Alternative Insulating Gases to SF_6: A Short Review

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Abstract

The present paper undertakes the study of sulfur hexafluoride (SF_6) as an insulating gas. SF_6 is a modern technology gas, with the extraordinary ability to instantly "extinguish" electric arcs, thus it is mainly used in the equipment of electricity generation, transmission and distribution grid, but it can also be used in a multitude of other kinds of applications. Despite its many advantages, the use of SF_6 also comes with some serious negative effects and it is important to be restricted. For instance, it is the gas that contributes the most to the "greenhouse effect" and it has a significant impact on global climate change. After the presentation of the gas and the applications in which it is used, reference is being made to the problems caused by its use and there will be a presentation of some other insulating gases that can be used as alternative solutions.

Keywords

Insulating gas, sulfur hexafluoride, electrical grid, circuit breaker, greenhouse effect, toxic by-products, alternative gases

Introduction

Sulfur hexafluoride (SF_6) is an electronegative gas which is appropriate for switchgear. Its ability to extinguish arcs is remarkable and this is the reason why it is widely used in the high voltage industry. More precisely, SF_6 used in substations, in gas insulated switchgear (GIS), in high voltage cables as well as insulating gas in electrostatic machines [1]. It was discovered by the Nobel prize winner in Chemistry Henri Moissan [2]. Its synthesis is obtained with the reaction of F with S. During this reaction other substances in smaller quantities are also obtained, such as S_2F_{10} and SF_4. Such substances, in contradistinction to SF_6, are toxic and they must be removed. Sulfur hexafluoride can be stable without any decomposition in its molecular structure up to 500° C, it is not flammable and it does not react with H_2O or Cl. The density of SF_6 is about 6kg / m^3 under normal temperature and pressure and this renders the aforementioned gas five (5) times heavier than air. Its specific thermal conductivity is three (3) times higher than that of the air. Consequently, SF_6 has an excellent cooling capability. Sulfur hexafluoride is under normal conditions non-toxic, chemically inert and stable. Both S and F are electronegative chemical elements and subsequently free electrons are attached to SF_6 creating thus negative ions SF_6^-. Such ions are heavy, moving slowly and thus they render ionisation more difficult, increasing in this way the breakdown strength of SF_6. In other words, the molecules of SF_6 render the phenomenon of electron avalanche slower. The dielectric strength of SF_6 is three times higher than that of the air under normal pressure [3].

Most of the byproducts – after a breakdown or arcing – do not degrade the dielectric strength of SF_6 and can be easily removed. During arcing there is no polymerisation with carbon or other conducting byproducts. SF_6 is compatible with most insulating and conducting materials. Its dielectric constant at 1.0133 bar is 1.0021 at 200° C, whereas with a pressure of 20 bar the dielectric constant increases by 6%. The dielectric strength of SF_6 follows Paschen’s law (i.e. with the breakdown voltage being dependent on the function of pd, where p is the gas pressure and d is the gap spacing in a homogeneous electric field) [4, 5]. Another advantage of SF_6 is its cooling ability with its time for the extinguishing of an arc being 100 times lower than that of air.

The usefulness of SF_6 is not limited to the electrical industry. In the metallurgical industry SF_6 acts as protective inert gas in order to prevent re-ignition of magnesium, to help in removing pollution and gases such as hydrogen (H_2) in the case of aluminium production, to the production of semiconductors (dry etching), in medicine (eye surgery as well as in ultrasound applications), in housing and in oceanography.

Regarding the electrical industry, 80% of SF_6 is used for the generation and transmission of electrical power. Its wide use includes switchgear (GIS) up to several hundreds of kV since it prevents the formation of arcing [6, 7]. Its thermal conductivity together with its speedy recovery of dielectric strength after arcing renders it suitable for switching devices. Such properties allow the size reduction of GIS in comparison to AIS. Its electronegativity gives the SF_6 GIS the capability of absorbing the energy of the electrons in case of arcing and thus to decrease the temperature of the arc. SF_6 can also recover easily and quickly its dielectric strength, consequently it is an ideal medium for quenching the arc. The total space required for a GIS with SF_6 is only a fraction of that required by a GIS with air [3, 4, 8].

