CIGRE-447

2021 CIGRE Canada Conference & Expo
Toronto, Ontario, October 25-28, 2021

Lifetime Impact of SF_6-Free Medium Voltage Switchgear Solutions

E. Ducharme
Dual ADE
Canada

C. Girardet
vadimUS
Canada

M. Ramesh
nuventura
Germany

SUMMARY

Gas-insulated switchgear (GIS) is among the most common types of switchgear technologies used in medium voltage (MV) applications today. The market has accepted GIS because of its advantages, such as its compactness, high reliability, and low-maintenance requirements. SF_6 is commonly used in GIS due to its exceptional dielectric and thermal properties.

Recent discussions in the electrical industry have focused heavily on its high global-warming potential (GWP), as operators deal with growing electricity demands and the need to implement more renewable energy sources which rely heavily on GIS. Increasing regulations, such as carbon pricing and taxes, and progressive phase outs of SF_6, have slowed down or curtailed the industry from investing in conventional SF_6 GIS.

However, some parties argue that non-SF_6 solutions, such as air-insulated switchgear (AIS) or novel SF_6-free switchgear, may not necessarily have a lower total carbon footprint during the product's life cycle. Also, not meet operators' objectives to lower the total cost of ownership of their assets.

The current contribution aims to benchmark the greenhouse gas (GHG) emissions of a typical primary medium-voltage switchgear from production until end of life. Medium-voltage switchgear is manufactured in many different countries and comes in various configuration compared to the limited number of manufacturers of high-voltage switchgear. Hence, the carbon footprint of the different manufacturers and product configuration is dependent on the design and manufacturing processes and operational excellence used.

Three technologies of switchgear, with the same specifications and performances, are considered for the study. AIS is compared with the existing SF_6 GIS and novel SF_6 free GIS in terms of the life-cycle GHG emissions. Additionally, topics such as reliability parameters, refurbishment possibilities, and the product's life expectancy are also considered to be influencing parameters in the total carbon emissions over its lifetime.

KEYWORDS

MV switchgear, GHG, GIS, AIS, SF_6, SF_6-free, Life-cycle emissions, Carbon footprint.

educharme@DUAL-ADE.com

1 Impact of SF_6 Emissions

1.1 SF_6 Properties

Sulphur hexafluoride (SF_6) is widely used in the electrical power industry, with a consumption of about 80% of gas production [1]. Due to its excellent insulation and arc quenching properties, it is used across electrical utilities, from large power stations, wind turbines, to electrical sub-stations in towns and cities.

Although it presents many advantages in terms of technical properties, SF_6 has the disadvantage of having the highest global warming potential (GWP) among greenhouse gases (GHG). Moreover, its extensive longevity in the atmosphere induces an increase of its GWP with the time horizon. While its current effect might be considered marginal versus carbon dioxide (CO_2), its 3200 years lifetime in the atmosphere makes it a legacy we must stop accumulating as quickly as possible.

Greenhouse Gases	GWP 20 Years Horizon	GWP 100 Years Horizon	GWP 500 years Horizon	Atmospheric Lifetime (Years)
Carbon dioxide (CO_2)	1	1	1	Variable
Methane (CH_4)	72	25	7.6	12
Nitrous oxide (N_2O)	289	298	153	114
Nitrogen trifluoride (NF_3)	12,300	17,200	20,700	740
Sulphur hexafluoride (SF_6)	16,300	22,800	32,600	3 200

Table 1: Greenhouse gas GWP [2]

The most important means by which SF_6 gets into the atmosphere is from the leakage from electrical apparatus equipment during its entire life span. Over the last two decades, the industry has made significant progress in reducing SF_6 leakage rates and handling losses because of a better understanding of the best practices and most suitable technologies for managing SF_6.

According to international standards, the leakages in operation for MV switchgear are 0.1% per year while end-of-life leakages are very uncertain. Since SF_6 must be either recycled or destroyed, either by the gas producer or a specialized service provider, end-of-life handling of the MV switchgear during decommissioning has a key role in their lifetime emission. There is a wide gap between industry best practices of about 1.5% end-of-life leakages and the worst-case assumption of about 40% end-of-life leakages for mainly uncontrolled end-of-life handling.

Emissions are estimated based mainly on the amount of SF_6 needed to top-up leakage during maintenance operations. According to the Canadian Electricity Association (CAE), the Canadian utilities add around 7 tons of SF_6 annually for maintenance purposes [3], which is consistent with the estimated 2019 SF_6 emissions for the electricity sector in Canada of 170,000 tCO_2e [4].

1.2 Carbon Pricing in Canada

Carbon pricing is now in force across Canada and different approaches were adopted by provinces. British-Columbia opted for a carbon tax, Quebec preferred cap-and-trade and provinces without their own system are subject to the federal scheme. For consumers in 2021, it means the carbon content of the fuel they purchase is subject to a surcharge between $25 and $45 per ton of CO_2 equivalent. This amount is expected to reach $170 in 2030 [5].

