PILOT OF AN ENVIRONMENTALLY FRIENDLY SF_6-FREE MV SWITCHGEAR TECHNOLOGY AND ASSESSMENT OF SENSOR TECHNOLOGIES

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ABSTRACT

SF_6 gas has been used as insulation medium as well as electrical current breaking medium for the past decades. Although SF_6 has exceptional gas properties for switchgear applications, an alternative to SF_6 is desired due to its very high global warming effects and high costs of gas handling and maintenance.
The start-up Nuventura has developed a new technology of gas insulated switchgear (GIS) using dry compressed air as an insulation medium for medium voltage (MV) applications up to 36 kV. Currently, a prototype of this new technology is set up for pilot testing in an MV grid of Westnetz. Additionally, innovative modern sensors applicable for medium voltage are tested and assessed in the demonstrational GIS prototype.
The goal of this project is to prove practical feasibility and assess the economic advantages of using compressed dry air as an insulation medium for GIS applications and examine the functionality and reliability of the sensors.

INTRODUCTION

Current MV gas insulated switchgear (GIS) technologies use SF_6 or other mixtures of synthetic gases as insulation medium due to its various benefits such as the dielectric strength and because it is non-toxic, non-flammable and chemically stable. However, a critical drawback is its environmental impact as it is classified as a hazardous greenhouse gas [1]. Therefore, handling the gas causes high costs in production and maintenance. For this reason, GIS are usually hermetically sealed and allow almost no serviceability. In case of the need for service, cost intensive gas handling processes are necessary.

Alternatives to SF_6 in GIS

The ideal replacement for SF_6 in MV switchgears would be a new chemical composition of gas which shows equal or higher performance in terms of dielectric, thermal and electrical breaking characteristics; at the same time possessing attributes such as no toxic by-products, being non-flammable and being environmentally friendly.

Although many alternate solutions have been discussed, they tend to have various limitations. One group of alternatives are natural gases such as air, nitrogen and carbon dioxide. These gases possess natural sinks in the atmosphere and are part of natural cycles such as carbon cycle. Moreover, the natural gases have been proven to be non-toxic and have been used in various applications, meaning the gas itself does not require gas qualification.

Advantages of dry compressed air

Dry compressed air is a naturally occurring gas without greenhouse gas potential [2]. One of the most important advantages of replacing SF_6 by dry compressed air is accessibility to the GIS vessel for maintenance and service. No SF_6 evacuation process is involved and leakage will not lead to adverse environment effects. In addition, a dry air solution is easier to maintain. The usage of air also eliminates expensive gas handling at the manufacturing line of suppliers and at the end user. Furthermore, installation and service of additional technologies such as wireless sensors becomes possible.

Design constraints for an SF_6-free design

By using SF_6 as insulation gas during the last decades, the components used in MV switchgears have been considerably simplified. The design of an SF_6-free GIS thus faces different challenges to be adequately modified. Nuventura’s novel solution has been developed to address these challenges and the two major concerns: namely dielectric performance and thermal performance.

Dielectric performance

Natural gases generally range from dielectric strength of 2.2 kV/mm to 3.0 kV/mm as compared to 8.9 kV/mm for SF_6 at ambient pressure. One of the most important aspects of the design involves the interaction of the dielectric medium with polymeric components. When a gaseous dielectric medium is in contact with a polymeric surface in combination with components at high voltage, a critical electric stress region is formed, generally known as triple points. In the current design, the failure points are generally regions with a low homogeneity factor η or unavoidable triple points. This enables a modular dielectric design which allows for increased dielectric performance with increase in the pressure. This enables a modular arrangement that can be used at various pressure levels to achieve 12 kV, 24 kV and 36 kV solutions [4].

Thermal performance

Natural gas such as air has better thermal conductivity than SF_6. Also, the heat capacity of air is slightly higher than SF_6. However, air is five times less dense than SF_6 at 25°C. Thus, the effective heat capacity in a given constant volume is 4.4 times higher for SF_6 as compared to air. Hence, an SF_6-free design using natural air requires cautious design to obtain better thermal performance. For instance, increase in pressure of the gas insulated tank not only increases the dielectric strength but also increases effective heat capacity.

In order to assess the thermal performance of the dry air insulation against SF_6 gas insulation, the gas tank module has been simulated using Ansys Fluent. The side walls were considered to be non-convective, the mid walls were considered to be convective.

