RMU WITH ECO-EFFICIENT GAS MIXTURES: FIELD EXPERIENCE

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ABSTRACT

SF_6 is widely used as the standard technology for power distribution products. However, due to its high global warming potential (GWP), low-GWP alternatives have been explored since the 1990's. ABB has developed eco-efficient gas-insulated switchgear (GIS) solutions based on a new gas mixture, AirPlus™, consisting of dry air and Novec 5110, C5-fluoroketone (C5-FK). A key requirement of the eco-efficient GIS was to maintain the external dimensions of existing SF_6-filled equipment.

In November 2015, Liander and ABB started a long term field experience program and four SafeRing AirPlus ring main units (RMUs) were installed in Liander's network in Flevoland, Netherlands. Gas samples collected on site were analyzed and showed no significant change since the units were installed. The outcome of the measurements and observations during the first year (2015-2016) of service will be discussed in this paper.

INTRODUCTION

Dutch utility Liander and power and automation equipment supplier ABB have a mutual interest in establishing a viable eco-efficient alternative to current SF_6-technology in medium-voltage (MV) ring main units (RMUs). A joint technical project was started in November 2015 to monitor SF_6-free switchgear under operation in a wind farm grid. The intention is to monitor behavior in service for three years.

Compact gas-insulated switchgear (GIS) are key components in MV distribution networks. SF_6 has excellent dielectric, thermal and arc-quenching properties, and has become the preferred insulation medium for GIS. There are currently a few emerging technologies which have in common that they seek to mitigate global warming by finding a non-toxic, non-flammable and low-GWP alternative to SF_6 in GIS [1,2,3,4]. The main technical challenges of replacing SF_6 are the reduced dielectric strength, thermal conductivity and arc-quenching properties of suitable alternatives. In addition, long-term chemical stability and compatibility of the alternative gas with the switchgear materials must be carefully evaluated to ensure that decomposition of the gas is negligible and does not affect the performance of the switchgear [2,4].

During the past years, ABB developed eco-efficient GIS solutions based on a new gas mixture, AirPlus, consisting of dry air and Novec 5110, $C_5F_{10}O$ fluoroketone (C5-FK) with a GWP < 1. The development process showed that since the C5-FK gas is not as inert as SF_6, all materials inside the gas compartment must be verified for compatibility with the gas mixture. A two-step accelerated aging procedure was used for qualifying materials to be used in the GIS. Both the decomposition of the gas and degradation of materials are being investigated during the material qualification process [2]. Long-term aging (up to 35 weeks) at extreme temperature (100°C) showed that gas degradation due to chemical reactions is time- and temperature-dependent, with temperature being the predominant driving factor. For a given temperature, equilibrium was reached within the first few weeks of aging and after an initial period no significant increase in the concentration of decomposition products was observed.

Due to the good dielectric properties of the C5-FK [3], GIS designed for rated voltage of 12 kV with dry air as insulation medium can be uprated to 24 kV rated voltage if filled with AirPlus without increasing the external dimensions of the existing SF_6-filled RMU [1].

In November 2015, four SafeRing AirPlus RMUs were installed in compact secondary substations (CSS) at wind turbines in Liander's grid. All the locations have service voltage of 20 kV and expected loads up to 625 A. Two of the four RMU's are reference units and equipped with instruments to continuously measure and log gas density, temperature and pressure. In addition, at site visits the units were inspected visually and gas samples were collected several times during the first year of operation. The purpose of collecting gas samples is to validate laboratory tests showing that no significant decomposition of the gas or degradation of the units will occur over the lifetime.

MOTIVATION AND EXPECTATIONS

Liander's Point of View

Liander currently mainly uses MV switchgear that is small in size, as it is used in both standard and compact secondary substations. However, this type of MV switchgear cannot be remotely controlled and is not suited for 20 kV. While compact MV switchgear suited for 20 kV and optional remote control do exist, these are SF_6 gas-insulated switchgear.

At Liander sustainability is high on the agenda. The policy regarding the acquisition of assets is to take the integral sustainability of the complete supply chain and use of the assets into consideration. Therefore, Liander actively encourages the development of sustainable grid solutions, such as SF_6-free switchgear.

During Cigré in 2014, alternatives to SF_6 were presented [4] that have not yet resulted in concrete opportunities. New developments now offer possibilities for compact SF_6-free MV switchgear. The aim of Liander in this pilot project is to accelerate the development of insulating media other than SF_6 by providing expert knowledge as well as test locations in the medium voltage grid. In return, Liander gets experience in the usability and operation of such gas-insulated SF_6-free switchgear in its medium voltage grid.

Decisive criteria for joining this pilot project were the successful completion of relevant tests, such as e.g. voltage withstand tests, performed according to IEC standards for MV metal-enclosed switchgear [5]. Also, the dimensions of the switchgear were critical, both the overall dimensions, which were limited by the size of the compact secondary substation, as well as the dimensions of the cable compartment in which standard cable terminations used by Liander had to be applicable.

