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The Phenomenon of Internal Arcing in F-Gas Free (Clean Air) GIS

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Abstract

Investigating the intricacies of internal arcs is essential for the effective design and maintenance of highly reliable Gas-Insulated Switchgear (GIS). This paper provides a concise overview of internal arc physics, the test setup and the outcomes of tests conducted with clean air. Additionally, it delves into the evaluation of arcing in alternative F-gases as insulating media, presenting a comprehensive perspective along with **S**ulfur Hexafluoride $(SF)_6$. The consequences of internal arc in clean air GIS are more and nonhazardous compared to SF_6 and other F-gases, thus leading to a remarkable reduction of Environment, Health and Safety (EHS) considerations.

Keywords: Clean Air, F-Gas, Gas Insulated Switchgear (GIS), Internal Arc

1. Introduction

Internal arc faults very rarely occur in gas-insulated substations, with the primary occurrence of faults predominantly happening at partition bushing and flange joints.

IEC 62271-203: Clause 6.103 defines requirements for the design, testing and performance of high-voltage switchgear, including considerations for internal arc withstand capability.

Internal arc can be initiated due to various reasons such as the presence of foreign particles, sharp protrusion, etc. leading to a breakdown and the formation of a conducting path. Once initiated, the arc creates a high-temperature plasma channel through which the current flows. The plasma is a highly conductive state of matter composed of ionised gas.

The enclosures used in a GIS substation vary in size, shape and volume. Therefore, the type test is performed on the compartment which, according to the design documents appears to have the least likelihood of withstanding the pressure and the temperature stresses, leaving the extension of the test results to other enclosures of different sizes and shapes to calculation methods[1].

Following a line-to-ground fault in a GIS, the induced short-circuit current creates strong electromagnetic fields, displacing the arc from its origin and guiding it along a helicoidal path through axial Lorentz force and azimuthal rotation[2]. The travel speed is proportional to the arcing current amplitude and is in the order of 1m/s per kA[1].

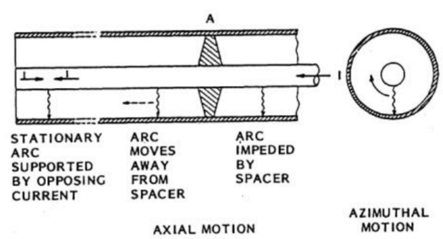

Figure 1. Arc behaviour during fault[3].

In the presence of unidirectional current flow, a fault originating at the current feeding side of the spacer forms a stationary arc. Conversely, if the fault starts on the opposite side, the arc travels away from the spacer until obstructed by the next spacer. When the current flows from both directions, resulting in a symmetrical current flow, the arc remains stationary (Figure 1)[3]. An insulator in GIS stops the axial displacement of the arc, causing it to potentially become stationary at a short distance from the insulator[2].

In addition to axial motion, the arc can also rotate in the azimuthal direction from the initiation point[3]. Azimuthal motion is mainly observed in conical-type spacers[4].

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During an internal arc, electrical energy is converted into thermal energy. The stress due to this thermal energy may result in burn through of the enclosure. The time until enclosure burn-through depends on arc current, enclosure properties, and movement. In a moving arc supplied by current from one direction, the risk of burn-through is minimal due to increased arc speed with higher fault current. However, for a stationary arc, prolonged local heating poses a risk to the enclosure. Along with a temperature increase in the gas during and after arcing, there is also a pressure rise inside the enclosure which is dependent on the volume, current, voltage and arc duration[4]. The bursting of the enclosure because of pressure rise can be avoided by installing a pressure relief device in the gas compartment.

2. Effects of Internal Arc in Different Insulation Media

2.1 Sulfur Hexafluoride [SF_6]

SF_6 has been used as an insulation media in high-voltage applications owing to its excellent insulation characteristics and stability under high voltage. Although SF_6 remains inert under typical operating conditions, the occurrence of internal arcs within SF6-filled GIS can lead to the generation of decomposition of SF_6 leading to the formation of toxic byproducts.

Gaseous SF_6 byproducts, including SF_4, SiF_4, SO_2F_2, SO_2, and HF, can irritate the eyes, nose and throat, causing health issues such as pulmonary oedema, skin and eye burns, nasal congestion and bronchitis. Solid byproducts like AlF_3 and CuF_2 dust also irritate the skin, eyes and the respiratory system when inhaled.

