Sf6 gas is widely used in electric power transmission and distribution systems, as for example in gas insulated switchgear (GIS), circuit breakers (CB) and load break switches. It combines unique electrical insulation and arc interruption capability. However, it is also a very strong greenhouse gas with a global warming potential (GWP) of about 23500 over a time horizon of 100 years and its use and release are regulated with further restriction being discussed.

Consequently, the search for alternative gases for use in power applications has been ongoing since about two decades ago. In this article briefly reviews the status of the present solutions of alternative gases, with a focus on switching application.

**Sf6 alternative gases:**

An intensified search for alternative gases started about two decades ago after the Kyoto protocol was agreed in 1997 and gained increased focus in the last 10 years. The following important requirements for alternative gases were identified:

- Low global warming potential (GWP) and zero ozone depletion (ODP) potential
- Low toxicity and non-flammability
- High dielectric strength, arc quenching capability and heat dissipation property
- Stability and material compatibility
- Availability on market

From various studies of gases of natural origin, CO2 is the most promising arc quenching
gas, possibly enhanced in performance by some additives. However the switching and dielectric performances of CO2 are both below those of SF6. Other interesting gases were identified to be fluorinated gases like CF3I, perfluoroketones (e.g. C5F10O) and perfluoronitriles (e.g. C4F7N). Taking all the requirements into account, the most promising candidates at present appeared to be the C5 perfluoroketone (CF3C(O)CF(CF3)2 or C5-PFK) and the iso-C4 perfluoronitrile ((CF3)2-CF-CN or C4-PFN).

The dielectric performance of pure gases typically scales with the boiling point, i.e. gases with high dielectric strength usually also have a high boiling point. For C5-PFK and C4-PFN, the boiling points at 0.1 MPa are 26.5°C and -4.7°C, respectively.

Thus, for application in switchgear, where a sufficiently low boiling point is needed for low temperature requirements, an admixture of a buffer gas is needed. CO2 is selected for this role in HV due to its good arc quenching capability. In MV application clean air is also reported as the buffer gas in combination with C5-PFK for insulation purposes. The concentration of C5-PFK and C4-PFN, and by this the performance of the mixtures, will depend on the minimum operating temperature requirement of the switchgear. An additional alternative approach is proposed to use air for insulation.

The possible candidates are introduced, which are air, N2, CO2, perfluorocarbon (PFC), hydrofluorocarbon (HFC), gas mixtures containing SF6 as shown in Figure 1 by boiling temperature. These gases do not have higher dielectric strength but lower GWP than SF6, and their boiling points are below 0 °C. Other approaches to apply new alternative gases with low GWP to gas-insulated systems are now under study.

These are CF3I, Fluoronitrile (C4F7N) and Fluoroketones (C5F10O: C5 F-ketone, C6F12O: C6 F-ketone), and suggested to use as mixed gas with CO2 and O2. These gases have a feature of more excellent dielectric strength but higher boiling point than SF6.
Figure 1: Dielectric strength versus boiling temperature of gases

The investigation of any alternatives should look beyond the technical characteristics and ensure that it is assessed holistically. These factors included safety, reliability, long term stability, environmental impact and health. The summary of their output can be seen in Figure 2.
Whilst the environmental impact of SF6 has been known and quantified for decades, there has been significant difficulty in finding an alternative medium which not only matches the technical performance of SF6, but also can provide the same compact solution to serve current applications.

Any potential alternative must have a low GWP and also be compliant with the strict criteria that current switchgear must meet. These specifications include:

- High dielectric strength;
- High heat dissipation;
- Low boiling point;
- Low toxicity;
- Fast arc-quenching capability;
- No Ozone Depletion (ODP);
- Non-flammability;
- Compatible with switchgear materials (Non-Corrosive);
- Chemically inert;
- Similar footprint to SF6 units;
- High stability;

Figure 2: Outcome of holistic assessment of SF6 alternative mediums
• Market availability; and
• Easy to handle during maintenance work.

Table 1 show summarizes key technical characteristics of the sf6 alternative pure gases:

<table>
<thead>
<tr>
<th>Mediums</th>
<th>SF6</th>
<th>CO2</th>
<th>C3-PFE</th>
<th>C4-PFN</th>
<th>HFO1234zzc</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAS Number</td>
<td>2551-62-4</td>
<td>124-38-9</td>
<td>756-12-7</td>
<td>42532-60-5</td>
<td>1645-83-6</td>
</tr>
<tr>
<td>Boiling Point (°C)</td>
<td>-64</td>
<td>-78.5</td>
<td>26.5</td>
<td>-4.7</td>
<td>-19</td>
</tr>
<tr>
<td>GWP</td>
<td>23900</td>
<td>1</td>
<td>&lt;1</td>
<td>2100</td>
<td>6</td>
</tr>
<tr>
<td>ODP</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Flammability</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Dielectric Strength (relative to SF6)</td>
<td>1</td>
<td>0.3</td>
<td>1.4</td>
<td>2</td>
<td>Yes</td>
</tr>
<tr>
<td>Toxicity (ppm)</td>
<td>1000</td>
<td>5000</td>
<td>225</td>
<td>65</td>
<td>800</td>
</tr>
<tr>
<td>Potential Insulator</td>
<td>-</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>-</td>
</tr>
<tr>
<td>Potential Interrupter</td>
<td>-</td>
<td>✓</td>
<td>X</td>
<td>✓</td>
<td>-</td>
</tr>
<tr>
<td>TRL</td>
<td>9</td>
<td>8.9</td>
<td>7</td>
<td>6</td>
<td>3</td>
</tr>
</tbody>
</table>

**Table 1: Properties of pure mediums considered for alternatives to SF6**

The pure mediums developed by 3M have been blended with common gases such as air, nitrogen and carbon dioxide to reduce the boiling point of the pure products to make them suitable for switchgear applications as an interrupting medium; however this has reduced the dielectric strength.

