the best dielectric strength can be achieved at R407C/ CO_2 (70/30 %) at 50 psi that is 0.85 times of SF_6 and at 80/20 % from 20–45 psi is 0.80–0.85 depending upon experimental setup and environmental conditions. As from Fig. 8. the breakdown voltage at different mixing ratios(90 %/10 %, 80 %/20 %, 50 %/50 %) show good results, but at R407C with CO_2 (70 %/30 %) ratio by keeping the pressure range from 40–50 psi the breakdown strength is 0.8–0.86times of SF6.

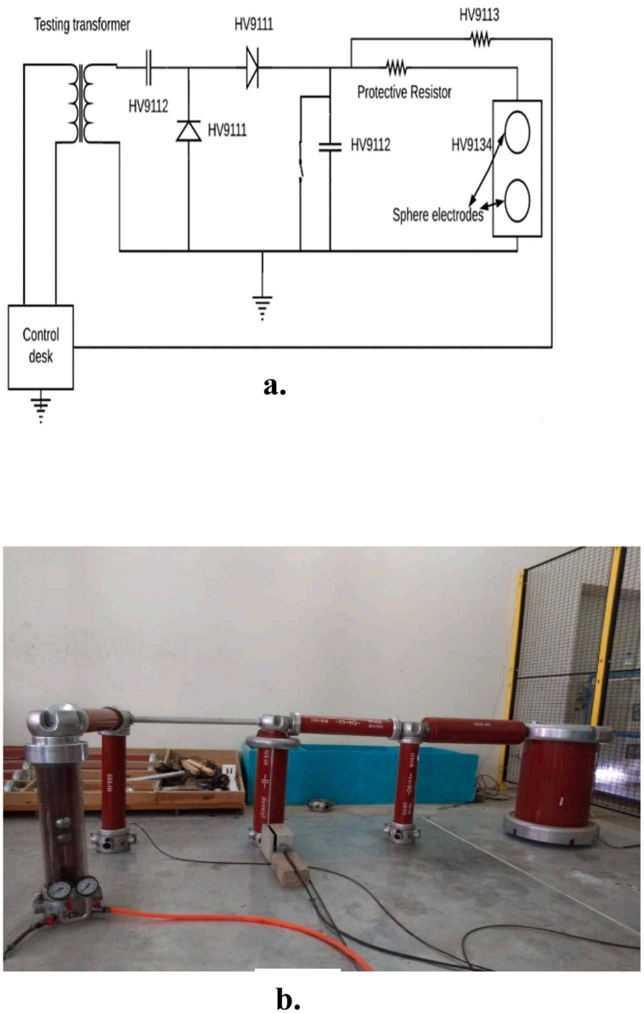


Fig. 5. DC schematic (a) and experimental (b) circuit.

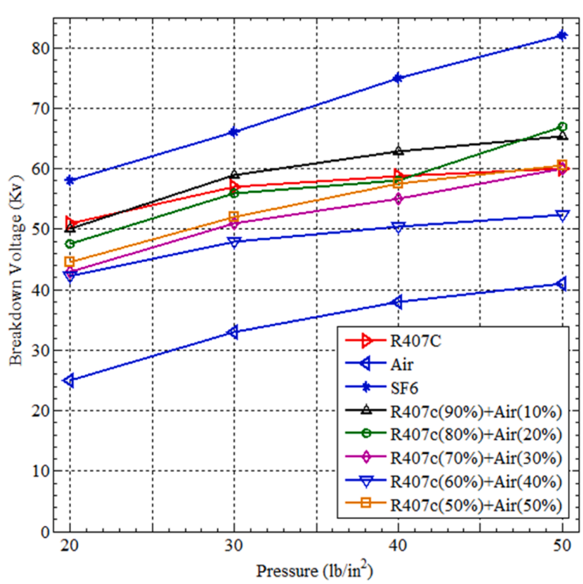


Fig. 6. AC Breakdown voltage of R407C and air mixture with 6 mm electrodes gap.