The first international climate agreement was adopted by 195 countries in 2015 and came into force on November 4th, 2016. It states that the emission of greenhouse gases has to be reduced rapidly. A serious task, and one in which distribution system operators, like Liander, carry a social and moral responsibility. Both in reducing their emissions and supporting the development of sustainable grid solutions.

ABB's Point of View

The motivation for developing an SF_6-free RMU dates back to March 22nd, 2002 when the electrical energy industry in Norway, including ABB as sole manufacturer, signed an agreement with the Norwegian Minister of Environment to reduce SF_6 emissions by 50%. In addition, ABB committed itself to exploring design opportunities to exclude the use of SF_6 in the next generation of compact gas-insulated switchgear for secondary distribution. ABB stood by its commitment in two steps. First in 2013, for 12kV needing only dry air to meet the IEC requirements [6], and second in July 2016 when an RMU for 24 kV utilizing AirPlus was released for selected markets. However, the path was long and many lessons had to be learned in order to introduce a new green technology to compete with the mature SF_6-technology. Field experience was needed to be able to validate lifetime expectancy and foresee potential opportunities for improvement. Typically, the conservation of the C5-FK content is imperative for lifetime operation and changes to its quality is seen as an important health indicator for the insulation gas in the switchgear.

A cooperation between Liander and ABB has made it possible to embark on long-term field test.

AIRPLUS TECHNOLOGY

During the last decades, many gases and gas mixtures have been explored while searching for a more favorable medium than SF_6 for breaking currents and insulating live parts within electrical switchgear. In the 1960's, the motivation was initially to find a less hazardous medium than SF_6, and later in the 1990's it was the awareness of global warming and the extreme GWP of SF_6. At the very first international symposium organized by the US EPA in San Diego in 2000 dedicated to SF_6 as the most potent climate gas, it was then predicted that no stone would be left unturned to fight the emissions of SF_6. Candidates identified throughout time were either toxic, corrosive, unstable or incompatible with their environment [7].

Over the past ten years, a new generation of gases with acceptable properties have emerged. These gases typically have a low GWP, and contemporary research and analysis tools have made it possible to explore these as promising alternatives to SF_6 even if many compromises are made tolerable to arrive at a reliable technology. Eco-efficient alternatives typically lack the excellent arc-quenching, dielectric withstand and cooling properties of SF_6. These technical challenges must be solved by careful switchgear design.

ABB has recently introduced a low-GWP gas mixture, AirPlus, as an alternative to SF_6. AirPlus is based on the Novec 5110 Dielectric Fluid and dry air. The C5-FK has a very low GWP (< 1) and good dielectric properties, but pure C5-FK has a high boiling point (26.9°C) and vapor pressure (94 kPa @ 25°C). To avoid condensation of the C5-FK within the required IEC temperature range of -25°C to 40°C for MV secondary switchgear, the fluoroketone must be mixed with a background gas such as dry air. For a total RMU filling pressure (@ 20°C) of 1400 mbar, 107 mbar is C5-FK and the rest is dry air.

DESCRIPTION OF PROJECT

The project comprises the installation of SF_6-free MV switchgear in the MV grid of Liander.

As the Liander medium voltage grid operates under various conditions and considering the wish for accelerating development as well as the need to establish a viable, sustainable alternative to SF_6, a statistically representative number of four units was agreed upon.
The installation of these four units under the following varying grid conditions was proposed:

1. High variable load (one switchgear unit)
2. Low variable load (one switchgear unit)
3. Average variable load (two switchgear units)

Based on these grid condition criteria, test sites were determined where the existing MV switchgear was already due for replacement in the near future. The selected compact secondary substations are located in the province of Flevoland in the Netherlands and are supplied from the primary 150/20 kV substation Zeewolde. This area holds many wind farms, resulting in diverse load conditions:

1. CSS 1 - High variable load: Expected load between 35A and 625A
2. CSS 2 – Low variable load: Expected load between 0A and 25A
3. CSS 3 – Average variable load: Expected load between 0A and 275A
4. CSS 4 – Average variable load: Expected load between 0A and 275A

The RMUs in the CSSs in Zeewolde are 3- and 4-way SafeRing AirPlus units. The switchgear configurations consist of cable switch (C) and vacuum circuit-breaker (V) panels where switching is done by vacuum interrupters for both types of panels. Three CCV units and one CCCV unit are installed in the respective CSS locations. All SafeRing RMUs are sealed-for-life and the different modules (e.g. CCV) share one common gas compartment. One motivation for the project is to verify the behavior of the gas during switchgear service under wind farm conditions. The switchgear units in CSS 1 and 3 were therefore equipped with data logging equipment and extra valves for easy access to gas sampling to monitor the quality of the gas over the duration of the project. Remote read-out of this equipment was not possible, however, so it was agreed that read-outs of e.g. gas composition data, would be done on-site for a period of three years. The switchgear units in CSS 2 and 4 have no additional monitoring equipment.

