RMU with eco-efficient gas mixture: Evaluation after three years of field experience

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ABSTRACT

Gas-insulated switchgear (GIS) are key components in medium voltage (MV) distribution networks. SF_6 gas is the preferred insulation medium for GIS. However, SF_6 has a high global warming potential (GWP) of 22800 and might be targeted for replacement by the EU Commission. Power and automation equipment supplier ABB has developed eco-efficient GIS solutions based on the AirPlus™ gas mixture consisting of dry air and Novec 5110 $C_5F_{10}O$-fluoroketone (C5-FK). For MV secondary distribution applications, the AirPlus gas mixture must have a dew point below -25°C.

A three-year field experience program was started in November 2015. Four SafeRing AirPlus ring main units (RMUs) were installed in Liander's network in Flevoland, Netherlands. Gas samples were collected and analysed several times per year and the units were visually inspected during site visits. Two of the four RMUs were returned to ABB for further inspection at the end of the 3-year period.

The results of the gas analysis and measurements confirmed that no significant change has occurred since the units were installed and energized. The outcome of the measurements and observations during and after the three years (2015-2018) of service will be discussed in this paper.

INTRODUCTION

Dutch utility Liander and ABB have a mutual interest in establishing a viable eco-efficient alternative to current SF_6-technology in MV ring main units. A joint field experience project was started in November 2015 with the objective to monitor SF_6-free switchgear under normal service conditions in a windfarm network. The intention was to monitor the behavior of the equipment in service for several years. For this pilot project, four SafeRing AirPlus RMUs were installed in compact substations at wind turbines in Liander's network. All installations have a service voltage of 20 kV and loads up to 630 A. The motivation for this joint project and results after the first year were discussed in more detail in [1].

Two of the installed RMUs were used as reference units and were equipped with instrumentation to measure and log gas density, temperature and pressure. In addition, the units were inspected visually and by Infrared Thermography and samples of the C5-FK insulation gas were collected from the RMUs during site visits several times per year. The gas samples were analyzed for C5-FK and decomposition product concentration by gas chromatography mass spectroscopy (GC-MS), Fourier transform infrared spectroscopy (FT-IR) and UV absorption [2]. The objective of the gas measurements was to verify laboratory measurements showing that the insulation gas was not degraded during switchgear operation. The outcome of the measurements and observations during the three years will be discussed in this paper.

Another objective of this project was to confirm that the gas did not adversely affect the properties and expected lifetime of components in the gas compartment. All materials used in the SafeRing AirPlus products have been selected based on a rigorous two-step material qualification procedure that was described in [3]. This procedure considers the possibility of chemical reactions causing degradation of the insulation gas, switchgear components or both. Two of the units were therefore taken out of service after three years and returned to ABB for evaluation. The gas compartment of the switchgear was opened to verify that the gas had not negatively impacted the condition of the RMUs internal components. This was done through visual inspection and verification of mechanical and electrical condition of the switchgear. Results and observations of the evaluation will also be discussed in the paper.

AIRPLUS TECHNOLOGY

Many gases and mixtures have been considered as possible alternatives to SF_6 for current interruption and insulating parts within electrical equipment. Candidates investigated over the past decades were found to be either toxic, corrosive, unstable or incompatible with their environment [4]. ABB has been committed to exploring design opportunities to exclude the use of SF_6 in compact gas-insulated switchgear for secondary distribution since 2002 when the electrical energy industry in Norway signed an agreement with the Norwegian Minister of Environment with the intent to reduce SF_6 emissions by 50%.

ABB's approach was to solve this in two steps. In 2013, a solution for 12 kV needing only dry air to meet the IEC requirements [5] was introduced. ABB then introduced the low-GWP gas mixture, AirPlus, as an alternative to SF_6 which was suitable for use in RMUs with rated voltage higher than 12 kV. AirPlus is based on the Novec 5110 Dielectric Fluid and dry air. Pure C5-FK gas has a GWP < 1 and good dielectric properties, but the 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 (abs.), 107 mbar is C5-FK and the rest is dry air. In 2016 the first RMUs for 24 kV utilizing AirPlus insulation gas was released as an official product for selected markets.

DESCRIPTION OF PROJECT

For the project, four SafeRing AirPlus switchgear were installed in the MV grid of Liander in the province of Flevoland in the Netherlands. Secondary substations in this area are connected to the primary 150/20 kV substation in Zeewolde.

