POSITION PAPER

CIGRE Position Paper on the Application of SF_6 in Transmission and Distribution Networks

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Introduction

SF_6 is essential for the transmission and distribution equipment and switchgear, because of its excellent dielectric, arc quenching, heat transfer and chemical recombination properties.

This has been successfully proven since the 1960s for high-voltage equipment and since beginning of the 1980s for medium-voltage equipment. The size of equipment and switchgear has been significantly reduced since the beginning of the SF_6 technology. Nowadays, SF_6 technology is even more important to bring bulk power at high-voltage level closer to the consumers as for mega cities.

Moreover, compact SF_6 switchgear support applications such as offshore platforms or wind power installations where small sizes and light weights are requested.

In spite of all the technical advantages of the SF_6 technology, SF_6 is a potent greenhouse gas which is covered by the Kyoto Protocol [1]. Therefore SF_6 must be managed within a closed cycle, avoiding any deliberate release to the atmosphere. During the last 20 years, as a consequence, significant effort has been undertaken to reduce SF_6 emissions. The focus for manufacturers and asset owners was on finding ways of increasing the tightness of equipment and reducing handling losses.

In spite of the fact that during the last 30 years significant efforts were made to search for SF_6 alternatives, no industrially viable alternative to SF_6 technology has been found with the same performance.

Properties of SF_6

Sulphur hexafluoride (SF_6) is a synthetic compound showing a unique combination of physical properties: high dielectric strength, high arc quenching capabilities (see Figure 1) and high heat transfer performance, which is about twice of air.

SF_6 is an odourless, tasteless, colourless, non-toxic, non-flammable, very stable and inert gas at room temperature.

Due to spontaneous recombination the molecule is extremely stable even at very high temperatures in the arc plasma during switching operation.

Advantages of SF_6 technology

Since the early 1960's, the Electrical Industry utilises $_{SF6}$ in Gas Insulated Switchgear (GIS), Gas Circuit Breakers (GCB), Live Tank Breakers (LTB), Dead Tank Breakers (DTB), Gas Insulated Lines (GIL), Gas Voltage Transformers (GVT), Gas Insulated Transformers (GIT), Gas Insulated Reactors (GIR).

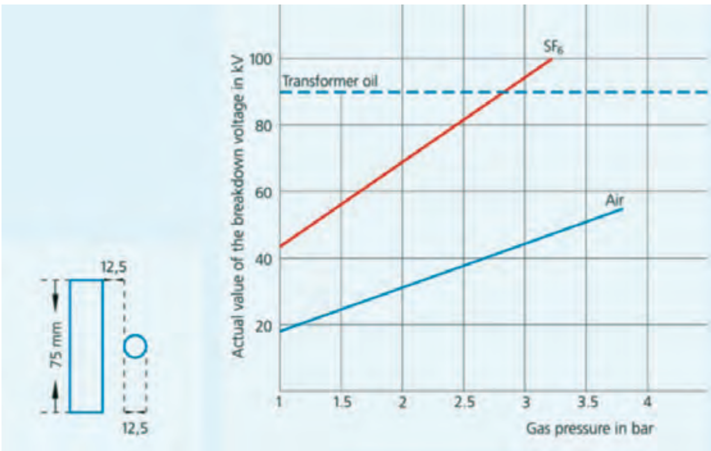
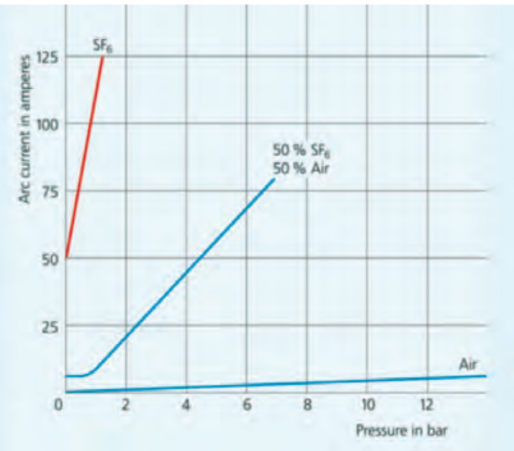


Figure 1 - Example of breakdown voltage in SF_6, transformer oil and compressed air in a non-uniform electric field (sphere - plane gap) vs. pressure (Kali und Steinsalz, 3, issue 10 [1963] 319 [2].