The federal regulation targets large emitters, over 50,000 tCO_2e per year, through a benchmark approach. It measures how emission-efficient a corporation is compared with its industry peers to decide how much the company should pay or if it should receive credits. Therefore, with current price and emission quantity, SF_6 emissions currently represent a potential cost of 5 million, and soon 29 million CAD for the industry.

1.3 Adoption Trends by Utilities

Globally, the utilities sharing most of the energy generation, transportation and distribution assets have come into scrutiny in recent years regarding actions and commitments towards net-zero plan. One of the steps taken in this regard has been to fundamentally replace power plants run on fossil fuels such as coal, oil and natural gas with systems based on renewable sources such as solar and wind power. Additional storage systems such as battery energy storage systems or hydrogen are also deployed or in development to supplement the fluctuations in supply.

It is interesting to note that each solar and wind power stations consist of MV switchgears directly at the source of energy generation or in a collector substation which in many cases contains SF_6. Needless to mention that such installations are planned for 30 or more years of operation.

Given the very long lifetime of SF_6, the real emission caused by SF_6 banked emission becomes a significant factor and must be considered together with the advantages of the carbon neutral energy production.

2 Existing and New Switchgear Technologies

2.1 Air-Insulated Switchgear

Air-insulated switchgear (AIS) is commonly used and is well-accepted because of its flexibility of configuration and long history of use. It uses ambient air as an insulation medium in a metal-clad or metal-enclosed housing. For this reason, it is susceptible to local environmental conditions such as humidity, corrosive substances, dust, and salty air, which are all contributing factors to switchgear failure over time. Also, due to the low dielectric withstanding of ambient air, the dimensions of the AIS become larger at higher voltage levels limiting their use when access to space or cost of land is a significant factor.

2.2 SF_6 Gas-Insulated Switchgear

Due to its high dielectric withstanding properties, SF_6 has enabled the development of very compact gas-insulated switchgear (GIS). For several reasons, these have become widely adopted: smaller footprint, low total cost of ownership (TCO) due to, reduced maintenance requirements, greater safety due to no exposed live parts and higher reliability [6].

However, SF_6 is a greenhouse gas with an extremely high GWP. Due to increase SF_6 regulations and the announced phase-outs in some regions, the broad industry has been seeking alternatives to maintain the benefits of GIS.

2.3 SF_6-Free Gas-Insulated Switchgear

SF_6-free GIS, while novel in its use of alternative gases to SF_6, maintains the advantages of traditional GIS that operators have become used to without the environmental harm associated with SF_6.

The use of alternative gases as an insulation medium, with generally lower dielectric withstand capabilities as compared to SF_6, means that SF_6-free switchgear would have to be designed to compensate for these differences. The alternative gases may need to operate under higher pressures to improve their dielectric performance.

Such change would require more steel and other materials in the gas vessel construction to be considered because the mass of any material with carbon footprint may vary for different switchgear technologies.

3 Comparison of Switchgear Technologies

3.1 SF_6 Applications in High-Voltage and Medium Voltage Switchgears

Across the grid top down starting with the highest voltage ratings, SF_6 gas insulated equipment is used in high voltage (HV) and medium voltage (MV) technologies, with the latter being further sub-divided into primary and secondary switchgears based on their applications.

The voltage ratings between 1,000 volts to 52,000 volts are classified within the MV range, whereas HV is above. The primary switchgears are installed at the substation level, generally at short circuit rating of 25,000 amperes and above normally with current ratings between 1,200 and 4,000 amperes. Secondary switchgears are generally used where short circuit requirements are under 25,000 amperes and continuous currents below 800 amperes.

The switchgears used in high voltage as compared to medium voltage primary and secondary differ based on a few factors including pressures well as technologies used for insulation or breaking mediums. HV gas-insulated switchgear uses SF_6 with pressure of 10 bar or above, and SF_6 is also used as a breaking medium [7]. Replacing the breaking medium in HV gas-insulated switchgear requires a replacement of the existing SF_6 based breaking technology.

In the case of primary MV gas-insulated switchgear, the vacuum-based breaking mechanism has been an industry standard for many years and SF_6 has only been used as an insulation medium. In the case of secondary MV gas-insulated switchgear, SF_6 has been predominantly used as insulation and breaking or switching medium [7] [8].

3.2 Impact of Primary MV SF_6 Switchgear Alternatives

The replacement of SF_6 switchgears should be prioritized based on the amount of SF_6 emissions and the availability of environmentally friendlier alternatives.