Table 1: Thermal Properties of SF_6 and air [3]

Properties at 25°C	**SF_6**	**Air**
Density (kg/m^3)	6.04	1.18
Heat capacity (C_v) kJ/(kg·K)	0.61	0.718
Thermal conductivity (mW/m·K)	13.4	26.2
Effective heat capacity (kJ/m^3·K)	3.68	0.85

In order to find out the total effect of the gas on the conductors, the average temperature of the conductor is calculated for dry air and SF_6 insulation under varying filling pressure with an input electric current of 650 A. The results are plotted in figure 1.

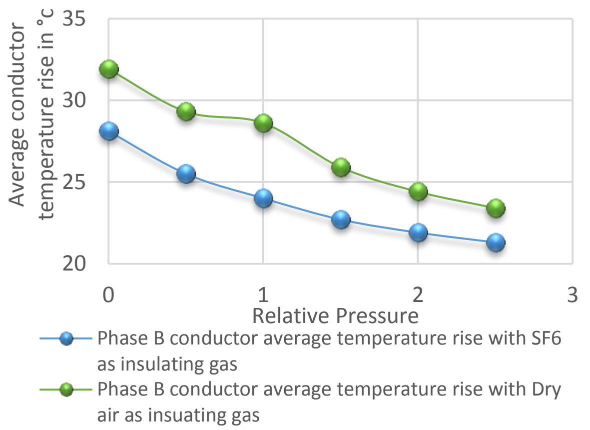

Figure 1: Simulation results of thermal performance of SF_6 and dry air at varying pressure

It is interesting to compare the performance of two gases for the same boundary condition. It can be seen that the average temperature of the conductors in SF_6 at 0 bar and 1 bar overpressure can be reached in dry air at 1 bar and 2 bar overpressure respectively. Hence, an increase in pressure of the system can help both dielectric and thermal performance with dry air insulation.

A higher pressure requires a more expensive structural design of the steel compartment to withstand the operative pressure as well as short time pressure peak in case of a destructive internal arc event.

THE NOVEL PRIMARY GIS SOLUTION

In the current design of the start-up Nuventura, a GIS based on dry air insulation is realized. The dimensions have been kept under the limits such that an existing SF_6 switchgear can be replaced by the new solution.

In the current solution, the busbar compartment is replaced by a solid insulated busbar system. This solution has many advantages as compared to an SF_6 based busbar solution. The assembly and disassembly of the busbar compartment is easier and faster. This is particularly important in situations when one of the switchgear panels should be replaced in the switchgear bay or an extension of the gear becomes necessary. Also, the solid insulated busbar provides good adjustment against the dimensional tolerances as compared to solid insulated links from the SF_6 insulated busbar compartments. Hence, such a solution is interesting for end users.

Figure 2: GIS solution based on dry air insulation and solid insulated busbar for 36 kV (Source: Nuventura)

Accessibility to the switching compartment

One of the important characteristics of common GIS solutions is that they are sealed for life time. Most of the MV GIS consist of a completely welded gas tank. Such a solution reduces the SF_6 gas leakage and thereby increases the reliability of the GIS. However, the welded gas tanks make the switching components inaccessible for the complete life time. This limits certain maintenance which may improve product life time. Furthermore, such a solution offers limited opportunities to include active or passive sensors which can measure switchgear health parameters such as partial discharge and temperature on conductors.

In the novel solution, an access is provided from rear end of the product by means of a sealed lid that can be reached through the AFLR gas duct. During normal operation, the AFLR gas duct is completely closed. For maintenance or repair work, the switching components can be accessed through the AFLR gas duct and the removable sealed lid in the gas tank. Considering the fact that the insulation medium is dry air, the gas evacuation process before accessing the gas chamber is completely simplified. This feature can save cost, time and maintenance efforts for the end users. However, such a solution requires complex design in the gas tanks in order to take out the data without losing the gas pressure.

Figure 3: Accessibility to the core tank through the gas insulated tank and the AFLR gas duct. (source: Nuventura)

PILOT PROJECT

In the pilot project, an SF_6-free primary switchgear is installed in an MV grid in coordination with Westnetz GmbH and innogy SE to test and assess the performance of the product.

Setup

Nuventura's current prototype configuration consists of a circuit breaker and a three-position disconnector inside a gas insulated vessel. The earthing of the cable is achieved through the disconnector and the circuit breaker. Only the circuit breaker and the disconnector are included inside the dry air insulated gas compartment. The busbar compartment is insulated by a solid insulated busbar.