SF_6 byproducts such as SOF_3 and SF_4 have a strong irritating "rotten egg" odour at low concentrations and high concentrations are irritating to the eyes, nose, throat, and lungs. Detecting SF_6 byproducts under normal conditions is challenging due to the presence of various decomposition products, impurities and SF_6 itself, posing measurement difficulties[5].

2.2 Other Alternative F-Gases to SF_6

Recently, in the market, different alternative F-gases such as fluoronitrile (C4-FN), fluoroketone (C5-FK), trifluoroiodomethane, hydrofluoolefin1234 zeE have been introduced.

The major decomposition products of C4-FN and C5-FK are HF, CO, COF_2, CF_4, C_2F_6 etc[6]. Precautions and personal protective equipment currently employed with SF6 are also proposed for use with these SF6-alternative F-gas mixtures as both gases fall into the same category[7]. Consequences of Internal arc in F-gases are similar to SF_6.

Fluoronitrile (C4-FN) contributes to the dielectric strength of the mixture due to its nitrile triple bond and multiple carbon-fluorine bonds. CO_2 facilitates the arc interruption process and serves as a background gas, lowering the partial liquefaction temperature. O_2 is crucial for gas chemical decomposition, particularly during heavy arc interruption[7].

Post-arcing, a marginal decline in C4-FN and O_2 concentrations is anticipated, along with minor CO_2 and CO production[7].

Gas mixtures with fluoro nitrile show good dielectric properties, but degradation effects in High Voltage (HV) GIS disconnecting switches have to be challenged for proper GIS design[6].

The Occupational Exposure Limits (OEL) for C4-FN gas is set at 65ppmv. If there is an internal arc leading to the opening of the burst plate, it is essential to clean the environment, including the removal of toxic decomposition products. This process requires specific safety procedures, akin to those applied when dealing with arced SF6[8].

3. Clean Air

Clean Air consists of 80% nitrogen and 20% oxygen. Clean Air boasts outstanding long-term stability, a liquefaction temperature below -50°C, a global warming potential of zero, no toxicity, and positive life cycle aspects[9].

In GIS with clean air, internal arcing is the rarest phenomenon. The main decomposition products are ozone and NOx. Ozone (O_3) is recombined to O_2 within 1-2 h. NOx is slowly disappearing[8].

Handling of used clean air poses minimal safety concerns and requires special equipment and procedures only in the case of heavily arced clean air. In comparison to SF_6, the management of clean air offers significant time and cost savings throughout its lifecycle, including installation, commissioning, operation, maintenance and end-of-life considerations[9].

Moreover, the total CO_2 emissions are reduced by 81% by applying clean air instead of SF_6 in GIS[9]. Notably, the application of clean air gas in GIS involves no toxicological considerations.

Clean air has low health and environmental impact, good safety and long-term stability after arc quenching (Figure 2)[10].

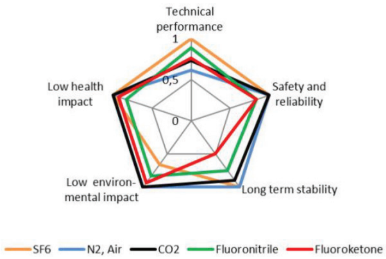

Figure 2. Overall evaluation of SF_6 alternatives[10].

Clean air as well as the major by-products from arcing do not contribute to the destruction of the stratospheric ozone layer because they do not contain either chlorine or bromine.

Different ageing and switching tests with GIS containing clean air have shown that no critical concentrations of decomposition products occur during normal operation and that no special safety precautions must be considered[9].

4. Internal Arc Test on SF_6 GIS

The primary goal of internal arc testing is to verify that the GIS design effectively contains and withstands the energy released during an internal arc fault. While preparing the test object, it shall be fully equipped and arranged with protection devices such as a pressure relief valve to limit the consequences of the arc.

The voltage applied while testing can be lower than the rated voltage of the equipment if the arc does not extinguish prematurely and the arc current is practically sinusoidal. The instant of short-circuit making shall be chosen to ensure that the first loop of the arc current has a peak value of at least 1,7 times the RMS value of the stated short-circuit current AC component (Table 1). For three-phase tests, this applies to the current in at least one phase.