MV primary switchgear products with alternative gases such as dry air are now available. Such products do not change the state-of-the-art vacuum breaking medium and only the insulation medium is replaced by dry air. The result is that no long-term testing and observation is required in terms of large-scale integration on the grid. The compactness, specifications and cost of these products are already competitive with existing SF_6 switchgears on the market.

Both in the case of high voltage switchgear and medium voltage secondary switchgear, the current state of-the-art breaking medium is SF_6. In the case of HV switchgear, there are presently alternative gases available or under development [9] but long-term testing remains necessary to complete the approval of new gas mixtures. In the case of MV secondary switchgear, the breaking technology is not the true bottleneck. Although technologies are available (such as vacuum breaking), footprint and cost competitiveness remain challenging. Hence additional regulatory policies and subsidies are essential to roll out new alternatives at scale for those applications.

In terms of general SF_6 usage, a recent study from ECOFYS, Germany [10] shows that in the European Union about 50% of SF_6 is used in HV equipment even though less HV switchgear units are used or refilled every year compared to MV switchgear units. It is difficult to find the exact ratio of SF_6 use between primary and secondary MV switchgear units but in general, it can be considered that for every 10 to 20 secondary switchgear units, one primary switchgear is used as a main feeder. Considering this mix is resulting in 5% to 10% of the total SF_6 usage for primary switchgears and that the volume of primary switchgear gas vessels is at least three (3) times the size of secondary switchgear vessels for a given technical specification, it can be argued that in terms of SF_6 usage, the primary MV switchgear contributes to 15% to 30%. These figures can change in each country depending on local grid topologies.

Therefore, it is possible to conclude that all primary MV switchgear units contribute up to 15% of the entire SF_6 in general use. Given that alternative products to SF_6-based MV primary GIS are finally available, the large-scale transition will easier than utilities thought not so long ago with a significant opportunity to reduce scope 1 emissions in line with their sustainability plans.

3.3 Carbon Footprint Comparison of MV Primary Switchgear Technologies

In this section, we focus on the carbon footprint of MV primary switchgear technologies to compare the three types described in section 2.

For the comparison, it is considered that one and the very same original equipment manufacturer (OEM) has designed and manufactured the three different switchgear technologies described in section 2: the well-established air-insulated switchgear (AIS), SF_6 gas-insulated switchgear (SF_6 GIS) and a new generation SF_6 free GIS, which might employ a gas such as technical (dry) air as an insulation medium.

Similarly, a rating of 35,000-38,000 volts, an interrupting capacity of 31,500-40,000 amperes and a single busbar configuration are considered hard specifications.

Indirect emissions (i.e. scope 2, and scope 3 per the GHG protocol) are considered the same pertaining to the raw material characteristics required to build the three technologies.

The components used to build an AIS are compared in Table 2 with those used to build a SF_6 GIS and a SF_6-free GIS employing a naturally occurring gas such as technical (dry) air.

	AIS		SF_6 GIS		SF_6 free GIS	
Material	Weight (kg)	CO_2e	Weight (kg)	CO_2e	Weight (kg)	CO_2e
Steel	1,050	3,045	550	1,595	785	2,276.5
Copper	105	840	60	480	80	640
Epoxy resin	55	313.5	35	199.5	35	199.5
SF_6 Insulation with 100% lifetime emissions	0	0	3	68,400	0	0
SF_6 Insulation with 4.5% lifetime emission	0	0	0.135	3,078	0	0
SF_6 Insulation with 10% lifetime emissions	0	0	0.3	6,840	0	0

Table 2: CO_2e comparison per mass of materials and leakages over lifetime.

The carbon footprint is chosen from the benchmark values for steel, copper and epoxy resin (see Table 3). Other material footprints are considered equal between the three technologies. As assumed before, if the OEM moves toward a supply chain with lower carbon emissions, the overall carbon footprint reduces in all the technologies.

Materials	Carbon Footprint ($kgCO_2e/kg$)
Steel	2.9 [11]
Copper	8 [12]
Epoxy Resin	5.7 [13]

Table 3: Material carbon footprint.

Regarding SF_6 GIS, three possibilities are considered. First, as a worst-case scenario, all the SF_6 initially contained in the vessel is emitted to the atmosphere during its lifetime. This results in a carbon footprint of SF_6 GIS at least 16.8 times higher than AIS. In the second case, which corresponds to current best practices, 0.1% leakage is considered annually over 30 years plus 1.5% at decommissioning for a total of 4.5% during lifetime.

In such case, the SF_6 GIS carbon footprint is 1.27 higher than the one of the AIS. Finally, we consider 10% leakage over the lifetime. A study from Frauenhofer in 2020 [14] used this percentage as an estimate for end-of-life leakages only, hence 10% lifetime emissions is considered conservative. In this case, the SF6 GIS emission carbon footprint is 2.17 times higher than the one of the AIS.

Table 4 summarizes the comparison largely in favor of the SF_6 Free technology.

