

INTERNAL ARC FAULT TESTING OF GAS INSULATED METAL ENCLOSED MV SWITCHGEAR

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ABSTRACT

An investigation on internal arc fault tests in gas-insulated metal enclosed MV switchgears is described and discussed. The influence of different gases (SF₆ and air) and electrode materials (Cu, Al, and Fe) has been put into evidence. This is highly relevant based on the fact that IEC Standards and utilities technical specifications allows that internal arc fault tests are performed with air replacing SF₆ with some precautions.

The experimental tests were carried out at NEFI High Power Laboratory in Skien, Norway. Full-scale test objects representative of typical gas insulated metal enclosed MV switchgear were prepared, filled with air or SF₆ and tested. The short circuit current was 16 kA_{rms} and the duration was 1 second. Electric input energy, internal gas pressure in different locations, opening time of bursting discs and temperature were acquired. The arc was ignited at the end of the simplified, but still representative, 400 mm long bus bars that were located in the middle of the metal enclosure. The full-scale experiments were additionally analyzed by means of Finite Element Method. The comparison between experiments and simulations show that there was possible to set up an arc model and tune it in to the results.

The main difference between testing of units filled with air versus SF₆ is the significant faster pressure increase in air. As a result of this and the fact that the bursting discs need a certain time to open, the pressure inside the test object will be higher at the time the bursting discs open when testing with air. The maximum pressure reached during a test with air however may be equal or lower than in SF₆ depending on dimensional parameters of bursting disc and encapsulation. Furthermore it is evident that there is a clear difference in the exhaust characteristics of SF₆ and air from an internal arc test.

INTRODUCTION

Since many years internal arc testing of different kind of switchgears has been a focused area. As a result the testing procedures in the standards have step by step become better described and standardised. The most important result however is that the quality of switchgears in this respect have improved significantly.

There is limited literature about fault arcing in compressed air. Dullni [1], Chu [2] and Fohrmann [3] have however

reported about fault arcing. Given the complexity of testing the internal arc performance of switchgears according to the standards, still some basic open questions remains. The work described in this report has focused on the potential difference one may observe when testing SF₆-insulated equipment either with the unit filled with SF₆ or when testing the same equipment with air replacing the SF₆ inside. This is highly relevant based on the fact that IEC Standards [4] and utilities technical specifications [5,6] allows that internal arc fault tests are performed with air replacing SF₆ with some precautions. The test program leading to this report has been performed in two steps, initial tests with SF₆, then later tests with air to compare. The metal enclosure described in this report is comparable to the physical size of ABB's ring-main units (RMU). However the internal design is significantly simplified compared to the real design of an RMU. When performing a real internal arc fault test on a product, there are many criteria that have to be met to successfully pass the test. The investigations reported here does not take into consideration these criteria as normally judged, but only focus on the pressure build-up within the enclosure, the opening time of pressure relief devices (bursting discs) and the characteristics of the gaseous outflow from the test vessel.

TEST OBJECTS AND EXPERIMENTAL SET UP

The test objects were typical gas insulated metal enclosed switchgears representative for the MV segment (Figure 1). These objects were equipped with cable bushings located in the middle of the enclosure. Inside the enclosure there was mounted three 400 mm long bus bars with a thin Cu-wire at the end in order to ignite an arc. All test objects had a filling pressure of 140 kPa regardless of insulating gas (SF₆ or air).



Figure 1 Photo from test set up at NEFI (photo: TRB)

Pressure-rise was measured at different locations on the test object with stat./dyn. transducers from BD-sensors and Kistler. In order to measure the temperature rise there were mounted ordinary thermocouples (Seebeck-effect) in the gas-flow at one meters distance from the bursting discs. The rupture of a wire caused by the bursting event of the bursting

disks, gave the exact measurement of the bursting instant.

In all experiments arc voltage, current, pressure, and temperature rise were measured and recorded by the metering system at NEFI High Voltage Laboratory. This system has maximum 12-bit resolution and optional sampling frequency. Two video cameras and one high-speed camera were used for image recording.

EXPERIMENTAL RESULTS

The current was in all tests 16 kA_{rms}. The arc voltage varied from about 250 V to 500 V depending on the electrode material and insulation gas. The electric input energy is calculated using equation 1:

$$W_{electric} = \int_0^t P_{tot}(t) dt \quad \text{where:} \quad P_{tot} = \sum_{X=L_1, L_2, L_3} U_X \cdot I_X \quad \text{Equation 1}$$

In the following experimental tests described, all values are presented in proportion to the experimental test with Cu-electrodes in SF₆. The smoothed maximum pressure rise, and sum energy is defined as the basic unit “1”. All test objects were tested with two bursting discs operative. Opening times of the bursting discs varied from about 30 to 90 ms.

