The Use of Sulphur Hexafluoride (SF6) as an Insulating Medium in High Voltage Switching and High Voltage Power Distribution

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Background

High voltage systems and their subsequent components enable the distribution of electricity around the world. With regards to some basic electric theory, utility companies rely heavily on the principle of ohm's law. Ohm's law states that voltage (E in volts) is a product of a current (I in amps) multiplied by a resistance (R in ohms), or can be thought of as the formula E=IR. We can also relate ohm's law in terms of power . Electrical power is defined as the rate, per unit time, at which electrical energy is transferred in an electrical circuit. The relationship between current and power is such that power (P in watts) is a product of a voltage (E in volts) multiplied by a current (I in amps), or can be thought of as the formula P=EI (Pryor and Ryan 2013). Utility companies transmit power via small diameter copper transmission lines by taking advantage of this relationship. The transmission lines operate at a very high voltage, usually 36KV and higher and are able to transfer a large amount of power on a small sized copper conductor as compared to the same size copper conductor that operates at a lower voltage (Pryor and Ryan 2013).

Utility companies that incorporate very complex electrical transmission networks rely heavily on numerous pieces of equipment that primarily have one purpose. This purpose is to switch electrical loads on and off. We can think of how a light switch in our home switches a light on and off, and we can apply the same criteria to a high voltage switch, except that your home would be considered low voltage while a high voltage switch would be required to operate at a very high voltage, usually 36KV as mentioned earlier.

The fundamental principle of switching in high voltage systems involves interrupting current by introducing a non-conductive gap into a metallic conductor (Pryor and Ryan 2013). This simply means to interrupt current flow, or to break the path of an electrical circuit, one must interrupt this current by creating a gap between the conducting medium. This can be achieved mechanically by separating two metallic contacts so that the gap formed is automatically filled by a liquid, gas, or vacuum (Pryor and Ryan 2013). This gap that is formed by a liquid, gas, or vacuum introduces the importance of the dielectric strength in the choice of a suitable insulating medium for high voltage switching applications. The dielectric strength of a medium can be thought of as its ability to resist voltage breakdown when it is exposed to an electric field. As well, when a gap is formed between two metallic conductors and this distance is varied but the insulating medium is not changed, a larger gap will result in an increased dielectric value. Similarly, when the gap is the same, but the insulation medium is varied the substance that has the greater dielectric strength will act as a better insulator and thus will have a larger breakdown voltage, which can be defined as the minimum voltage that can be applied to an insulating material before it starts to become a conductor. Due to these physical characteristics of insulating materials it has been determined that gases are a great insulating medium. For low voltage applications air is the most common dielectric, mostly due to its abundance, but also its adequate dielectric strength for low voltage applications. In terms of high voltage switching, however, a substance called sulphur hexafluoride (SF6) is the most commonly used. SF6 was first used as a way to make high voltage equipment smaller, as it was found to be a superior dielectric material. However, there exists one major disadvantage for its continued use in high voltage equipment. SF6 is more than 23000 times more effective at trapping infrared radiation in the atmosphere and when SF6 is released into the atmosphere it has a life span of more than 3200 years (Li, Zhao, and Murphy 2018). These facts classify SF6 as having a high global warming potential. In recent years society has become more environmentally conscious and research has been accelerated with regards to finding environmentally friendly ways to reduce the use of SF6 in high voltage switching equipment.

Discussion

From providing the means to operate important equipment in hospitals to extracting oil from Canada's oil sands to powering a light bulb in your home, electricity and the way it is distributed is very much a priority in the world today. Sulphur hexafluoride (SF6) gas has been regarded as an ideal insulating medium and is used as an integral component in high voltage switching and high voltage power distribution (Ullah et al. 2018, 532-537). SF6 gas possesses a high dielectric strength making it effective in high voltage switching applications. Although the use of SF6 as an insulating medium enables the use of much smaller switching equipment, in turn resulting in a smaller environmental footprint, it poses a significant threat to the environment due to it's high global warming potential (GWP) (Ullah et al. 2018, 532-537). Researchers are currently exploring alternatives to using SF6. These alternative methods involve the use of different gases with a significantly lower GWP, the dilution of SF6 using these new gases, as well as the elimination of these harmful gases by further developing vacuum switchgear technology in the use of hybrid-gas-insulated switchgear.