Technology	kgCO_2e	Reference unit of measure
AIS	4,198.5	1
SF_6 GIS with 100% lifetime emission	70,674.5	16.8
SF_6 GIS with 4.5% lifetime emission	5,352.5	1.27
SF_6 GIS with 10% lifetime emission	9,114.5	2.17
SF_6 Free GIS	3,116	0.74

Table 4: Summary of the carbon equivalent due to the material composition.

The comparison shows that with best practices, the carbon footprint of SF_6 GIS can theoretically be close to the one of an AIS product. However, going by the common practices, the carbon equivalent of 2.17 times is more realistic.

Although the SF_6 Free GIS requires more material when compared to SF_6 GIS, the footprint is only 74% of the AIS product. In addition to its better footprint, the SF_6 Free GIS also provides all advantages of a traditional GIS in regards with compactness, safety and TCO.

4 Conclusion

Not only SF_6 but all matters with a global warming potential must be prioritized by all utilities without further delay. Twenty years ago, the CIGRE Study Committee 23 published the paper "SF_6 in the Electric Industry, Status 2000" following the Kyoto protocol blacklisting. The urgency is obviously far higher today.

For sure over the last two decades, SF_6 has been favorable for switchgear designers seeking ways to reduce footprint and maintenance costs associated with the use of their products. When comparing the three most important switchgear technologies, total emissions can now be weighted to determine which one is the most suitable to reduce GHG emissions while keeping the cost of capital and maintenance less challenging for utilities.

More than ever, those requirements matter for both traditional transmission utilities and the new ones emerging around local distributors with renewable energy. So, it must be for managing the climate crisis and the balance sheets of all utilities. If utilities have been reporting a lot less emissions than what is measured in the atmosphere, the pressure applied on them will only get a lot greater with carbon tax expected to continue being adjusted upward to manage the energy transition we all need.

The future for designers seeking SF_6 Free alternatives has undoubtedly already started, or it may soon be late as carbon taxes kick in. The new switchgear design scheme, especially at the MV level, must be environmentally friendly, flexible to adapt to existing physical constraints, and safer than ever. If the latest trend is safety-by-design, the new generation of switchgear will be emission-free-by-design.

Knowing that emissions from primary MV switchgears account for up to 15% of the total SF_6 emissions and that SF_6 Free switchgears could be 26% less emitting than traditional AIS products, all substation or powerhouse planners should now turn their attention to the new dry-air MV switchgear solutions when footprint and asset management are on top of criteria.

After years of research and development efforts, thanks to SF6 Free switchgear designers for making MV switchgears as green as it could be while improving TCO further.

References

[1] A. Powell, "Environmental aspects of the use of Sulphur Hexafluoride," ERA Technology Limited, 2002.

[2] "Fourth Assessment Report," IPCC, 2007.

[3] "Sustainable Electricity Annual Report," Canadian Electricity Association, 2019.

[4] "National inventory report 1990-2019: Greenhouse gas sources and sinks in Canada," Canadian Government, Greenhouse Gas Division, [Online]. Available: https://publications.gc.ca/site/eng/9.506002/publication.html.

[5] "Pricing Carbon Pollution," Canadian Government, [Online]. Available: https://www.canada.ca/content/dam/eccc/documents/pdf/climate-change/climate-plan/annex_pricing_carbon_pollution.pdf.

[6] IEEE, "IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems,," in *IEEE 493 Gold Book*, IEEE, 2007, p. 479.

[7] Technical report on alternative to SF6 gas in medium voltage & high voltage electrical equipment, T&D Europe, 2017.

[8] "REPORT FROM THE COMMISSION assessing the availability of alternatives to fluorinated greenhouse gases in switchgear," European Commission, 2020.

[9] L. Xingwen, H. Zhao and A. B. Murphy, SF6-alternative gases for application in gas-insulated switchgear, Journal of Physics D: Applied Physics, 2018.

[10] ECOFYS, "Concept for SF6-free transmission and distribution of electrical energy," ECOFYS, 2018.

[11] ISSF, "Stainless Steel and CO2: Facts and Scientific Observations," in *International Stainless Steel Forum*, 2016.

[12] A. E. Nilsson, M. M. Aragones, F. Arroyo, V. Dunon, H. Angel, K. Komnitsas and K. Willquist, "A Review of the Carbon Footprint of Cu and Zn Production from Primary and Secondary Sources," 2017.

[13] C. Jones and G. Hammond, "Carbon Solutions," 2011. [Online]. Available: https://www.carbonsolutions.com/Resources/ICE%20V2.0%20-%20Jan%202011.xls. [Accessed 12 07 2021].

[14] "Impact assessment of F-gas free medium voltage GIS applications," Fraunhofer Institute of Energy Economics and Energy System technology, 2020.