Arc quenching capacity of SF_6, 50% air – SF6 mixture and pure air vs. pressure (Insulating Materials for Design and Engineering Practice, N.Y. [1962], p. 116, [2])

SF_6 technology is versatile: SF_6 equipment are air insulated substations, gas insulated substations and mixed technology solutions, all for application in indoor and outdoor environment in different layouts.

The success story of the SF_6 technology was accompanied by the corresponding development and application of the enabling technologies like gas handling equipment, gas measurement instruments and gas handling procedures.

Figure 2 shows examples of applications.

In the power industry, SF_6 is utilised in a closed cycle, and large quantities are supposed to be banked in medium-voltage and high-voltage switchgear [4]. The SF_6 technology provides the following advantages:

- high compactness and reduced size of the equipment;
- land saving and reduced dimensions required by the switchgear room;
- high personnel safety;
- high reliability and long lifetime of the equipment;
- easy integration into the landscape resulting in higher public acceptance;
- sealed design avoiding dust / rain / salt / ice penetration and humidity condensation;
- pre-assembled equipment resulting in shorter installation time;
- easy application for mobile solutions;
- special switching capabilities resulting in generator breakers;
- no periodical need for SF_6 replacement.

The CIGRE brochure no. 499 [3] underlines the positive field experience of high-voltage GIS gained during almost 50 years.

Environmental impact

The awareness of environmental aspects has been substantially growing during the last decades. Since 1997 synthetic fluorinated gases like SF_6 are greenhouse gases covered by the Kyoto Protocol [1]. •••

Figure 2 - 220kV GIS for TRANSELECTRICA, BRAZI VEST substation, Romania.

550kV hybrid-type gas circuit breaker for CEPCO Seibu substation, Japan.

245kV Gas Voltage transformer

Nowadays the SF_6 contribution to the overall anthropogenic greenhouse effect is approximately in the range of 0.1% [4].

The measure of the greenhouse effect is called Global Warming Potential (GWP). The calculation is based on the comparison to CO_2 (i.e. GWP of CO_2 is 1). As far as SF_6 is concerned, its strong infrared absorption and long lifetime in the environment result in a GWP value of 22 800 over a time period of 100 years [6].

Heavy current switching operations such as in circuit breakers can generate decomposition products [7, 8]. Some of them are fluorocarbons (e.g. CF_4, C_2F_6, C_3F_8); which are well–known as greenhouse gases. In very rare cases internal arcs may lead to the operation of safety devices resulting in release of SF_6 and its decomposition products into the environment.

SF_6 and its decomposition products from application in electric power equipment do not contribute to the destruction of stratospheric ozone layer [10] because they contain neither chlorine nor bromine.

Health and safety

SF_6 is non-toxic. However, it does not support life as it is not oxygen. As the gas is much heavier than air, under conditions of insufficient mixing with air the gas has a tendency to accumulate at low levels. Areas below ground level, poorly ventilated or unventilated areas (e.g. cable ducts, trenches, inspection pits, drainage systems), may contain a high level of SF_6 concentration. Personnel must be aware of the danger of asphyxiation in such places.

In case of incorrect gas handling or uncertainty, gas compartments may contain a residual amount of SF_6 and should not be entered without adequate ventilation and personal protection equipment.

Heavy switching operations like in circuit breakers can generate up to few per cent of decomposition products [7 and 8]. Some of them are SF_4, SOF_2, SO_2F_2, HF and SO_2 [9]; which are well-known as toxic and corrosive [10]. However, SF_6 "reclaimers" and handling procedures have been developed during the last decades to separate the gaseous decomposition products and reclaim SF_6 for reuse [9]. Handling procedures are also available to remove solid decomposition products, mainly powders containing fluorides, and dispose them in an environmentally sound manner.

Specific precautions are required when entering a switchgear room after release of SF_6 due to the very rare event of external fire or internal arcs [9].

