B3/A3 Colloquium 2023
PS 1. Description

Paper No: 121

Strategy to select SF_6-alternatives and to introduce new technology equipment in the transmission grid of TransnetBW

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SUMMARY

This paper describes the strategy of TransnetBW regarding the selection, testing and introduction of SF_6 alternative gases. This strategy has been defined based on important drivers such as, own experience from pilot projects, market analysis, public acceptance and requirements coming from the policy makers. It is a “must-have” tool, which allows TransnetBW to plan and execute pilot projects with SF_6-free equipment in a structured manner, without delaying the grid expansion projects required by the energy transition.

An important driver behind this strategy is the political context, setting a clear target for Europe to become climate neutral by 2050. In Germany the climate neutrality needs to be achieved by 2045 and the German climate law shows the way to get there. In this context, the regulation on fluorinated gases is again going to be revised, to support the achievement of the above-mentioned targets. Together with an SF_6 ban for the electrical industry, the listing and control through this regulation of other fluorinated gases used as SF_6 alternatives have been announced as well.

Another driver is the own experience of TransnetBW from trial projects of SF_6 alternative gases. In the upcoming years TransnetBW´s share of gas insulated substations will exceed 50 %. In order to solve the chicken-egg-question of “no pilot-projects without reference-projects” there have been both alternatives tested, a fluorinated gas blend and an alternative based exclusively on natural origin gases. This initiative started back in 2018. The projects were executed in parallel, so that the gas handling complexity and performance during the quality tests could be objectively assessed.

Another driver is the market situation. TransnetBW examined for each single substation equipment the availability of SF_6-alternatives. Presently, there is already equipment for air insulated switchgear on the market or under development based on SF_6 alternatives with natural origin gases, from at least two manufacturers. This is a promising situation, giving the confidence that the still missing products will come in time.

KEYWORDS

SF_6-alternatives, SF_6-replacement, emission reduction, substation equipment

1 Where do we come from? Discussions around SF_6.

Today SF_6 is most widely used as arc quenching and insulating gas in transmission and distribution (T&D) equipment. Its properties have been proven in high voltage applications for more than 50 years. However, regarding the climate effect SF_6 is about 25,200 times more harmful than the greenhouse gas (GHG) CO_2 and has a lifetime of 3,200 years in the earth's atmosphere [1]. Thus, despite of leakage rates below 0.1 %/year in case of state-of-the-art-GIS, SF_6 significantly contributes to global warming if it gets into the atmosphere. Consequently, its replacement is essential to mitigate climate change and move towards climate-neutrality. In this regard, SF_6 has been the subject of intense discussions world-wide at the regulatory level starting 1997:

- **1960**'s: Introduction of SF_6 as insulation medium of electrical equipment
- **1997**: Kyoto Protocol - SF_6 gets listed as GHG
- **2005**: Germany introduces a voluntary agreement to limit the SF_6 emissions
- **2006**: Introduction of a regulation on fluorinated gases (F-gas regulation)
- **2014**: First revision of the F-gas-Regulation
    - Introduction of an SF_6 ban in all industries (exceptions: military and electrical industry)
    - Introduction of global warming potential threshold limits for applications relying on F-gases
    - Introduction of an F-Gas-ban for those applications wherefor alternatives are available
- **2022**: Proposals in the second revision of F-Gas-Regulation
    - Introduction of an SF_6 ban in the electrical industry with transition times.
    - Reduction of the GWP-limits for applications relying on F-gases without alternatives
    - Introduction of a ban for further F-gases

The most important instrument in this respect is the regulation on fluorinated greenhouse gases, with the main objectives to discourage the use of F-gases with high GWP, to prevent leakage from equipment and proper end of life treatment of F-gases in all applications, and to enhance sustainable growth, stimulate innovation, and develop green technologies by improving market opportunities for alternative technologies. It can be noticed, that after the introduction of this regulation, the requirements regarding the use of all F-gases were progressively sharpened. The use of SF_6 has also been continuously restricted and it is going to be banned in the electrical industry as well. According to the latest draft of the F-gas regulation SF_6 can only exceptionally be used for military applications in the future [2]. In this context the policy makers need also to make it possible, that the existing SF_6 substation equipment can be operated till the end of their technical lifetime. Their replacement before this point is not sustainable, slows down the grid expansion and does not support the energy transition. Hence, usage of spare parts has to be permitted for repair and maintenance purposes.