Sulphur hexafluoride (SF6) has been commercially available since 1947, is a gas compound consisting of one sulphur atom bonded to six fluorine atoms, and is non-flammable, thermally stable and has an excellent dielectric strength as illustrated in Figure 1.

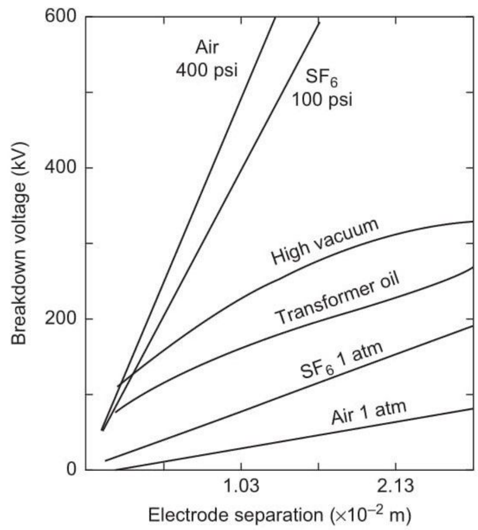


Figure 1

Dielectric strength (breakdown voltage) of various interrupter media (Pryor and Ryan 2013)

We can see that at a specific electrode separation, on the x-axis, that SF6 has a relatively high breakdown voltage. This means that SF6 can withstand exposure to very high voltages as illustrated on the y axis of the above figure. The dielectric strength of SF6 is approximately three times higher than that of air or carbon dioxide (CO2) at atmospheric pressure. SF6 possesses good thermal interrupting and heat transfer properties and most of the SF6 molecules can rapidly reform during an electrical discharge or an arc (Li, Zhao, and Murphy 2018). As a result of these ideal properties SF6 has been used as the preferred gaseous dielectric for high voltage applications such as for use in gas circuit breakers (GCBs), gas-insulated switchgears (GISs), gas-insulated transmission lines (GILs) and gas-insulated transformers (GITs) (Li, Zhao, and Murphy 2018).

The biggest advantage to the utilization of SF6 in gas-insulated switchgear (GIS) is to minimize the size of switching equipment. The atmospheric air insulation used in a conventional, air insulated substation (AIS) requires meters of air insulation to do what SF6 can do in centimeters (McDonald 2007). At very high voltages the interrupter capability is increased significantly and incorporating SF6 into gas-insulated systems was facilitated resulting in a net effect of decreased substation size and accompanying reduction in land and capital construction costs (Pryor and Ryan 2013). However, this decrease in environmental footprint created by the use of SF6 can be forgotten when one considers the impact SF6 has on the environment. SF6 is a strong greenhouse gas that can contribute to global warming. SF6 was listed as one of the six greenhouse gases whose emissions should be reduced at an international treaty conference in Kyoto in 1997 (McDonald 2007). Due to this negative environmental impact, research has begun to find possible alternatives to using SF6.

Preliminary research into possible alternatives to using SF6 results in three categories of methods. The search for new gases to act as insulating medium has got the attention of many researchers who are working on testing these new gases to observe their insulating properties and global warming potential (GWP) as compared with that of SF6. Secondly, researches are looking for ways to dilute the use of SF6 with other gases to minimize the overall environmental impact of these combined gases on the atmosphere. Finally, researchers are looking at ways of eliminating the need for a gaseous insulating medium in the use of high voltage switching by further developing alternate switching principles such as further development of vacuum switchgear technology in the use of hybrid-gas-insulated switchgear.

One replacement gas for SF6 in particular that has gotten the attention of much of the research community is dichlorotrifluoroethane (CF3CHCl2). This (CF3CHCl2) gas is found to be superior to SF6 in many respects as an insulating medium in high voltage switching applications. The gas electronegativity value of (CF3CHCl2) is higher than SF6 and it's ability to withstand voltage breakdown and it's dielectric strength is higher than that of SF6 and it has a much lower global warming potential (GWP) ("Comparison of CF3CHCl2 Gas with SF6 Gas as an Alternative Substitute for Gas Insulated Switchgear Equipment" 2017, 198). Figure 2 illustrates these comparisons between SF6 and (CF3CHCl2).