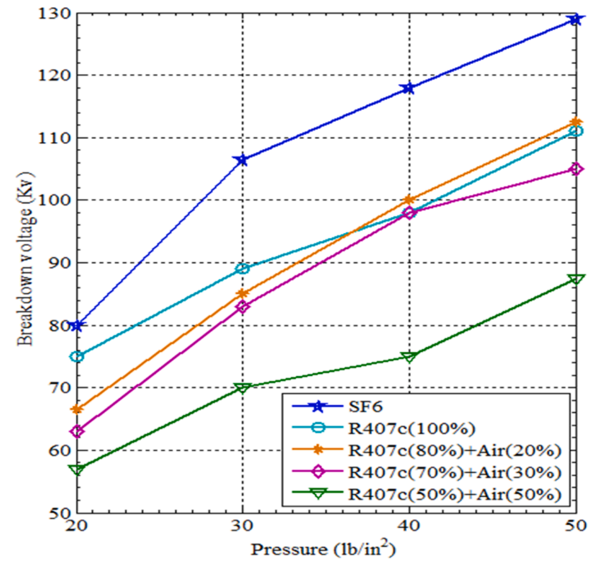


Fig. 7. DC Breakdown voltage of R407C and air mixture with 6 mm electrodes gap.

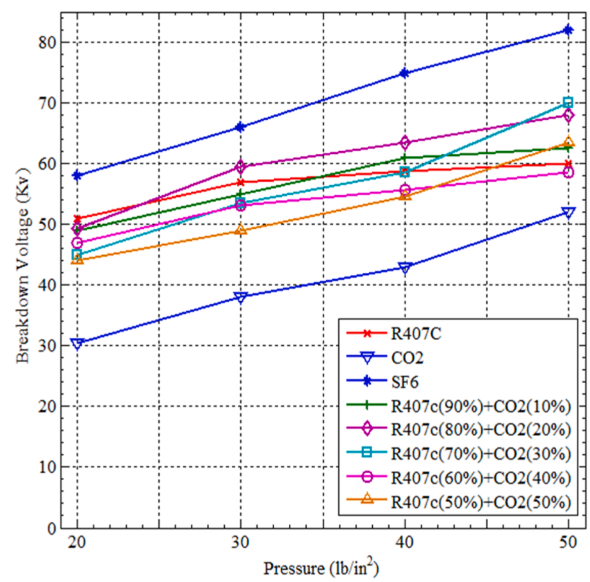


Fig. 8. AC Breakdown voltage of R407C and CO_2 mixture with 6 mm electrodes gap.

For DC generation from 0 to 140 kV, Grienacher voltage Doubler circuit is used. The DC characteristics in Fig. 9. shows good dielectric properties at 80 %/20 % mixing ratio. The breakdown strength of R407C (80 %) with CO_2 (20 %) by varying the pressure from 20, 30, 40, 50 psi is 1.03, 1.1, 1.07 and 1.04times of pure R407C respectively. This shows better results because of greater dielectric strength than pure base gas in comparison to SF_6. While at same ratio and pressure 20–50 psi, the dielectric strength is 0.89 – 0.96 times of SF_6.

3.3. Paschen's curve

Paschen's law was discovered by friedrich paschen in 1889, in which he showed the relation of the product of pressure (P) and gap length of the electrodes (D) over the breakdown voltage and the relation is graphically known as paschen's curve [22]. In paschen's curve, voltage is a function of the product of pressure and distance between electrodes. If the pressure is kept constant and decrease/increase the gap length or

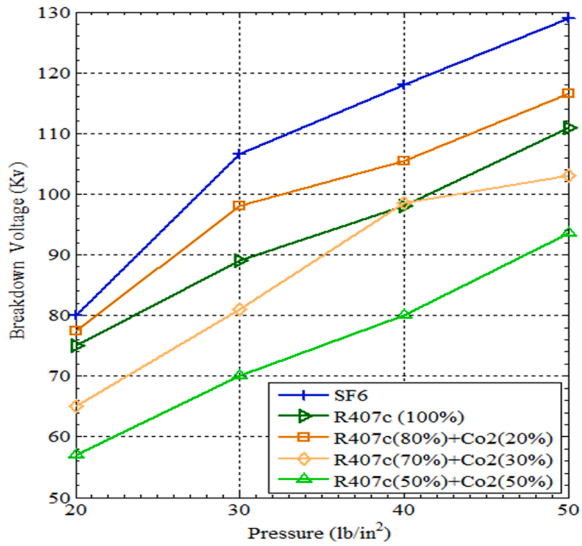


Fig. 9. DC Breakdown voltage of R407C and air mixture with 6 mm electrodes gap.