2 Where are we going to?

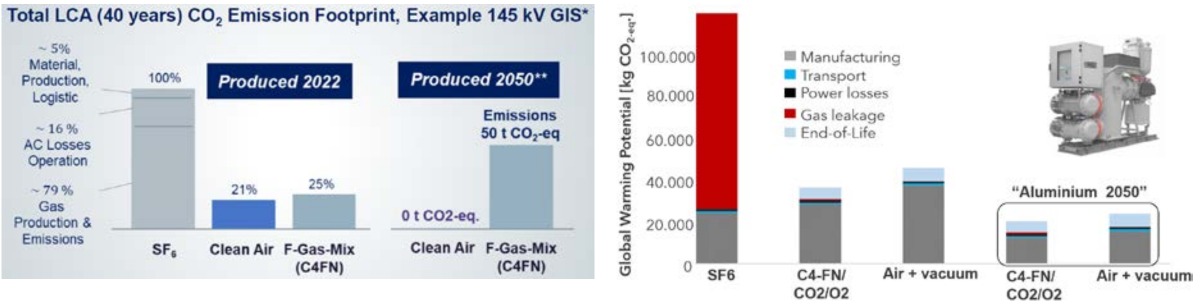
2.1 Potential technologies

Along the time TransnetBW adapted several measures to prevent, identify, and limit SF_6 leakages such as, installation of the switchgear in buildings, installation of gas density monitoring for each gas compartment and each phase separately, reduction of the size of gas compartments, periodic training, and certification of the operation personal etc. With all these measures in place, an average SF_6 leakage rate as low as 0,17 % (including leakages during repair and maintenance) was achieved between 2018 and 2021. This is well below the average of an ENTSO-E European survey accounting for 0.35 % in the same period [3]. However, due to the grid expansion required by the energy transition, it is expected that the amount of SF_6 in operation and the absolute quantity of leaked gas will increase. Under these circumstances, the only solution to sustainably reduce the SF_6 emissions is to reduce the amount of SF_6, which comes in operation with the new equipment. To do so, the grid operators can choose between two alternative concepts. The first one is F-gas free, based exclusively on natural origin gases (NOG), and is based on mixtures of O_2/N_2 or CO_2/O_2. The second alternative concept is based on F-gases, such as fluoronitril (C4-FN) and fluoroketone (C5-FK), proposed to be listed in the Annex 3 of the above-mentioned regulation. From these two products, only the fluoronitril (GWP = 2750) is presently still being used by two equipment manufacturers above 52 kV. However, the two gas mixtures have different compositions and are not interchangeable.

2.2 Compatibility with the European climate targets

The C4-FN belongs to a special category of substances – Per- and Polyfluoroalkyl Substances (PFAS), which are extremely persistent in the environment. Their production and use have resulted in severe contamination of soil, water and food and harmful exposure to humans. The Commission has outlined a comprehensive set of actions to address both the use of PFAS and the contamination they cause in the environment. To prevent further contamination, the actions aim to ensure that the use of PFAS is phased out in the EU, unless it is proven essential for society [4]. Despite of very good dielectric performance of the C4-FN, such intention of the policy makers, makes its future use very unsafe.

Intensive discussions have taken place around the true CO_2-footprint of equipment based on different SF_6 alternatives, as well. Indeed, not only the gas leakage during erection, operation and scrapping leads to CO_2 emissions. There are plenty of other contributors, which needs to be considered, to elaborate a trustful life cycle analysis (LCA). An important contributor is the production of the aluminium from bauxite, which is a very energy-consuming process. This factor is especially important for the NOG-based equipment, as it is larger by design, due to the limited dielectric strength of the natural origin gases. This fact needs to be compensated by larger dimensions of equipment and by an increased gas pressure. Figure 1 presents the LCA results of two important GIS manufacturers, whose equipment relies on NOG and vacuum interrupter (Manufacturer A – left) and a gas mixture based on C4-FN, CO_2 and O_2 (Manufacturer B – right). The results refer to a 145 kV GIS and an equipment lifetime of 40 years. Both manufacturers assessed not only its own product, but the competitor solution as well. Especially interesting from TransnetBW's perspective is the evolution of the LCA in the future. If today the use of more aluminium leads to considerable emissions due to its production, this CO_2-source will significantly decrease by 2050, when the power used by industry is supposed to be 100 % climate neutral. Based on this fact, the LCA proposed by the Manufacturer B shows similar CO_2 footprint results for both technologies. This study clearly indicates that despite of deployment of more material, the NOG-based equipment has a sustainable future.