Access to the GIS vessel is provided from the rear end. The vessel consists of a removable wall, which is usually only bolted. Furthermore, a safe AFLR type internal arc classification is achieved while providing an access to the maintenance personnel during a maintenance cycle.

Such a solution can also be considered as hybrid solution between AIS and GIS which consists of the advantages of GIS and at the same time possessing the flexibility of AIS while providing dry air insulation. With such an approach, serviceability of the product greatly improves the reliability of the product and allows installation and also replacement or service of modern wireless sensors to measure vital parameters of the switchgear.

Figure 4: Pilot product based on dry air insulation inside a concrete building. (source: Westnetz GmbH)

Procedure

The project is intended to run for one year. The switchgear is connected at 25 kV to the grid of Westnetz but does not supply customers. During this period, the product is placed inside a concrete housing to ensure the protection in case of an internal arc event. The prototype panel is exposed to all typically occurring grid situations. The quality of the insulating gas is regularly inspected to trace if any deterioration of insulating gas occurs over the period. So far gas chromatography tests have shown no trace of ozone or any other by-products that can be expected as a result of partial discharge.

SENSOR SOLUTION

Sensor applications in the GIS allow the measurement of critical parameters such as temperature on the critical components, partial discharge and humidity of the gas. The integration of sensors inside the GIS cubicle allows for their permanent measurement. This permits condition-based maintenance which leads to a decline in outage time and high repair costs.

Novel sensor technology in SF_6-free GIS design

Currently, effective passive cost competitive sensor solutions have been commercially available. These sensors offer continuous data collection of transduced events due to partial discharge or temperature rise or change in humidity. It is important to note that such sensors cannot replace conventional measurement systems. However, the continuous measurement system has such advantages compared to the conventional system that they are cost-effective and can be an integrated solution designed along with the switchgear components. More important, any invasive sensor which will be mounted inside the gas tank or on the conductor needs to be type tested according to standards to ensure no adverse effects on the performance of the switchgear.

Although a conventional measurement system is highly reliable and accurate, such system cannot be connected to switchgears throughout the lifetime. They are only used to diagnose any issue if found by any other means. The non-conventional sensor system is not very accurate in terms of measurement sensitivity. However, it can be used as an alarm system to assist as condition-based monitoring system.

A number of non-conventional sensor systems based on various transduced effects are available, most important being ultra-high frequency (UHF) based measurement systems, high frequency current transformer (HFCT), transient earth voltage (TEV) and ultrasonic-acoustic systems. Furthermore, in order to measure temperature on the conductors, surface acoustic wave (SAW) based passive sensors are used coupled with a high frequency antenna. In this test, UHF have been in focus.

UHF-based measuring systems

The UHF method is a non-conventional method that includes passive sensors installed inside the metallic chambers of GIS compartments such as the core vessel. The absence of active electronics and moving components in the sensors means that they can be expected to operate for long periods of time without maintenance. As they are classified as invasive, they can also be mounted inside the core GIS vessel during manufacturing. The advantages of this are the high sensitivity to discharges due to inner electrical resonance, low inherent losses and high immunity to electrical noise interference. Additionally, it is expected that any insulation defect detected from a sensor inside the switchgear confines the detection to be inside this particular switchgear.

While this method has previously been used in AIS solutions, it will have to be adapted to the SF_6-free GIS technology to integrate the wired antenna into the pressurised gas compartment.

Test method

The main challenges involved in implementing the sensor system inside a GIS core vessel include maintaining the reliability of the switchgear, ensuring that the sensors are easy to access for maintenance and that the design does not add excessive cost or complexity to manufacture.

In the current project sensors from different manufac-turers have been compared in a GIS test bed to assess the functionality, feasibility and reliability. The sensitivity and applicability of various sensors have been studied.

The used GIS tank consists of a steel compartment, with a steel lid providing an access to the compartment. When the lid is closed, the compartment can be pressurized up to 0.5 bar pressure. Pressurised dry air is used as the insulation medium in the GIS tank. The lid consists of a holding arrangement for the antennas as well as hermetically sealed feedthroughs for the SMA interface for the signal reception. The testing of all sensors is run in parallel and data is logged into the respective systems for each of the tests.