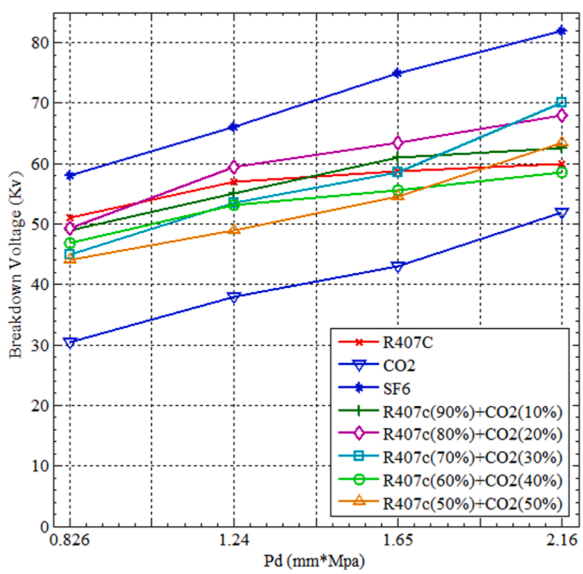


Fig. 10. Paschen's curve of R407C and CO_2.

vice versa, the breakdown voltage will also decrease/increase with variation in gap length and pressure Figs. 10. and 11. shows the paschen's curve characteristics of base gas with different mixing ratios for the product of varying pressure(P) and gap length(D) whose range of values are in between 0.826–2.16 (mmMPa).

Theoretically, for ideal gas the breakdown voltage appears to be linear, however the experimental arrangement for electrodes were sphere-sphere in this research and the breakdown voltage increased with increase in pressure and gap length but steadily the slope decreased. This decay in slope shows deviation to paschen's law.

3.4. Self-recovery

Self-recoverability means the dielectric gas/medium when exposed to over voltages and high temperature, the medium regains its original properties of insulation instead of damaging. The self-recoverability tests were performed by the same experimental circuit as for the power frequency breakdown voltages, 18–20 shots of breakdown were

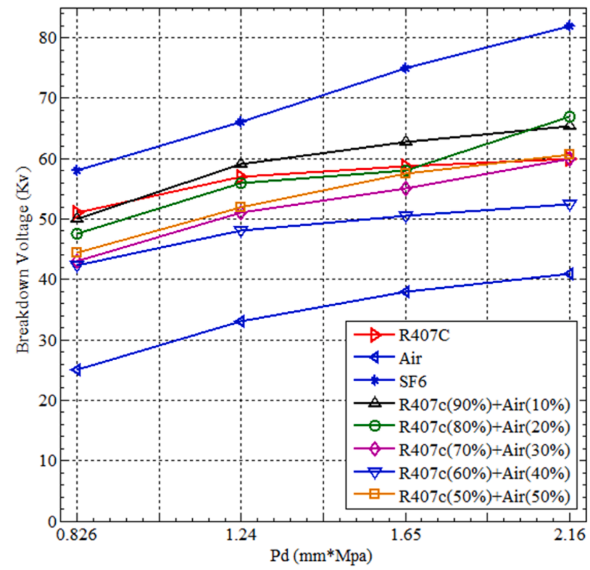


Fig. 11. Paschen's curve of R407C and air.

performed with a delay of one minute to check the insulation recoverability of the base gas. Up to 10–12 shots, a minor decay in the breakdown voltage was observed, but after 12th shot the decay was significant as shown in Fig. 12. The reason behind this decay is the formation of carbon deposits on the surface of both sphere electrodes. So, the presence of carbon deposit incurs breakdown of the insulator, as carbon is a good conductor of electricity. The usage of R407C in HV applications is limited due to this drawback but can be compensated by applying methodologies provided in literature.