The data loggers are of the type ISSYS GDM (Density measurement for Gases), which is an instrument that can measure and log gas pressure, temperature and density. Data from the units' internal memory would be downloaded at the times of site visits for gas sampling.

Figure 1. SafeRing AirPlus CCV switchgear installed at CSS 3 in Zeewolde, Netherlands.

Gas samples for laboratory analysis have been collected several times during the first year after energizing the units. The gas samples were collected in Swagelok stainless steel sample cylinders. The sample cylinders were evacuated to a pressure of 1-2 mbar before each site visit and closed with a needle valve in one end and a quick-connect valve in the other end. For safety reasons, the RMUs had to be turned off before each gas sampling.

Prior to collecting each sample, a DPI 705 Digital Pressure Indicator was connected to the quick-connect valve of the sample cylinder. This device was used to measure the gas pressure in the cylinder before and during sample collection. It was expected that there would be some leakage of air into the cylinders during the period between evacuation and sample collection. The pressure readings before gas sampling would therefore be used to correct the measured C5-FK concentration due to dilution by gas trapped in the sample cylinder. This is reported as uncertainty in the measured concentrations. The cylinder needle valve was closed when the pressure indicator reached equilibrium. Two samples were collected from each RMU at each site visit. The samples were shipped to ABB Corporate Research Center (CRC) in Dättwil, Switzerland, for gas composition analysis by gas chromatography with mass spectrometric detection (GC-MS), Fourier-transform infrared spectroscopy (FTIR) and UV-absorption of Novec 5110. The UV-absorption method uses a fiber-optic sensor system developed by ABB CRC to determine C5-FK concentration in a gas mixture [8].

Figure 2. Gas sample cylinder with digital pressure indicator, DPI 705, connected before sampling.

MEASUREMENT RESULTS

Laboratory measurements have shown that heptafluoropropane (C_3HF_7) is a decomposition product of the C5-FK that can be measured in the gas. The concentration of heptafluoropropane can therefore be used as a measure of the condition of the gas over time.
GC-MS analysis was performed with an Agilent 7890B gas chromatograph with an Agilent 5977A mass spectrometer. These measurements are made to quantify the heptafluoropropane concentration in the insulation gas. The UV-absorption method was then used to determine the C5-FK concentration in each sample. Examples of chromatograms are shown in Figure 3. The main results of gas sample analyses (C5-FK and decomposition product concentrations) given in Table 1 a) and b). The lowest calibration standard used for heptafluoropropane was 50 ppm, so concentrations below this level are reported as < 50 ppm.

During the first download of data from the data loggers, problems were experienced with the communication port and only pressure and temperature data from the first 3 months of operation were transferred. The remaining data will have to be extracted at the end of the project (3 years) when the internal memory of the instrument can be accessed. The graphs below show examples of gas temperature and pressure over several days taken at different times since energizing the switchgear in CSS 3 on 11.11.2015.

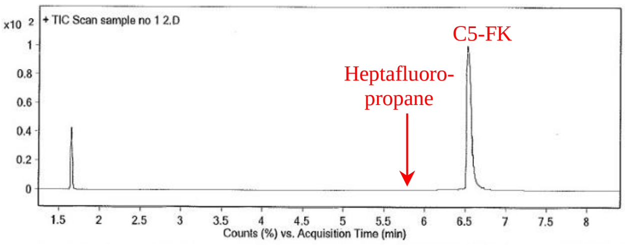
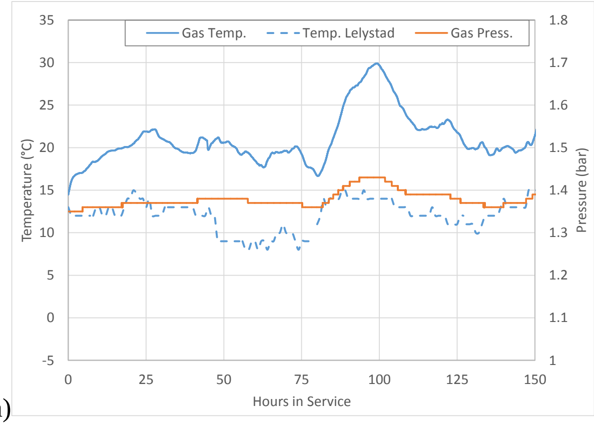
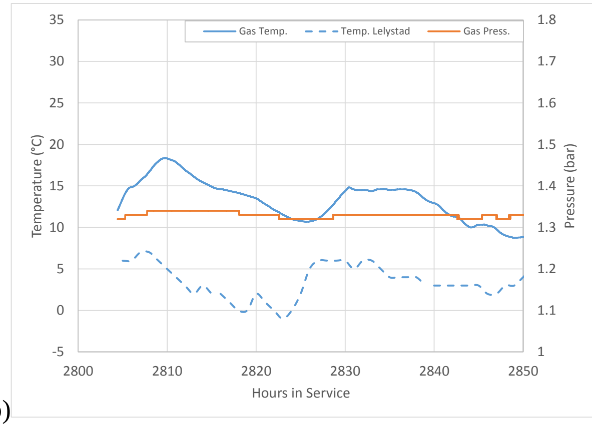