In order to expose the switchgear to different operating conditions, secondary substations for the 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)

This area holds many wind farms, resulting in the following load conditions for the selected compact secondary substations (CSS):

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 installed RMUs were 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 were 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 objective of the project is to verify the behavior of the insulation gas during switchgear service under wind farm conditions. The switchgear units in CSS 1 and 3 were therefore equipped with data logging equipment and a quick connect valve for collecting gas samples during site visits. The switchgear units installed in CSS 2 and 4 have no additional monitoring or gas sampling equipment.

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

Gas samples for laboratory analysis were collected from the units in CSS1 and CSS 3 several times per year during the three-year period after energizing the switchgear. The gas samples were collected in 150 ml 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 in Liander's installations 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 after each sample collection. It was noticed that there would be some leakage of air into the cylinders when moving the pressure sensor from one sample cylinders to the next. The pressure measurements taken directly before the 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. Once the quick-connect valve was connected to the sample cylinder, the needle valve was opened, and a gas sample collected. The cylinder needle valve was then closed when the pressure indicator showed that equilibrium between the cylinder and switchgear had been reached. The equilibrium pressure was recorded for each sample collected. Two gas 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 GC-MS, 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 [2].

During several of the site visits, the RMUs were also evaluated for abnormal activity using IR thermography. IR thermograms were acquired with a FLIR T620 camera equipped with a FOL25 lens.

EVALUATION OF SWITCHGEAR AFTER THREE YEARS

In December 2018, the RMUs that were not equipped with gas monitoring equipment and sampling valves were returned to ABB for evaluation. The RMUs in CSS 1 and 3 will remain in service. Both returned units were CCV configurations.

At ABB's factory in Skien, Norway the condition of the switchgear was evaluated by performing dielectric and mechanical tests as well as visual inspection of the components within the gas volume.

Dielectric Testing

The dielectric condition of the switchgear was evaluated by repeating two of the normal routine tests performed before the switchgear was delivered from the factory:

1. Power frequency dry test according to IEC 62271-200, clause 7.1 [6]. The test was performed with a test voltage of 50 kV AC for a duration of 1 minute.
2. Partial discharge (PD) measurement according to IEC 62271-200, clause 7.101. Partial discharges have been measured according to procedure as described in Annex B with a test voltage of $1.1U_r$

Mechanical Operations

To verify that the switching components had not been structurally weakened by the exposure to the gas over the three years, mechanical endurance testing of the switches in the first C-panel was performed. 1000 close/open (CO) operations were performed on the vacuum interrupter, disconnector and earthing switch in panel C1. Resistance measurements along the current path C1 – C2 were performed before and after the 3000 switching operations.

Visual Inspection of Components

Once the electrical and mechanical testing was completed, the insulation gas was evacuated from the switchgear and the gas enclosure opened by cutting out the rear wall. The switching assemblies were then removed from the encapsulation for visual inspection of the components.

MEASUREMENT RESULTS

Gas Analysis

During the development phase of the AirPlus products, laboratory measurements showed that heptafluoropropane (C_3HF_7) is a stable decomposition product of the C5-FK that can be quantified in the gas by GC-MS. The concentration of heptafluoropropane can therefore be used as an indicator 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. A typical chromatogram from a gas sample is shown in Figure 2. The UV-absorption method [2] was used to determine the C5-FK concentration in each sample. Examples of chromatograms are shown in Figure 2. The main results of gas sample analyses (C5-FK and decomposition product concentrations) given in

Table 1. The lowest calibration standard used for heptafluoropropane was 50 ppm, so concentrations below this level are reported as < 50 ppm. For the last sampling at each location the recorded equilibrium pressures were 1391 mbar (abs.) and 1379 mbar (abs.) at CSS1 and CSS3, respectively. The recorded pressure readings have been corrected for a temperature of 20ºC.