COMPARISON OF SF_6 GAS AND CF_3CHCL_2 GAS

Specification	SF_6	CF_3CHCl_2
Chemical name	Sulphur Hexafluoride	Dichlorotrifluoroethane
Molecular Weight	146.065	152.93
Thermal Conductivity	101.3 kJ/m.hr.K	34.38 kJ/m.hr.K
Freezing Point	-63.72^oC	-107^oC
Critical Temperature	45.5^oC	183.79^oC
Critical Pressure	37.59 Bar	37.44 Bar
Vapour Pressure	320 kgf/cm^2	0.940 kgf/cm^2
Electronegativity	3.98	7.14
Relative Dielectric Strength	2.5	2.76
GWP	23900	23
ODP	0.08	0.016
Atmosphere Live Time	3200 Year	1.5 Year

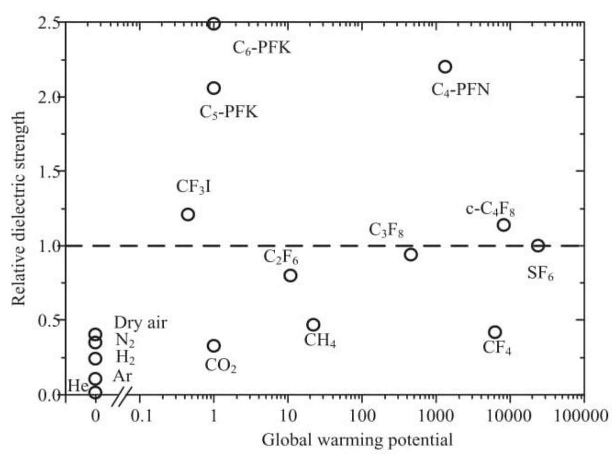
Figure 2:

Comparison of SF6 Gas and CF3CHCL2 Gas

("Comparison of CF3CHCl2 Gas with SF6 Gas as an Alternative Substitute for Gas Insulated Switchgear Equipment" 2017, 198)

We can pay close attention to the environmental comparison of SF6 and CF3CHCl2 using this table. SF6 has a GWP value of 23900 while CF3CHCl2 has a GWP value of only 23. As a result some researchers have recommended (CF3CHCl2) gas a viable alternative to SF6 gas used in gas-insulated (GIS) equipment.

More recently the emphasis on research has been on new environmentally-friendly gases with high insulation and dielectric ratings and low global warming potentials (GWP). Both 3M and General Electric (GE) have used C4-perfluoronitrile (C4-PFN) and carbon dioxide (CO2) mixtures in prototype studies in applications as an insulating and interrupting medium (Li, Zhao, and Murphy 2018). The C4-PFN gas had an insulation performance of about 2.2 times or more than that of SF6 and a global warming potential (GWP) of 2200. The one drawback to this gas mixture in comparison to SF6 was it's higher liquefaction temperature. This puts a constraint on it's use in colder ambient temperatures as compared to SF6. ASEA Brown Boveri (ABB) has recently focused on insulation properties of C5-perfluoroketone (C5-PFK). Their new gas mixtures contain C5-perfluoroketone (C5-PFK), carbon dioxide (CO2), and oxygen (O2) for high voltage gas insulated switchgear (GIS) and have been successfully in operation since 2015 in Switzerland and Germany (Li, Zhao, and Murphy 2018). Figure 3 illustrates comparisons between these newly researched gases by looking at their dielectric strengths as compared to their global warming potential.



Comparison of SF6 Gas and CF3CHCL2 Gas

("Comparison of CF3CHCl2 Gas with SF6 Gas as an Alternative Substitute for Gas Insulated Switchgear Equipment" 2017, 198)

Various gas dielectric compounds are compared regarding their respective global warming potentials as compared to their relative dielectric strengths. Specifically if we focus on the comparison of SF6 and N2, we can see that SF6 has a much higher GWP than that of N2, while N2 has a much lower relative dielectric strength. We can further deduce that gases closer to the middle of the chart are preferred, as they have a much lower GWP but have an adequate relative dielectric strength.