The closed cycle concept and its implementation in Standards

The Electrical Industry has been extremely active during the last two decades in reducing the SF_6 emissions. SF_6 is handled in a closed cycle, banked into equipment and not released into the environment. Design features and SF_6 handling procedures have been further developed to reach an efficient cradle to grave concept with very low emissions. CIGRE took a leading role in creating and developing the technical frame on the application and handling of SF_6 in a closed cycle.

State-of-the-art medium-voltage equipment are sealed pressure systems; while high-voltage equipment comprises closed pressure systems requiring very limited SF_6 handling [11 and 12]. State-of-the-art instruments enable to check easily and quickly SF_6 quality on-site. They have a small compressor to pump back the gas sample into the gas compartment.

The CIGRE brochure no. 430 [13] reviews all significant aspects of measuring and ensuring tightness of electric power equipment during its expected lifetime.

A new version of the SF_6 Recycling Guide [7] was published in 2003, the following year its technical content was transferred into revision 2 of IEC 60480 [14] and then two years later, in 2005, into revision 2 of IEC 60376 [15]. The quality of SF_6 to be used in electric power equipment has been therefore reviewed to allow SF_6 reuse.

CIGRE issued the brochure no. 276 [16] with the aim of regulating SF_6 handling and minimising the SF_6 handling losses onsite. Three years later, in 2008, the same concepts have been first implemented into the IEC Technical Report 62271303 [17] and recently enforced and replaced by IEC 622714 [9]. The content of the CIGRE brochure no. 276 was also moved to the IEEE Guide C37.122.3 [18]; which has been published in January 2012.

Nowadays, the "Guide to minimise the use of SF_6 during routine testing of electrical equipment" is under preparation by Working Group B3.30. Given the fact that the SF_6 emission rate during manufacturing, onsite commissioning included, has been recently estimated to be in the range of 1 to 3% of the SF_6 mass banked in electrical equipment [4], the target is to understand whether there is still a practical potential for achieving a further reduction of the SF_6 emission.

Regulations

The Kyoto Protocol [1] triggered the activity of the legislators all over the world. Three approaches are followed: regulations on monitoring and containment, taxes on SF_6 and voluntary agreements or partnership programmes. A typical example of regulation on monitoring and containment is the European Regulation 842/2006 [5] which introduces minimum requirements concerning certain fluorinated greenhouse gases, SF_6 included. Recovery has to be performed by certified personnel, equipment have to be duly labelled and the quantity of fluorinated gases produced, imported and exported have

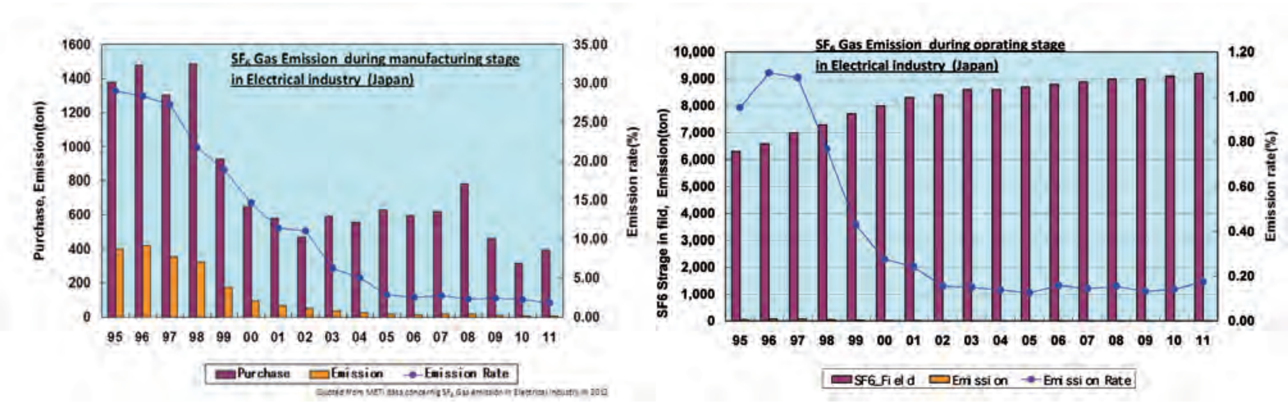


Figure 3 - SF_6 emission during manufacturing and operation of electrical equipment in Japan.

to be annually reported. Nowadays, it is under revision and will be replaced by a new one in 2014 (the final reading in EU-parliament and approval by the EU-council is scheduled for April 2014). As this regulation mainly applies to HFCs for refrigerant applications, SF_6 electrical switchgear will be affected by additional measures, with the objective of avoiding emissions.