Arc initiation is done by metal wire between the phase and enclosure of the test object as shown in Figure 3 i.e., at the vicinity of the partition at the longest distance from the point of supply.

In the case of a three-phase common gas insulated switchgear enclosure (Figure 4), an arc between phase and ground will, within a few milliseconds, evolve into a three-phase fault between conductors, owing to the ionisation of the gap between the conductors and at the same time the phase-to-ground arc will extinguish. Consequently, an enclosure burn-through is not likely, which is a positive characteristic of the three-phase common enclosure[11].

4.1 Single-phase GIS

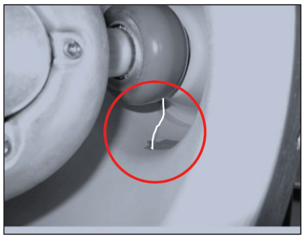

Figure 3. Ignition wire between phase and enclosure [Courtesy Siemens Energy].

4 .2 Three-phase GIS

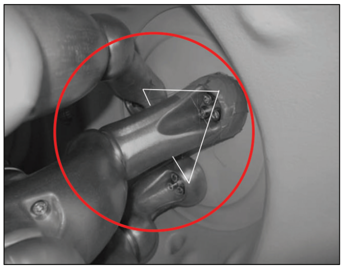

Figure 4. Ignition wire between all three phases of test object before test [Courtesy Siemens Energy].

Table 1. Performance criteria acc. to IEC 62271-203

Rated short-circuit current	Protection stage	Duration of short-circuit current	Performance criteria
<40 kA RMS	1	≤0.2s	No external effect other than the operation of suitable pressure relief devices
	2	≤0.5s	No fragmentation (burn-through is acceptable)
≥40 kA RMS	1	≤0.1s	No external effect other than the operation of suitable pressure relief devices
	2	≤0.3s	No fragmentation (burn-through is acceptable)

SF_6 is about 24,300 times more harmful than the greenhouse gas CO_2 and has a life span of 3,200 years in the earth's atmosphere if released into the atmosphere[12].

Due to the temperature rise and overpressure, SF_6 gas decomposes by thermal destruction of the molecules to toxic mixtures after internal arcing. To avoid mixing these toxic by-products[5], directly into the environment during an event of Internal arc fault, a test object is placed in a test vessel if burn through happens (Figure 5). In both three-phase and single-phase GIS testing.

Figure 5. Test object (Single phase) inside test vessel (before test) [Courtesy Siemens Energy].

Figure 6. Test object (three phases) after test [Courtesy Siemens Energy].

As the by-products of SF_6 take a week or so to settle inside the test vessel, the test object is subsequently assessed as per standard. (Figure 6)

5. Internal Arc Test on Clean Air GIS

The test setup was arranged using clean air as insulating media and the test object was made as stated by IEC 62271-203:7.105 (Annexure B) i.e., arcing initiation between phase and the enclosure using metal wire.

Figure 7. Test setup for clean air GIS [Courtesy Siemens Energy] (before test).

The pressure rise in case of clean air will be high compared to SF_6. The higher and faster pressure rise is due to different gas dynamics and power dissipation of the arc discharge in Clean Air[13]. Clean air has non-toxic by-products[9] hence, the test can be performed without using a test vessel. Inspection of the test object can be done immediately unlike SF_6, F-gas GIS.

Test results (Figure 8) satisfy the requirements as stated in IEC 62271-203.

Figure 8. Test setup for clean air GIS [Courtesy Siemens Energy] (after test).

6. Conclusion

Understanding the physics of internal arc is crucial for designing and maintaining safe and reliable gas-insulated switchgear. This paper highlights the phenomenon of internal arcing in F-gas-free GIS that utilises clean air, focusing on the formation of gaseous by-products and the environmental implications associated with the arced gases.

The move towards SF6-free alternatives in GIS is not only driven by environmental considerations but also by the need to understand and mitigate the challenges posed by internal arcing events. This paper contributes to the broader understanding of the behaviour of GIS under internal fault conditions, paving the way for enhanced safety and reliability in sustainable power distribution systems.

7. References

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