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

a)

Date (mm-yy)	C5-FK (%)	C_3HF_7 (ppm_v)
11-15	7.6 ± 0.1[1]	< 50
09-16	7.6 ± 0.1	55
09-16	7.6 ± 0.1	< 50
12-16	7.3 ± 0.3	< 50
12-16	7.7 ± 0.3	< 50
07-17	7.3 ± 0.1	100
12-17	7.8 ± 0.1	< 500[2]
12-17	7.8 ± 0.1	< 500[2]
04-18	7.7 ± 0.1	N.D.[3]
04-18	7.6 ± 0.1	N.D.[3]
10-18	7.3 ± 0.1	< 50
10-18	7.4 ± 0.1	< 50

b)

Date (mm-yy)	C5-FK (%)	C_3HF_7 (ppm_v)
11-15	7.6 ± 0.1[1]	< 50
03-16	7.7 ± 0.2	< 50
03-16	7.5 ± 0.2	< 50
09-16	7.2 ± 0.1	91
09-16	7.5 ± 0.1	< 50
12-16	7.5 ± 0.2	< 50
12-16	7.6 ± 0.2	< 50
07-17	7.1 ± 0.1	< 50
07-17	7.8 ± 0.1	51
12-17	7.8 ± 0.1	< 500[2]
12-17	7.8 ± 0.1	< 500[2]
04-18	7.6 ± 0.1	N.D.[3]
04-18	7.7 ± 0.1	N.D.[3]
08-18	7.2 ± 0.1	N.D.[3]

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.

2. Lowest available calibration standard for these measurements was 500 ppm.

3. Not detectable with GC-MS.

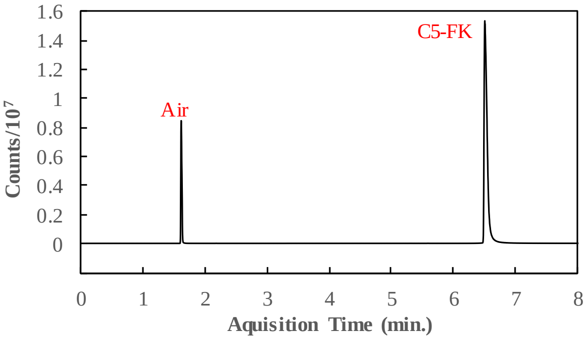

Figure 2. Example chromatogram from gas sample taken 02.01.2019.

IR Thermography

An example of an IR image showing temperature distribution in the cable compartment of an RMU at CSS 4. The load at this location during this visit was greater than 50%. It is clear from the image that there were no signs of thermal abnormality of the cable terminations and cable compartment.

Figure 3. Example of IR image acquired during inspection of RMU on 29.09.2016.

Dielectric Tests

Both the 50 kV power frequency and the partial discharge tests performed on the returned switchgear were passed in the factory. PD levels were measured before and after the power frequency (P. F.) test and compared with the values recorded during routine testing of the product in 2015. These values are shown in Table 2.

Table 2. PD values measured in phase, L_1, L_2 and L_3 of returned SafeRing AirPlus before and after 3 years in operation for RMU installed at CSS 4.

	PD_{L1} (pC)	**PD_{L2} (pC)**	**PD_{L3} (pC)**
Routine Test Sep. 2015	11	8	7
Before P. F. Test Jan. 2019	6	8	4
After P. F. Test Jan. 2019	6	4	6

Mechanical Operations

The 3000 CO operations were performed successfully without damage to mechanical components. Resistance of the three phases of the current path from panels C1 to C2 was measured before and after the switching operations and compared with values recorded during manufacturing of the switchgear.

Table 3. Resistance of the main current path in phases L1, L2 and L3 of returned SafeRing AirPlus measured before and after 3 years in operation for RMU installed at CSS 4.

	R_{L1} (μΩ)	**R_{L2} (μΩ)**	**R_{L2} (μΩ)**
Routine Test Sep. 2015	188	172	192
Before P. F. Test Jan. 2019	200	181	200
After P. F. Test Jan. 2019	238	212	214

Visual Inspection

Once the gas enclosure of the switchgear was opened the internal components were thoroughly inspected for signs of degradation. All components and the inside surfaces of the gas enclosure appeared as new and unused.