On the one hand, Australia is a typical example of taxation on SF_6 [19]. An import tax based on the CO_2 equivalent mass has been introduced in 2012.

On the contrary, the Environmental Protection Agency of United States (US EPA) employs a voluntary code of practice and voluntary partnership with industries as a major tool for reducing emissions of fluorinated gases [20]; while in Japan the voluntary agreement and self-commitment actions [21] involve:

- Establishment of targets for total emissions;
- Implementation of measures to attain these targets;
- Follow-up of progress toward attainment by the Industrial Structure Council; and
- Establishment of revised targets once achieved.Figure 3 - SF6 emission during manufacturing and operation of electrical equipment in Japan.

Figure 3 shows the SF_6 emission during manufacturing and operation of electrical equipment in Japan.

Alternatives to SF6 technology

Vacuum and Air Insulated Switchgear technologies are already available on the market as alternative to SF_6 in mediumvoltage, up to 52 kV. Given the fact that the SF_6-free equipment need much more space than SF_6 equipment, users can select the technology which better fits to their specific needs and evaluation criteria. The critical issue is still to be able to design general purpose SF_6-free equipment with the same performance, functionality•••

Figure 4 - Comparison between mediumvoltage air insulated switchgear (larger equipment on the left of each picture) and SF_6 switchgear (smaller equipment on the right of each picture). 24 kV switchgear (left picture), 36 kV switchgear (right picture).

and compactness as SF_6 equipment, as clearly shown in Figure 4.

The large difference in size, weight and high compactness of equipment assures that SF_6 technology will continue to play a fundamental role even in mediumvoltage, up to 52 kV.

The first pilot circuit breaker applications based on vacuum or CO_2 technology have been installed in the field to gain confidence in application of the new technology to the highvoltage range between 72.5 kV and 170 kV.

However, the GWP of SF_6 alone is not adequate to measure the environmental impact of electric power equipment based on SF_6 technology. The environmental impact of any specific application should be evaluated and compared using the Life Cycle Assessment – LCA approach as regulated by ISO 14040 [22].

Interrupting performance of high voltage circuit breakers

The development of circuit breakers with larger interrupting and current carrying capacities has been advanced in applications with different interrupting media in accordance with the increase of rated voltage of power systems. Bulk Oil and Minimum-Oil circuit breakers were a leading technology until the 1970's up to 145 kV. 245 kV live tank oil circuit interrupters with two-breaks and 420 kV interrupters with four-breaks were also developed but they were supplanted at the EHV level by air-blast circuit breakers. Air-blast circuit breakers for rated voltages 800 kV and 1200 kV needed ten or even twelve interrupters in series per pole. Noise reducing measures were necessary as compressed air used for interruption was released into the atmosphere.

Air and oil circuit breakers were manufactured until the 1980's, when production shifted toward circuit breakers using sulphur hexafluoride (SF_6) gas. In the 1970's, EPRI made an extensive investigation of the interrupting performance with various gases and gas mixtures and concluded that SF_6 is the best interrupting media for high-voltage circuit breakers [23]. In particular, the thermal interrupting capability (short-line fault interruption condition with a line surge impedance of 450 ohm) using a double pressure type circuit breaker with a mixture of SF_6 (50%) and N_2 (50%), and pure CF_4 was reported to be 71% and 53%, respectively compared with that of pure SF_6 of similar pressure. [24]

Figure 5 shows the interrupting capacity of air-blast, vacuum and SF_6 circuit breakers per break. The interrupting capacity of SF_6 puffer circuit breakers per break surpassed that of air blast circuit breakers around 1970 and significantly advanced in the 1980's and 1990's. SF_6 puffer circuit breakers at 245 kV 40 kA and 300 kV 50 kA were developed with a single-break in the early 1980's, followed later by 420 kV and 550 kV 63 kA single break circuit breakers and 800 kV, 1100 kV and 1200 kV circuit breakers with two-breaks per pole were achieved in the mid 1990's. [25] Highly reliable and compact designs lead to the dominance of SF_6 puffer circuit breakers over the complete transmission voltage range. The low number of breaks brought by the SF_6 technology leads to a lower environmental impact.