Figure 3. Example chromatogram from gas sample taken 30.3.2016 from RMU installed at site CSS 3.



(a)



(b)

Figure 4. Examples of gas temperature (blue) and absolute pressure (orange) vs. time recorded a) 0 – 150 hours and b) 2800 – 2850 hours after energizing the unit in CSS 3.

DISCUSSION OF MEASUREMENT RESULTS AND FIELD EXPERIENCE

Pressure and temperature:
Recorded data shows that the absolute gas pressure as expected will vary as a function of gas temperature. No significant drop in pressure that would indicate gas leakage has occurred. The temperature of the surrounding air is not measured at the installation sites. Hourly data from the nearby weather station (Lelystad, Netherlands) was used for comparison with the measured gas temperatures. As expected, the temperatures measured by the ISSYS device follow the variations of the ambient air with some variations that are likely due to the load variations at CSS 3. On average, the gas temperature is ~10°C higher than the air temperature in the area.

C5-FK concentration:
The measured fluoroketone concentrations given in Table 1 show some variations between the different measurements. However, the fluctuations are both above and below the initial filling concentration and are most likely due to measurement uncertainty. The UV-absorption method used for quantification of C5-FK has a measurement uncertainty of ±0.07%. Another factor contributing to the measurement uncertainty is that the

Table 1. Measured C5-FK and heptafluoropropane concentrations in the gas in the RMUs at (a) CSS 3 and (b) CSS 1 over a period of approximately one year.

a)

Sample date	Novec 5110 Concentration	Heptafluoropropane Concentration
11.11.2015	7.6% ± 0.1%[1]	< 50 ppm
30.03.2016	7.7% ± 0.2 %	< 50 ppm
30.03.2016	7.5% ± 0.2 %	< 50 ppm
23.09.2016	7.2% ± 0.1 %	91 ppm
23.09.2016	7.5% ± 0.1 %	< 50 ppm
01.12.2016	7.5% ± 0.2 %	< 50 ppm
01.12.2016	7.6% ± 0.2 %	< 50 ppm

b)

Sample date	Novec 5110 Concentration	Heptafluoropropane Concentration
16.11.2015	7.6% ± 0.1%[1]	< 50 ppm
22.09.2016	7.6% ± 0.1 %	55 ppm
22.09.2016	7.6% ± 0.1 %	< 50 ppm
01.12.2016	7.3% ± 0.3 %	< 50 ppm
01.12.2016	7.7% ± 0.3 %	< 50 ppm

amount of gas trapped in the sample cylinders was different for each measurement. A simple procedure for estimating total measurement uncertainty based on the initial pressure in each cylinder was used and is reported in the tables. Most of the readings are within the measurement uncertainty of the initial concentration, but one sample on 23.09.2016 from CSS 3 has a particularly low C5-FK concentration. However, the next samples taken from this RMU all had C5-FK concentration at or near the initial concentration. It is therefore likely that the one low result is an outlier due to sample contamination or measurement error.

Heptafluoropropane concentration:
The results show that except for one data point, all the measurements of heptafluoropropane are near or below the lowest calibration limit (50 ppm) of the GC-MS. One measurement is significantly higher than the rest; however, the concentration was back to less than 50 ppm for the next sample from this unit. It is reasonable to assume that the higher concentration was caused by sample contamination or measurement error.

Field data from the first year of service indicate no significant changes in gas composition or pressure. The measurements show that the concentration of decomposition products is consistently below the lowest calibration limit. This agrees well with the expectations for this gas when the materials inside the gas compartment have been qualified for material compatibility.

CONCLUSIONS

Four SafeRing AirPlus RMUs have been in service in compact secondary substations in Liander's network in Flevoland, Netherlands since November of 2015. Data and gas samples collected from two of the four units show that the insulation gas behaves as expected. The outcome of this field experience so far, combined with years of scientific research, strengthen the expectation that the use of AirPlus insulation gas will not affect the common lifetime expectation of gas-insulated MV secondary switchgear.

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1. This value was not measured by the UV-LED method, but is the target Novec 5110 concentration when the units were filled in the factory and measured with the ISSYS gas density measurement instrument.