Figure 5: overview of test setup to create discharges in a demonstrational GIS (Method #2)

A partial discharge (PD) activity can be established in a controlled manner by applying high voltage across two points and varying the distance between these points. As the points get closer, a discharge is induced due to the increased electric field strength. The GIS core vessel is evacuated to remove any moisture so that testing could be carried out with dry air at atmospheric pressure (1.0 bar abs). Different test configurations were used to induce different types of discharge as shown in table 2.

Table 2: Overview of test configurations

Test Method	Test Configuration	Expected Primary Discharge Type
#1	Wire to plate	Corona discharge
#2	Rod to acrylic sheet	Surface discharge
#3	Metallic Particles	Particle discharge

The Omicron MPD600 with a coupling capacitor, which uses the conventional method described in IEC 60270, is used as a reference system. The different sensor systems that were under test are shown in table 3. Anonymity of the sensors is maintained in this contribution.

Table 3: Overview of sensors tested

Sensor ID	Technique	Location	Frequency Range
Ref.	IEC 60270	External cable sensor	<1MHz
A1	UHF	Internal to GIS vessel	300 - 1500MHz
B1	UHF	Internal to GIS vessel	150 - 1200MHz
B2	UHF TM	External cable sensor	30 - 900MHz
B3	TEV	External on GIS vessel	200 - 800MHz
C1	TEV	External on GIS vessel	10 - 500MHz
C2	HFCT	External cable sensor	1.5 - 20MHz
C3	Ultrasonic Contact	External on GIS vessel	30 - 88kHz

Test results

Table 4 summarizes the results of the test methods. It must be noted that for method 2, where the table shows strong detection, it was only tested with high amounts of discharge and the actual sensitivity of the sensors could not be discerned with accuracy.

Table 4: Summary of testing

	Internal UHF		External UHF cable	TEV		HFCT	Ultrasonic Contact
	A1	B1	B2	B3	C1	C2	C3
Method #1 - Corona discharge	●	○	●	○	○	●	●
Method #2 - Surface discharge	●	●	●	●	●	●	●
Method #3 - Particle discharge	●	◒	◒	○	○	○	◒

● Strong detection of discharges ◒ Weak detection of discharges ○ No detection of discharges

UHF sensor A1 was able to detect all different methods of discharge tested with a sensitivity of less than 300pC.

UHF sensors B2 were able to detect all methods tested with varying sensitivity and are also able to act as an early warning detector. Other offline methods and processes could be used additionally to provide detailed diagnoses such as identification of the type of discharge and localization of the defective part(s).

UHF sensor B1 was not able to detect discharges in method 1. However, it was able to provide a discharge pattern which could be useful in helping operators further identify the type of occurring discharge(s).

Other non-invasive methods can be used additionally to supplement the internal UHF sensors and the combined results can be used to make further diagnoses remotely.

Conclusion

In summary, the results indicate that UHF sensors within a GIS vessel are able to detect different types of discharge and in some cases clearly detect small amounts of discharge as low as 300 pC. This can be supplemented by other types of non-conventional measurement methods that are non-invasive and can be installed by the operator at a later stage. Existing processes and methods, such as portable diagnosis devices, will still be important in performing detailed diagnoses.

Future work is required to determine the quality and long-term suitability of the sensors within GIS vessels. Lifecycle testing will be important to understand how the sensors perform over long periods of time and if there is a degradation of the sensors. It needs to be tested if there is any decomposition of the sensor housing that can impact the system, for example by causing surface deterioration of the insulators leading to surface discharges.

Outlook

The benefits of continuous monitoring and predictive maintenance have the potential to reduce downtime, increase the useful lifetime of the switchgear and optimise its utilisation providing cost savings and increasing the network reliability for operators. However, the use of newly developed technologies without long-term experience poses an enormous challenge for network operators. The risk from their potential impact on security of supply has to be kept to a minimum and the following are recommendations for further work.

The novel sensor technology is expected to be used as an early warning detection. More gathering of data is needed to understand what these thresholds are. Depending on the sensitivity and accuracy of the measurement solution there will be need for fine tuning to improve the system and reduce the occurrence of false alarms. It will have limited ability to isolate the exact location of faults and will likely rely on existing processes and specialist offline equipment to determine this with accuracy.

The modern sensor integration coupled with SF_6-free modular technology with benefits such as solid insulated busbar, access to switching compartment, maintaining compact dimension up to 36 kV opens up a new generation of SF_6-free product category in MV switchgears.

Acknowledgements

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