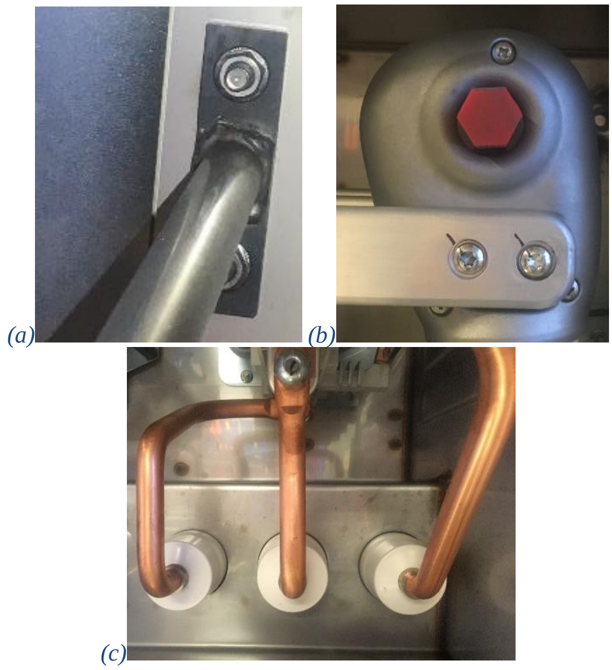

Figure 4. Pictures showing metal components within gas enclosure of field test unit after 3 years of service. (a) Stainless steel internal supporting rod welded to stainless steel plate, (b) cast aluminum vacuum interrupter pole house and extruded aluminum bus bar and (c) bare copper conductors.

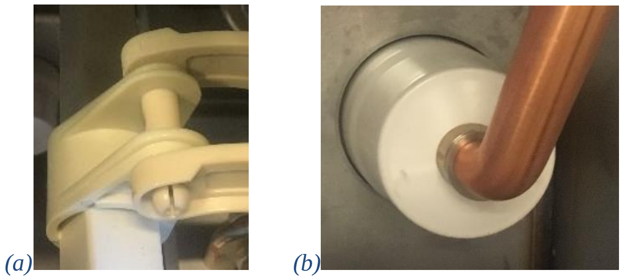

Figure 5. Pictures showing polymer parts from returned and opened field test switchgear. (a) Molded glass fiber filled PBT parts and (b) cast epoxy bushing.

DISCUSSION OF RESULTS

C5-FK and heptafluoropropane concentrations

The measured fluoroketone concentrations given in Table 1 show some variation over the three-year duration of the project. At initial filling of the unit, the C5-FK concentration was 7.6%. The data showed fluctuations that are both above and below this initial filling concentration. The UV-absorption method used for quantification of C5-FK has a measurement uncertainty of ±0.07%. A significant factor contributing to the measurement uncertainty is that the 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. Except for the first samples acquired in July of 2017 all samples are within ±5% of the initial concentration. It is clear that there is no trend of a change in C5-FK concentration over the 3-year period.
Except for a few data points, all the measurements of heptafluoropropane are below the lowest calibration limit of the GC-MS. As discussed for the C5-FK concentration, 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. The data from three years of service indicate no significant changes in the gas composition. The concentration of decomposition products is consistently below the lowest calibration limit which agrees well with the expectations for this gas when all the materials inside the gas compartment have been qualified for compatibility.

Dielectric Tests

Both dielectric tests performed in the factory were passed. All the measured PD-values are well below the highest acceptance criterion and there are no signs of degradation after the three years.

Mechanical Operation

The main purpose of performing the 3000 CO operations on the one panel was to verify that no switching components were mechanically weakened. The switching operations were performed without causing damage to the parts and only slight increase in the resistance was the results. This increase is to be expected after 2000 CO operations with knife type contacts.

Visual Inspection

When the switchgear gas compartment was opened it was clear that the material qualification procedure had worked as expected. There are no visual signs of degradation to any materials that had been exposed to the gas during the three years of the project. Example images showing the as-new surface conditions of different metals and polymers are shown in Figures 4 and 5. From the same images it was also clear that the inside of the stainless steel gas enclosure was unaffected by the gas.

CONCLUSION

Four SafeRing AirPlus RMUs have been in service in compact secondary substations in Liander's network in Flevoland, Netherlands since November of 2015. Gas samples have been collected during the three years and two RMUs were returned to ABB for testing and inspection. The results showed that the AirPlus gas mixture is stable and does not adversely affect the switchgear materials. This three-year field experience project has strengthened the confidence in the material qualification procedure and the expectation that the use of AirPlus insulation gas does not affect the common lifetime expectation of gas-insulated MV secondary switchgear.

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