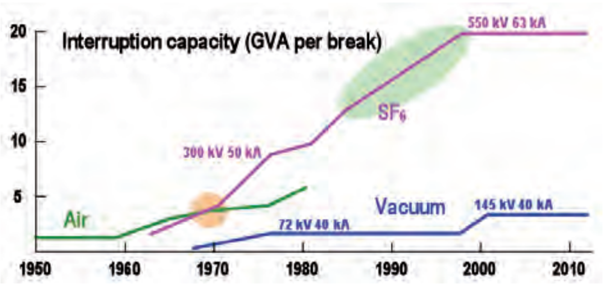


Figure 5 - Interruption capacity per break for different circuit breakers

More recently, the self-blast technique applied to SF_6 circuit breaker leads to lower operating energies and therefore increased reliability.

State-of-the-art high voltage vacuum switchgear appeared on the market up to 145 kV even though its current carrying capability is limited to around 2500 A. It should be noted that the withstand voltage of vacuum for large gap does not increase linearly with gap length, whereas the voltage strength of SF6 is linearly increasing with gap length and pressure. The primary reasons for utilities to be interested in transmission vacuum circuit breakers are their capability to operate frequently and the reduced maintenance work during its lifetime as well as the absence of SF_6. [26] Potential users see issues concerning capacitive switching and dielectric performance. However, current chopping transients and X-ray generation are not an issue for rated voltages up to 145 kV.

Gas mixtures such as SF_6/N_2 and SF_6/CF_4 have been applied to circuit breakers for applications at low ambient temperature (less than -40 °C) in order to avoid SF_6 liquefaction which leads to an impaired interrupting capability. When these gas mixtures are used, the interrupting capability is generally reduced by one breaking rating, for example, the short-circuit breaking capability of a 50 kA circuit breaker with pure SF_6 circuit breaker would be degraded to 40 kA or less depending on the gas mixtures and interrupter designs. In addition, the dielectric interrupting capability under small capacitive current switching conditions is also de-rated by approximately one voltage rating, for example, the dielectric interrupting capability of a 245 kV circuit breaker with pure SF_6 would be degraded to 170 kV with gas mixtures [27], [28].

It should be noted that the interrupting capability with other gases such as CO_2, N_2 and air (at similar pressure as SF_6) is much inferior to that of circuit breakers with gas mixtures that include SF_6. Therefore these interrupting media lead to larger interrupters (often multi-breaks) with a higher gas pressure that requires the use of a larger driving energy of the operating mechanism, resulting in a higher environmental impact.

Figure 6 - Vacuum switchgear at transmission level

Conclusions

During the last 50 years, SF_6 technology has had a huge development because of the excellent insulation and arc quenching properties of the gas with no comparable equivalent at the moment. This has enabled the design and manufacturing of extremely compact equipment with optimised usage of material, high operational reliability and safety, minimised fire load, high availability.

Despite of all these advantages, SF_6 is a potent greenhouse gas; which is covered by the Kyoto Protocol [1]. As a consequence of that, the Electrical Industry has made a huge effort in developing and implementing a responsible application of SF_6 in transmission and distribution networks.

During the last 15 years, concepts have been developed within CIGRE to keep SF_6 in a closed cycle, avoiding any deliberate release to the environment. These concepts have been introduced into IEC and IEEE Standards and are going to be adopted worldwide. The focus is on the sustainable implementation of stateoftheart equipment and best available practices on SF_6 handling.

The Kyoto Protocol also triggered the activity of the legislators worldwide and three different approaches have been developed: regulations on monitoring and containment, taxes on SF_6 and voluntary agreements and partnership programmes. On the other hand, the Manufacturers of Electric Equipment are continuously seeking for alternatives to SF_6 technology and are committed to make available any industrially viable replacement. However, SF_6 technology will remain essential for the transmission and distribution network until a new technology is found. ■

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