Another method to alleviate the use of SF6 gas is to dilute SF6 using a gas mixture of SF6 with other, more environmentally friendly, gases. There has been considerable research activity to find alternative gases and gas mixtures that have comparable breakdown, or dielectric, strengths to SF6 (Pryor and Ryan 2013). Binary mixtures with inexpensive gases such as nitrogen (N2), air and carbon dioxide (CO2) have been researched to try and find efficient and economical mixtures of SF6 gas to be used as a dielectric medium. To date, the mixture of SF6 and N2 is the only mixture to achieve significant commercial application in switchgear (Pryor and Ryan 2013). The key advantage to using this gas mixture is that N2 gas can be used as the primary gas in the mixture enabling the amount of SF6 used to be kept to a minimum. Figure 4 illustrates breakdown voltages, or dielectric strengths, for various concentrations of SF6 in SF6-N2 gas mixtures.

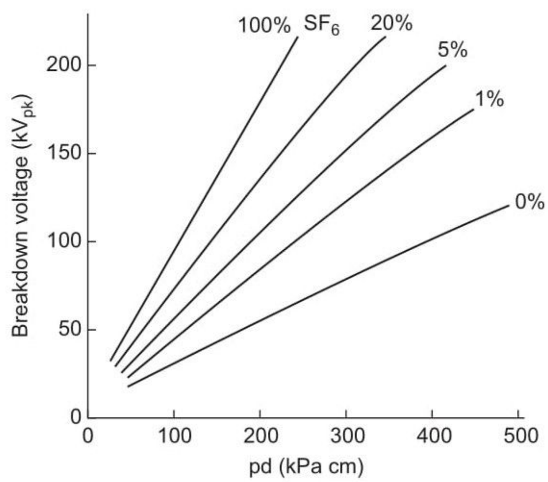


Figure 4:

Breakdown voltages for various concentrations of SF6 in SF6-N2 gas mixtures

(Pryor and Ryan 2013)

We can see from this graph that with only a 20% concentration of SF6 in an SF6-N2 mixture, a breakdown voltage value of over 200 KV can be obtained, and most importantly, an almost identical breakdown voltage as compared to a 100% SF6 mixture can be obtained. Currently, in such an environmentally conscious climate, a major reduction of SF6 gas for large power generation substations appears attractive to many people and this could provide adequate incentives for the strategic re-evaluation of N2-SF6 mixtures for gas-insulated switchgear (GIS) (Pryor and Ryan 2013).

The third category in the search for reduction of SF6 is employs eliminating the use of gas as a dielectric medium. Researchers are looking at ways of eliminating the need for a gaseous insulating medium in the use of high voltage switching by further developing alternate switching principles such as further development of vacuum switchgear technology in the use of hybrid-gas-insulated switchgear. In 2015 two chinese utilities agreed to implement prototypes of this newly developed hybrid-gas-insulated switchgear (“Application Experience of SF6-Free 72.5kV Hybrid-Gas-Insulated-Switchgears in China” 2017, 272). The findings from this pilot project concluded that current technologies regarding dry-air gas insulation support insulation of high voltage parts without any greenhouse gases. In fact, the use of this new method to employ hybrid-gas-insulated switchgear has shown it can be used in extremely low ambient temperature conditions without any gas liquefaction risk as compared to SF6 (“Application Experience of SF6-Free 72.5kV Hybrid-Gas-Insulated-Switchgears in China” 2017, 272).

The use of SF6 is widespread in today’s high voltage switching applications and power distribution around the world. The increased emphasis on the negative environmental impact of SF6 has lead to research methods to both eliminate the use of SF6 in gas-insulated switchgear (GIS) as well as reduce the use of SF6 by combining it with other gases that have a much lower global warming potential (GWP). Although SF6 does in fact have a high GWP as previously discussed and has been targeted as a greenhouse gas which needs to be reduced, the use of SF6 in gas-insulated switchgear (GIS) equipment cuts down on the environmental footprint of the equipment required as compared to that of air-insulated switchgear (AIS). This decreased environmental footprint can result in a net effect of decreased substation size and accompanying reduction in land and capital construction.

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