Manufacturer A – relies on NOG and vacuum interrupter [1]

Manufacturer B – relies on a gas mixture based on C4-FN, CO_2 and O_2 [5]

Figure 1. Life cycle analysis of 145 GIS of two European manufacturers

2.3 Know-How based on own projects

As presented in [1] TransnetBW decided from the very beginning to consider only gas mixtures with a GWP ≤1 as SF_6 alternative gases and decided to start pilot projects at all voltage levels up to 420 kV [9]. Obviously, due to the missing request of SF_6-free equipment on 420 kV level, there were no such products available on the market in 2016 (Chicken-Egg-Problem). Consequently, the next major step was to identify those manufacturers, willing to start the development based on climate neutral gas mixtures.

2.3.1 Experience with F-gas-based gas blends

The first project aiming to support the development of an SF_6-free, double busbar, 420 kV GIS was awarded by TransnetBW in 2018 and taken into operation, as scheduled, in 2021. It has all passive

components (indoor and outdoor) filled with a climate neutral gas mixture based on C5-FK, N_2 and O_2. The project is comprehensively described in [10].
Despite of a highly sophisticated GIS design from service continuity and accessibility perspective, the handling of such gas mixtures in this substation remains an extremely challenging task. As the SF_6-handling devices are not compatible to the C5-FK-gas mixtures, two sets of service carts, gas analysers, leakage detectors etc. were required. Additionally, the C5-FK-gas mixtures were prepared on-site before pumping them in the gas compartments. This is a complex task, which requires not only adequate mixing-devices, but a high level of expertise, as well.
Another challenge of this configuration is the difficulty to decide on how much gas mixture needs to be stored on site for repair or refilling. It needs to be considered that, in gas form a high number of cylinders are required in order to store a relatively small amount of gas. The number of gas bottles can be strongly reduced by gas compression, which in turn leads to the liquefaction of the gas mixture. Therefore, its homogenisation before toping up a gas compartment is mandatory. This step requires the use of an additional service devices and special expertise.

2.3.2 Experience with NOG-Equipment

TransnetBW awarded within a major grid infrastructure project the construction of probably the largest 420 kV GIS in Germany with 33 bays (including extension bays). Alone the gas insulated busducts (GIB) of this switchgear account for more than 4000 m. Considering that the failure risk of the GIB is relatively low [10] in comparison to other switchgear elements (circuit breaker, disconnecting and earthing switches, instrument transformers), TransnetBW decided to test another SF_6 alternative with GWP<1, but this time, based on NOG exclusively. Considering a gas mass of 4 kg/m of GIB at the operating pressure, it results that this measure least to an SF_6 saving potential of about 16 t, which represents 7-8 % of the total amount of SF_6 in the grid of TransnetBW.
Similarly, to the project presented above, the development of the NOG-based GIB was started after the project has been awarded. To mitigate the risks associated with the development of new products, several measures were agreed on together with the manufacturers. TransnetBW was allowed to witness the development progress and the quality tests in the factory. Additionally, TransnetBW, as end user, had had the chance to step out of the contract and to choose the SF_6-GIB, if challenges during the development had been faced. A time span of 36 months was set between the project award and the point of no return. After this milestone, the NOG-based GIB had to be accepted. On the other hand, to avoid delay of the civil works, TransnetBW committed to pay for the larger fundaments right at the beginning of the project. The larger fundaments are required by the NOG-based GIB which are larger (diameter of 60 cm) and heavier than the SF_6 GIBs (diameter of 40 cm). A detailed project description is available in [1] and an updated substation layout is presented in Figure 2.