SF_6 is also used in Gas Insulated Transmission Lines (GITL), where it is used, among others, as insulating medium in high density populated industrial areas. GITL offer high transmission ability, low losses, low capacitance, low external magnetic field, non-flammability, reliability, compact solutions in case of high density areas, no interference in telecommunication systems. On the other hand, some disadvantages are the high cost of such a line, the limited length, the danger of pollution from particles which diminishes the insulating capability. The cost at the moment is 6 to 8 times higher than that of conventional lines. A solution to that is the replacement of SF6 by a mixture of SF_6 and nitrogen, which is cheaper [9]. GITL are used mainly for shorter transmission lengths since they can be deformed because of the change in volume (and consequently of pressure). An alternative is also the replacement of SF_6 with air of high quality and high pressure.

SF_6 is also used in transformers, where it may replace the oil. Because of its non-flammability it is preferred (besides its high dielectric strength, its compatibility with solid insulation and its cooling capability). In transformers, the lower noise, the lower cost of maintenance, the higher expected lifetime, the high reliability, are the significant advantages. On the other hand, its effect on the environment and its lesser thermal capacity than the oil, are distinct disadvantages [10 - 12].

Problems in the use of SF_6

When an electric discharge occurs a part of SF_6 decomposes in lower chemical substances which in turn give some chemical byproducts. The probable formation of byproducts such as SF_4, SF_2, S_2F_{10}, SO_2, $S_2O_2F_{10}$, HF, SOF_2, SOF_4, SO_2F_2, SOF_{10}, and H_2S is well established. Some of these byproducts are toxic, e.g. S_2F_{10}. The latter is due to the reaction

$$SF_5 + SF_5 \rightarrow S_2F_{10}$$

where, SF_5 is formed from the decomposition of SF_6 as a result of the collision with electrons. Minute quantities of SO_2F_2 and S_2F_{10} may cause severe health problems to humans [13].

Furthermore, byproducts of SF_6 are related to the greenhouse effect. Greenhouse gases are gases that absorb part of infrared radiation from the earth and they return it to the earth. Such gases appear either in the natural environment (e.g. H_2O, CO_2, CH_4, N_2O) or they are artificial products such as SF_6 and products of fluorinated compounds (FFC) as well as reaction products such as CO_2, nitrogen, and sulphur oxides. The trapping of infrared radiation from the gases and the re-emission rises the earth temperature. The re-emission of infrared radiation back to earth has as consequence the rise of temperature. One of the man-made re-absorptions is leakage of SF_6 from substations and from the metal industry [14].

In a period of 100 years, SF_6 is 23000 times more efficient in trapping infrared radiation than an equivalent quantity of carbon dioxide (CO_2). SF_6 may be emitted and accumulated in the atmosphere and may affect the climate change for many centuries (the lifetime of SF_6 in the atmosphere is more than 3000 years). Since it is not easily decomposed, its contribution to the rise of temperature of the earth may be cumulative and permanent. Leaks of SF_6 may come from the electrical industry, from substations, from testing of electrical equipment etc. [15 - 18].

The situation today - Alternative proposals

Substations and related systems continue to use SF_6. Researchers from Bristol confirmed significant increases of the said gas since 1995 from 3.5 ppt per trillion to 10.5 ppt per trillion in 2021 [17]. It is true that SF_6

concentration is still small compared with that of CO_2. Its concentration, however, is expected to increase until the year 2030. Another worrying aspect is that SF_6 is a gas that cannot be decomposed or destroyed by physical means. The fact that SF_6 is still be used is that there are very strong reactions from the electrical industry. Another reason is that there are not still in sight alternative solutions to the use of the SF_6.

SF_6 was first used as insulating medium for switchgear in 1938 by Grosse. Westinghouse Electric Co. was the first to manufacture SF_6 switchgear for the 115 kV network [19]. From then on the said gas was used in various types of electrical equipment as insulating medium. It is still a widely used gas because of the properties mentioned above. As alternatives to SF_6, mixtures of the said gas with nitrogen (with 50%-60% SF_6) were used. The dielectric strength of the mixture may reach 85-90% of the dielectric strength of the pure SF_6. It was shown that an 800 kV transmission line using this mixture costs only 21% of the cost when pure SF_6 is used. Mixtures of SF_6 with air, N_2O, N_2, CO_2 were also tried [20]. A transmission line with a mixture of SF_6 /N_2 was used in the beginning of this century in Geneva, Switzerland. Efforts were also made to use the above mixture in a 420 kV line in France, where the percentage SF_6 in the mixture was reduced by 30% [21]. Such mixtures are also tried in DC systems, the main counterargument being that in DC conditions metallic particles may play in even more crucial role in the degradation.