3.5. Insulation characteristics of R407C and its mixture with air and CO_2

The experimental data is analyzed mathematically based on standard deviation, mean and coefficient of variation to show the variability of the achieved results. The insulation characteristics of R407C and mixtures with air/ CO_2 are given in Tables 2 and 3 respectively. In the tables, values of Standard Deviation (SD), Coefficient of Variation (CV) and Mean (μ) from the experimental results are given. The SD shows the variation of data from its μ.

Table 3 shows the insulation characteristic of R407C and CO_2. We

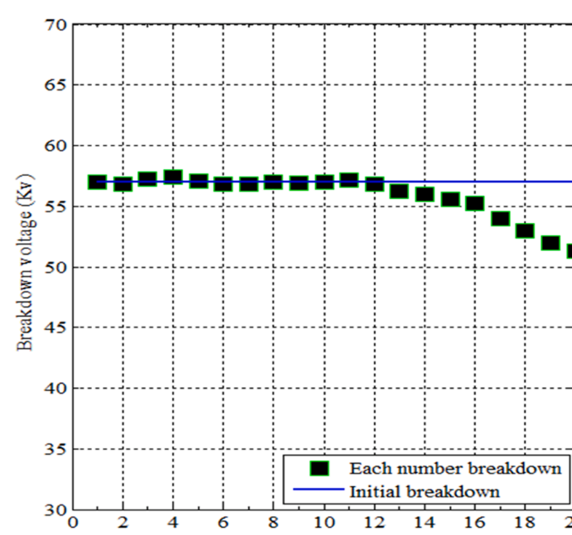


Fig. 12. Self-recoverability of R407C.

Table 2
Insulation characteristics of R407C and air mixture.

BG	R407C				
MG	Air				
BGR	**50 %**	**60 %**	**70 %**	**80 %**	**90 %**
SD	**7.06**	**4.40**	**7.18**	**8.00**	**6.71**
M	**53.65**	**48.27**	**52.25**	**57.12**	**59.28**
CV	**0.131**	**0.091**	**0.137**	**0.140**	**0.113**
Max (kV)	**60.6**	**52.4**	**60**	**67**	**65.35**
Min (kV)	**44.5**	**42.25**	**43**	**47.5**	**50**

BG(Base gas); MG(Mixed gas); BGR(Base gas ratio); SD(Standard deviation); M (Mean); CV(Coefficient of variation).

Table 3
Insulation characteristics of R407C and CO_2 mixture.

BG	R407C				
MG	CO2				
BGR	50 %	60 %	70 %	80 %	90 %
SD	8.35	4.96	10.44	7.93	6.19
M	52.75	53.57	56.75	60.09	56.86
CV	0.158	0.092	0.184	0.132	0.108
Max (kV)	63.5	58.6	70	68	62.5
Min (kV)	44	46.9	45	49.39	48.95

BG(Base gas); MG(Mixed gas); BGR(Base gas ratio); SD(Standard deviation); M (Mean); CV(Coefficient of variation).

can analyze that R407C with CO_2 (60/40 %) provides us with the smaller value of standard deviation which can displays that here is a quick change occur in the values. The tables provide the calculated values for various proportion. In Table 2, the standard deviation of R407C and air (60/40 %) gives the lowermost value which gives an abrupt change in the value.

3.6. Synergistic effect

The mixing of gases show non-linear behaviour and this behaviour is used to define the synergistic effect. Basically synergistic effects are of four types (a) positive synergistic effect (b) negative synergistic effect (c) synergistic effect (d) linear relation effect. The effect that exists by mixing two or more gases which shows greater breakdown strength than the individual one is known as positive synergistic effect, and if the breakdown strength is less than the individual gas is the negative synergistic effect. The relation of synergistic effect index with various parameters are expressed in Eq. (3).

$$\boldsymbol{V}_m = \frac{\boldsymbol{K}(\boldsymbol{V}1 - \boldsymbol{V}2)}{\boldsymbol{K} + (1-\boldsymbol{K})\boldsymbol{C}}\boldsymbol{V}1 > \boldsymbol{V}2 \tag{3}$$

Mixed gases breakdown voltage is denoted by V_m, V1 and V2 are the voltages of base gas and mixing gas respectively, K is the mixing ratio and C is the synergistic effect. The C value indication is given below,

- $C > 1$ shows negative synergistic effect.
- $C < 0$ indicates positive synergistic effect.
- $C = 1$ is linear synergistic effect.
- $0 < C < 1$ gives synergistic effect.