Figure 2. Updated design of the GIS with NOG-based GIBs

Gas handling aspects were discussed during the product development and the reduced complexity in comparison with the handling of F-gas-based blends was confirmed. The GIS modules can be topped up directly from commercially available gas cylinders. As this NOG-based gas mixture is a standard commodity, there is no need for its homogenisation before the filling process, which implies only the connection of the cylinders to the gas compartment over a universal pressure regulator. The same cylinder can be used for all pieces of equipment relying on N_2/O_2 gas mixtures (GIS, GIB, instrument

transformers, AIS circuit breakers). From TSO perspective the simple and safe handling provides significant advantages, such as, less gas handling equipment, no need for additional mixing, shorter lead times, simplified procurement, logistic and storage, less resources and knowledge etc. This gas mixture can be released into the atmosphere, speeding up the gas works. Special safety equipment and procedures are only required, if heavily arced gas needs to be handled, i.e. only after internal arc faults or making of short circuit currents with make-proof earthing switches [1].
An open point is represented by the possibility to detect leakages on site. After installation the tightness of the GIS will be tested by filling the bays with helium following a well-known factory procedure. However, the detection of leakages during service remains a challenge. There are still no devices, which basically can detect air leakages in air. However, the manufacturer presents in [1] some practical methods meant to overcome this challenge.

2.3.3 Further aspects to take into consideration

The inventor and manufacturer of the C4-FN announced end of 2022, that it will exit the manufacturing of all PFAS by the end of 2025. Among these products is the C4-FN and the C5-FK [6].
In addition, there have been studies published showing that the by-products of C4-FN-based gas mixtures have a higher toxicity than the SF_6 by-products [7]. Other lab study reports on reproducible chemical reactions between C4-FN and gas moisture, resulting in crystal formation, despite of a technically dry gas with desiccants. The formation of polar crystal was observed especially in C4-FN, CO_2, O_2 mixtures being operating down to -10 °C [8].

2.4 Market analysis

As a next step, the substation equipment has been split in three distinct categories relevant to the grid of TransnetBW: GIS, AIS circuit breaker (CB) and AIS instrument transformers (IT) – Table 1. After a careful market analysis relevant for TransnetBW grid, it has been found out, that currently there are at least two suppliers, who have AIS equipment (CB and IT) based on SF_6-alternatives with NOG already on the market or under development. This is a satisfactory situation, even though their portfolios still do not cover all grid applications, and even some standard products are still in the development phase. A more challenging situation has been noticed looking at the development of the SF_6-free GIS with NOG. In this case, there is presently a single European manufacturer going this way. Looking at the international level, there are at least two other manufacturers using the same technology, but they are at an earlier development stage of the product. However, having three manufacturers following the NOG-strategy gives enough confidence in the future.
All above mentioned drivers (political context and public acceptance, technical aspects and market) were put together and led to a strategy, which supports TransnetBW to move progressively away from SF_6 keeping in the same time the risks on a low level.

Table 1. Market analysis of substation equipment with SF_6-alternative gases ($U_m \geq 123$ kV)

Alternative solution to SF_6 1)	GIS		AIS-Circuit breakers		AIS-Instrument transformers	
	Technology	Number of suppliers	Technology	Number of suppliers	Technology	Number of suppliers
F-gas-based blends	$C4 + CO_2 + O_2$	GE HITACHI Energy LS Cable	$C4 + CO_2 + O_2$	GE	$C4+CO_2$ 2)	GE
Natural origin gases	CO_2	SIEMENS Energy MITSUBISHI TOSHIBA	$CO_2 + O_2$	SIEMENS Energy HITACHI Energy PFIFFNER	$N_2 + O_2$	TRENCH PFIFFNER
	$N_2 + O_2$ and vacuum interrupter		$N_2 + O_2$ and vacuum interrupter			

3 Strategy to replace SF_6

The derived strategy proposes a differentiated approach based on voltage level and equipment category and includes two phases: a trial phase to test products (Table 2, light green), and a standard implementation phase, which implies the deployment of NOG-based equipment as “first option” before

SF_6 apparatus (Table 2, dark green). A product will remain in the “light green” phase, if a specific product can be delivered by a single manufacturer only. In this case the SF_6-equipment remains the first preferred option. This way a monopoly situation and dependency of one manufacturer are avoided. Further, it has been decided, that only type tested products are accepted.

According to this strategy, TransnetBW will focus on the AIS equipment of the 110 kV grid firstly and will move towards higher voltage levels, depending on how fast the NOG-equipment is developed and made available to the market with reasonable lead times. On one hand this approach limits the technical risks related to the product development itself (design, field distribution etc.). On the other hand, it allows TransnetBW to faster replace a faulty NOG-based piece of equipment in case of teething problems, as an AIS CB or IT can be easily exchange one-to-one on the existing fundaments.