Such a mixture of SF_6 with other gases may well offer a solution w.r.t. the satisfactory functioning of electrical equipment and may reduce the use of SF_6 to a significant degree but its use cannot be totally excluded. Consequently, various researchers tried to propose gases with similar characteristics which may not be detrimental to the environment. Given the electronegativity of SF_6 efforts were made so that the alternative gases preserve this characteristic without the toxicity.

Devins studied the breakdown voltage of several electronegative gases, such as CF_4, C_3F_8, C_4F_{10} and C_2F_6. These fluorocarbons are stable and electronegative. Regarding their insulating properties the above gases are classified with the following order $C_6F_{14} > C_4F_{10} > C_3F_8 > C_2F_6 > CF_4$ [22]. The problem with the above gases is that they are also included in the gases whose use must be limited according to Kyoto protocol because of their global warming potential (GWP).

The gas CF_2Cl_2 has dielectric strength similar to that of SF_6 whereas the mixture CF_2Cl_2-CO_2 has insulating properties similar to CF_2Cl_2-N_2 but it differs considerably from the mixture SF_6-CO_2 [21]. Towards the end of the nineties with the greenhouse effect to having worsened, attention was paid to perfluorocarbons (PFC) and hydrofluorocarbons (HFC) because of their remarkable insulating properties [23]. By the end of the last century but also earlier, the physico-chemical and insulating properties of the pure c-C_4F_8 were studied. With a uniform electric field, the aforementioned gas presented 1.18 to 1.25 times higher dielectric strength than SF_6. Such a mixture, however, cannot be used in high altitudes because of its high temperature of liquefaction [24]. Research efforts were made with other combinations, such as c-C_4F_8/N_2, c-C_4F_8/air, and c-C_4F_8/CO_2 regarding their insulating properties thus finding that they have higher dielectric strength than the mixture SF_6/N_2 with a uniform electrode arrangement [25].

Yet research on c-C_4F_8 with gases such as N_2, CO_2, N_2O, CHF_3 and CF_4 revealed that the dielectric strength of the mixtures c-C_4F_8/N_2, c-C_4F_8/CO_2 and c-C_4F_8/CF_4 increases linearly with increasing percentage of C_4F_8. The best mixture analogies of the c-C_4F_8/CO_2 and c-C_4F_8/N_2 are 10% and 20% respectively regarding the AC dielectric strength. With respect to the insulating properties the classification of the above gases is

c-C_4F_8/N_2 > c-C_4F_8/CHF_3 > c-C_4F_8/CO_2 > c-C_4F_8/CF_4

with the remark that c-C_4F_8 renders sedimentation of the carbon atoms unavoidable during discharge diminishing thus the insulating properties of the mixture [26]. Work was done on c-C_4F_8/N_2 with different pressures and different electrode distances. The inception voltage for the pure c-C_4F_8 is about 1.3 times higher than that of SF_6. c-C_4F_8 and N_2 show that they have a sort of synergistic effect when mixed together [27].

Relatively recently it was shown that in tests with switchgear of 145 kV a mixture of C_4F_7N/CO_2 in analogy of 18-20% could obtain the same dielectric strength as the pure SF_6. Experiments with AC voltages as well with impulse voltages showed that the above mixture presented satisfactory electrical behavior. An important point that was emphasized is that the above data are valid for uniform and quasi-uniform electric fields but not for non-uniform fields. This implies that attention must to be paid to the equipment design so that non-uniform fields are avoided since the mixture of fluoronitrile/CO_2 tends to give lower dielectric strength than SF_6 with non-uniform fields [28].

The gases c-C_4F_8 and C_3F_8 are not typical greenhouse gases, however, their GWP is rather high (8700 and 7000 respectively) and they can stay in the atmosphere for a very long time (3200 and 2600 years respectively) [23].

Novec 5110 - $C_5F_{10}O$ and Novec 4710 - C_4F_7N are also alternatives to SF_6.These are high density gases that are non-flammable and they do not destroy the ozon of the atmosphere. Their dielectric strength is superior to that of SF_6 and their GWP is much lower to that of the SF_6 [29, 30]. Their boiling point is much higher than that of SF_6, which means that their pressure is lower at any temperature. They can cause much lesser damage to the environment since they remain in the atmosphere 0.4 and 30 years respectively. They are much less damaging for the environment since their contribution to the greenhouse effect is minimal. When the above gases are mixed with air, their dielectric strength gets higher when the percentage of the gases in the mixture is higher. It must, however, be noted that for the same pressure the mixtures of the aforementioned gases with air, their dielectric strength is lower than that of the pure SF_6. The mixtures can be used at higher pressures (in the range of 5.2 bar) in order to reach the dielectric strength of the pure SF_6. Both $C_5F_{10}O$ and C_4F_7N have a better electronegativity than SF_6 and their thermal properties are satisfactory and from a medical point of view are safe [31].