Also, pure CO2 has been discounted as a viable alternative for the purposes of this study, due to the increase in switchgear physical dimensions, relative to a similarly rated SF6 unit. However, CO2 mixtures make up some of the gas mixtures which have been trialled previously by developers.

**Available MV switchgear technology by alternative gases in market:**

**ABB- AirPlus model switchgers:**

AirPlus, developed in collaboration between 3M company and ABB, is a fluoroketone (C5-
PFK) compound. As with other pure gases, the addition of fluorine increases the dielectric strength at the cost of increasing the boiling point. Subsequently, it required a buffer compound to lower the boiling point.

For medium voltage design, Novec 5110 is blended with dry air. At HV levels, CO2 and dry air are both added to improve the gas electrical properties.

ABB have developed, and commercially advertised SafeRing AirPlus as a medium voltage gas-insulated indoor RMU, which can operate at 24kV with a 630 A rating. This product uses AirPlus as an insulating medium for live components and vacuum interruption.

In addition, ABB have also developed SafeRing Air which uses dry air insulation up to 11kV. Both products have the same physical dimensions as SafeRing, ABB’s SF6 insulating RMU design.

In figure 3 we can see MV switchgear ABB ZX2 AirPlus:
Figure 3: ABB ZX2 AirPlus medium voltage switchgear

SIEMENS-Clean air and vacuum technology:

SIEMENS company medium-voltage switchgear that doesn’t require SF6 as the insulating gas: the 8DA The system uses clean air consisting only of the natural constituents of ambient air as the insulating gas.

The switchgear is a new addition to the 8DA and 8DB product family and also works with the proven vacuum switching technology. A vacuum-interrupter unit handles switching and arc extinguishing, while the natural gas insulates the current-carrying conductors inside the housing of the metal-encapsulated, gas-insulated switchgear (GIS). This type-tested system is used to switch high currents at the primary distribution level.
GE - g3:

The compound g3, was developed in collaboration by GE and 3M and has been fully type tested and is commercially available. Similar to AirPlus, it required a buffer compound to lower the boiling point. For MV design,

Novel 471010 (a C4-PFN) is blended with Nitrogen. At HV levels, CO2 is blended to improve the gas electrical properties.

Technically, g3 has been found to have similar performance characteristics to SF6 for instance, it is able to deliver the same dielectric strength as SF6 under ambient conditions.

Nuventura - Synthetic Air:

Nuventura have outlined their product which uses synthetic air as an insulator without compromising on the compactness offered by SF6 switchgear, matching the typical width of SF6 solutions. Furthermore, they have suggested that the capital and operational expenditure is lower when compared to SF6 switchgear, by 7-10%, due to the lack of need for gas handling procedures or gas regulations. Their product is able to work for 12-36kV.

Solid Insulation:

Multiple manufacturers have put forward traditional vacuum interrupting technology as an alternative interrupting medium to SF6 gas, which has been available for several years.

Companies such as Eaton, Schneider, ABB and Lucy all have commercially available products which are capable of interrupting medium voltage fault currents.

While some products still use SF6 as an insulating medium, others such as Eaton and Schneider have developed SF6-free products by deploying solid insulation. Such technology may have additional hurdles to overcome such as alternative components placement within the switchgear which may conflict with current installation procedures.

Research results and conclusion:

Research has shown that there are alternative solutions currently available for replacing SF6 within a circuit breaker. AirPlus and g3 are both currently under test in live networks,
and have been tested according IEC specifications. Furthermore, vacuum interrupting technology has been well researched with multiple companies offering commercial products using different insulating mediums; the alternatives to SF6 have included solid epoxy and common naturally occurring gases. HFC1234zee has also been investigated as a possible insulation alternative. Finally, Nuventura have proposed technology which uses dry air in relatively compact solutions.

Therefore, the insulating alternatives to SF6 gas which could be considered for retro-fitting into existing switchgear under laboratory conditions are AirPlus, g3, HFC1234zee and solid epoxy.

The interrupting alternatives to SF6 gas which could be considered for retro-fitting into existing switchgear under laboratory conditions are g3 and vacuum technology.

Also these main technical view point must be considered in alternative gases:

- basic and practical properties of the gases (N2, CO2 and N2/SF6 mixtures) for the potential gas insulated systems, e.g. insulation, PD diagnostics and monitoring techniques.
- small current interruption properties by disconnectors and earthing switches in GIS.
- recyclability of the potential gases, and application examples for the potential gas-insulated systems.
- alternative dielectric (routine) tests by using the potential gases and recyclable insulating materials and their recyclability for the improved SF6 gas-insulated systems.