Based on the favorable market situation with NOG-based equipment from at least two manufacturers, TransnetBW decided to install 123 kV IT and 145 kV CB for AIS as first option starting 2023, excluding the SF_6 equipment. In parallel all projects are assessed, to identify the possibility of further trials with 145 kV GIS, 420 kV IT and GIB, respectively.

The 420 kV GIS and CB for AIS will be handled separately. Presently there is a 420 kV NOG based CB under development. According to the manufacturer roadmap, this is a CO_2 CB and will be released towards the end of 2023 [12]. In this respect, TransnetBW searches already for locations to adequately test this new, innovative product.

Table 2. Strategy to stepwise replace SF_6 against natural origin gases (NOG)

		2023 - 2026	2027-2030	Starting 2031
110 kV Grid	Instrument transformers and circuit breakers for AIS			
110 kV Grid	GIS			
380 kV Grid	GIB and instrument transformers for AIS			
380 kV Grid	GIS and circuit breakers for AIS	Market analysis and technology assessment		
Projects in execution and existing assets are not considered in this strategy. Projects will be executed as contracted. Existing assets will be operated „as is“ till the end of their technical life. SF_6 and spare parts are required for their repair and maintenance.				

Installation of NOG-Equipment as standard products (dark green)

On-site testing of NOG-Equipment within trial projects (light green)

4 Getting SF_6-free

TransnetBW started already in 2016 a journey to replace the SF_6 against more sustainable solutions. The climate neutral gases or gas mixtures with a GWP ≤ 1 have been preferred from the beginning. At the second step, besides the GWP requirement, a NOG-based structure of the SF_6 alternative was included in all product specifications. Based on own experience, market analysis and considering the latest requirements of the policy makers, TransnetBW issued an own strategy on how to replace the SF_6, in an era, when all TSO are planning and executing a high number of grid expansion projects, to make the energy transition possible. In this case, the need to replace SF_6 has to be carefully planned and separately integrated in all projects without delaying them. Having this strategy, TransnetBW can stepwise integrate SF_6-free equipment within the grid expansion projects, necessary for a successful energy transition, without delaying it.

Due to the very positive experience acquired with gas insulated ITs of the previous generation, their replacement against NOG-based ITs is preferred by TransnetBW (instead of the oil insulated ITs). They match to the existing configuration of the substation (bay width) and only the fundaments may need in some cases to be reinforced. There are about 120 oil-IT in the grid of TransnetBW which are approaching their technical end of life and are planned to be progressively replaced within the coming years. Both IT manufacturers prequalified at TransnetBW use the same gas mixture N_2/O_2, with the same concentrations. Therefore, the selection of the NOG as insulation system, enables synergy effects regarding the grid operation and maintenance. Thus, same gas handling devices can be used for gas quality checks, refilling can be performed from the same cylinder, no additional expertise is needed etc. Same way will be adapted to replace the AIS CB. Here products are available up to 145 kV, many applications are covered, but a point-on-wave switching of a shunt reactor is still not possible with an SF_6-free circuit breaker (CB with dedicated drives for each phase are required). Therefore, based on the above shown strategy, TransnetBW started already to assess all relevant projects in order to identify where and how many NOG-based CB are required to avoid project delays due to the very long lead times of these products. The first products are scheduled be delivered by the end of Q3, 2023.

As far as 420 kV GIS is concerned, the development may take some more years, especially, in the area of switching equipment. Here, a case-by-case analysis of the GIS-projects may be needed, which includes a feasibility study regarding the installation of SF_6-free GIB. The target could be, that the SF_6-free GIBs are specified in case of those projects, where at least 50 % of the SF_6 quantity is contained in these components.

In order to succeed in replacing SF_6 in a sustainable manner the repair and maintenance of existing SF_6-equipment in substations has to be guaranteed. Such activities need to be considered by the policy makers, and to be made possible till the end of life of the installed equipment. An SF_6-ban or a ban on spare parts would endanger the energy transition and would overwhelm system operators, as well as manufacturers.

Another important role is played by the equipment manufacturers. They need to intensify their developments efforts to timely release NOG-based products, allowing the TSO to test them within trial projects before the SF_6-ban gets into force. Additionally, the manufacturers have the task to ensure the product availability for the entire market, keeping the lead times within reasonable margins. Any delays possibly caused be the product unavailability leads to more CO_2 emissions, as the green power cannot be integrated.

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