Table 4
Synergistic effect of R407C and CO_2.

Pressure (Psi)	K (%)					
	0.5	0.6	0.7	0.8	0.9	
20	−1.9	−0.24	−0.41	−0.07	−0.10	
30	−1.74	−0.25	−0.22	0.11	0.004	**C**
40	−1.28	−0.26	−0.01	0.23	0.12	
50	0.31	−0.21	0.56	0.5	0.24	

Table 5
Synergistic effect of R407C and air.

Pressure (Psi)	K (%)					
	0.5	**0.6**	**0.7**	**0.8**	**0.9**	
20	−0.04	−0.49	−0.45	−0.15	−0.04	
30	−0.26	−0.61	−0.33	−0.05	0.07	**C**
40	−0.06	−0.67	−0.22	−0.05	0.16	
50	−0.02	0.91	−0.11	−1.03	−1.89	

Synergistic effect of base gas with Air/CO2 are given in Tables 4 and 5 respectively

The standard breakdown voltage for a 1 cm air gap is approximately 30 kV under normal atmospheric conditions. For comparison, SF_6 (sulfur hexafluoride) gas typically exhibits a breakdown voltage of around 500 kV with a corresponding current level reaching up to 30 kA, depending on the electrode configuration and pressure. In contrast, R407C demonstrates a breakdown voltage exceeding 750 kV with a discharge current above 3 kA under similar testing conditions. These values indicate that R407C has the potential to withstand higher voltages while maintaining a reasonable current interruption capability, making it a promising candidate for high-voltage applications [23,24]

R407C is a non-ozone-depleting hydrofluorocarbon (HFC) refrigerant blend, primarily used in air conditioning and refrigeration systems. Although it was originally developed for cooling purposes, recent research suggests that R407C could serve as an environmentally friendlier alternative to SF_6 in gas-insulated switchgear (GIS) and other high-voltage insulation systems. Its favorable dielectric strength, combined with lower global warming potential (GWP), makes it a strong contender in the move toward sustainable high-voltage technologies [25,26]

4. Conclusion

Without any doubt SF_6 is the most useful gas, since the day, the world has known about its excellent properties and increased its usage in high voltage applications due to outstanding dielectric strength. But on the other hand, it is considered as a greenhouse gas because of its high GWP, long atmospheric life and high environmental impacts which makes it bounded within some limits to be used. So the environmental organization demands the need of an alternative to SF_6. In this research R407C is the proposed alternative to SF_6 whose high Boiling points/liquefaction temperature were reduced by adding a very low boiling points/liquefaction temperature gas, so in this case CO_2 is mixed with the base gas and it also incorporated low GWP.

Basically, the main concern regarding this research is to check the breakdown strength of R407C and its mixture with Air and CO_2 as a sustainable alternative to SF_6 gas in high voltage applications. The breakdown characteristics of power frequency voltage under uniform quasi E.field lies in following order: SF_6>R407C>CO2>air. The dielectric strength of (a) R407C/Air (b) R407C/ CO_2 were 0.85–0.90 times of SF_6. Self-recoverability test of base gas showed excellent and also better synergistic effect results were provided by mixed gases compared to base gas

Author agreement

We the undersigned declare that this manuscript is original, has not been published before and is not currently being considered for publiccation elsewhere.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

CRediT authorship contribution statement

Imad M. Khattak: Writing – original draft, Project administration, Methodology, Conceptualization. **Faisal Khan:** Supervision, Data curation. **Syed Zulfiqar Ali:** Writing – review & editing, Supervision, Resources. **Rahmat Ullah:** Validation, Formal analysis, Data curation. **Irshad Ullah:** Funding acquisition, Formal analysis, Data curation, Conceptualization. **Muhammad Adeel Khan:** Conceptualization, Data curation, Validation. **Khalid Rehman:** Visualization, Validation, Funding acquisition. **Aftab Zaman Awan:** Investigation, Funding acquisition, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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