Regarding another possible replacement of SF_6 researchers proposed CF_3I, which is a gas which also captures electrons. It is colorless and non-flammable. Its environmental effects are negligible It has, however, a relatively high temperature of liquefaction (-22.5° C) which implies that for wider use it has to be mixed with other gases with a lower temperature of liquefaction. The main byproducts after discharge activity are C_2F_6, C_2F_4, C_2F_5I, C_3F_8, CHF_3, C_3F_6 and CH_3I with the first two to be the main decomposition byproducts, with C_2F_6 to be the main by-product independently of whether the applied electric field is uniform or non-uniform [32]. In an earlier investigation, the same authors noted that the V-t characteristics of CF_3I, SF_6, CF_3I/N_2 and SF_6/N_2 gas mixtures under non-uniform field gaps by using the steep-front square pulse voltage showed that with a more uniform electric field the sparkover voltage of CF_3I is higher than that of SF_6 whereas a CF_3I/N_2 gas mixture containing N_2 gas of 40% are equivalent to those in pure SF_6 gas as far as the V-t characteristics are concerned for uniform electric field [33]. CF_3I has low toxicity and does not cause any damage to the immune system of humans. On the other hand, C_3F_8 as a by-product of discharge activity can cause weakness and problems in sleep but it exists only in minute quantities. In case of a surface flashover, the concentration of C_3F_8 is only 0.00122 ppm under uniform field conditions and only 0.000501 ppm under non-uniform electric field. With a rod-plane electrode arrangement CF_3I has generally a higher dielectric strength than SF_6 for higher pressures whereas the relation is reversed at lower pressures [21] and with nonuniform electrodes. With lightning voltages, the dielectric strength of pure CF_3I is higher than that of SF_6 for spherical electrodes. With a mixture of CF_3I/CO_2, having 60% of CF_3I, the dielectric strength may reach the dielectric strength of the pure SF_6. The percentage increase of CF_3I in mixture with either CO_2 or N_2 results in an increase of the dielectric strength [34]. In a mixture of 30%/70% CF_3I/CO_2 the dielectric strength increases with the electrode uniformity, whereas the insulating properties of 30%/70% CF_3I/CO_2 are similar with those of the mixture 20%/80% SF_6/N_2 [18, 35]. Yet other work indicated that with a 60% percentage of CF_3I the V-t characteristic of CF_3I/N_2 or of CF_3I/air the dielectric strength is similar to that of SF_6 [36]. Research performed on mixed gas C_4F_7N/CO_2 indicated a dielectric strength comparable or even better than that of SF_6, drawing also attention to the faster decomposition rate of the former with increasing temperature [37].

Regarding the inception voltage of partial discharges with a point/plane electrode arrangement, it was found that this does not vary either with pure CF_3I or pure SF_6 at 0.1 Mpa. A mixture of CF_3I/CO_2

presents an inception voltage by about 0.9 – 1.1 times higher than that of a mixture of SF_6/CO_2 [20]. When the volume of CF_3I is about 20% in a mixture of CF_3I/N_2, the inception voltage was 0.92 – 0.94 times higher than that of a mixture SF_6/N_2 provided that the experimental conditions are the same [20]. With respect to the arc quenching, both the pure CF_3I and the mixture CF_3I/CO_2 present a satisfactory performance compared to SF_6 in the case of Short Line Fault (SLF) and in the case of Breaker Terminal Fault (BTF) [20].

Regarding modern applications of the above, one may emphasize that efforts are being made in several countries. Combinations of $C_5F_{10}O$ with dry air and CO_2 have been tried in RMU of 24 kV with a nominal current of 630 A with satisfactory results. Synthetic air in 12 - 36 kV/ 1250 A equipment is also being tried [38]. GIS with $C_5F_{10}O$ is also in use in Switzerland [39].

Conclusion

Since even a small quantity of SF_6 may have detrimental effects in climate change, alternatives were being sought. Today's alternatives suggest other gases as replacements. There are, however, some hindrances either because research is - and rightly so - slow or because industry seems to be even slower to react. Alternatives gases to the SF6 and/or mixtures of gases were presented and in all probability these seem to be viable alternatives. However, a lot will depend on the approach of the various governments to the problem of climate change.

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