Results SF₆

During the test with Al electrodes, the arc was interrupted after appr. one period, but re-ignited after about 2 periods. This may explain the less than expected steepness of the pressure-increase. As seen in Figure 2 the test results with arcing in SF₆ indicates a maximum pressure rise after appr. 100 ms, when concerning Fe and Cu electrodes.

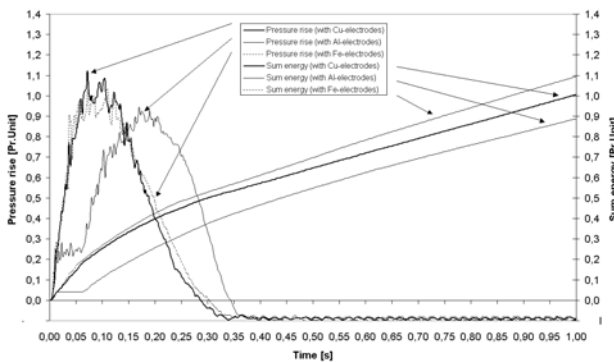


Figure 2 Pressure and sum energy as a function of time in tests with SF₆

Results Air

Compared to results with SF₆, the first striking observation in Figure 3 is the significant faster pressure increase with air. Maximum pressure rise was here observed after appr. 50 ms compared to 100 ms in SF₆. Even though the maximum pressure rise in these tests were appr. 5-10 % lower than in SF₆, the detailed tests results showed a 55 % higher opening pressure of the bursting discs.

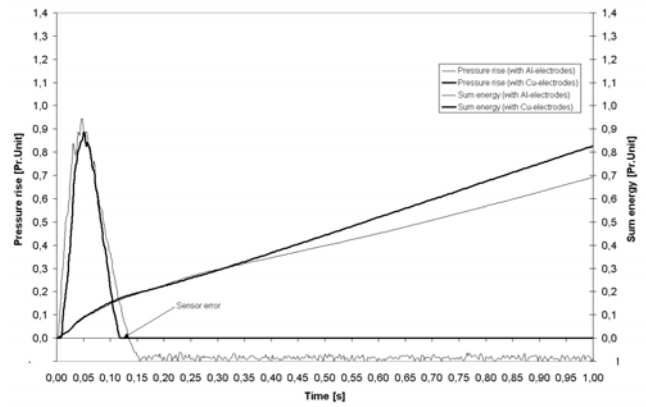


Figure 3 Pressure rise and sum energy as a function of time for tests with air

To have a key-parameter to compare these experimental results one can use the ratio between the energy of pressure built up and the electric energy put into the system. This parameter is called *k_p* and can be calculated with equation 2:

$$k_p = \frac{\Delta W_{pressure}}{\Delta W_{electric}} = \frac{\Delta p \cdot V}{(\gamma - 1) \cdot W_{electric}} \quad \text{Equation 2}$$

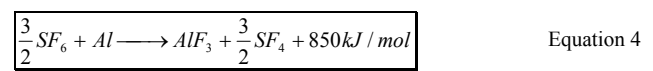
This equation is based on the assumption of an adiabatic process and that all pressure rise is caused by an increase of the gas temperature. The adiabatic constant γ is appr. 1,4 in air and 1,1 in SF₆. This *k_p* value varied from appr. 0,25 to 0,6 in experiments described.

PRESSURE RISE

In the literature it is described that one can assume that pressure rise is linear until the bursting discs operates. Equation 3 should then be prevailing.

$$\Delta p = C \cdot \frac{U_{arc} \cdot I_k}{V} \cdot \Delta t = C \cdot \frac{W_{electric}}{V} \quad \text{Equation 3}$$

There are also described some estimates for the factor *C*. In cases with SF₆ this factor is estimated to 0,6 when using aluminium as electrode materials, and 0,3 when using steel or copper. The deviation in these factors can be explained with the strong exothermal reaction between evaporated aluminium and dissociated SF₆ as mention in equation 4:



This reaction can also be seen in conjunction with Figure 4. The width of the individual parts in this figure indicates qualitative values. Appr. half of the electric energy that is converted in the arc is heating the gas which gives directly pressure build up. The other part goes to radiation, convection, conduction, melting, and evaporation of electrode material and encapsulation. The SF₆ gas dissociates at high temperatures to sulphur and fluorine. This reaction needs some energy. Most of the gas recombines after cool down and contributes to further heating of the gas through released energy. Some fluorine together with evaporated aluminium reacts to aluminium fluoride AlF₃. This reaction is severe

exothermal and liberate energy which further heats up the gas.

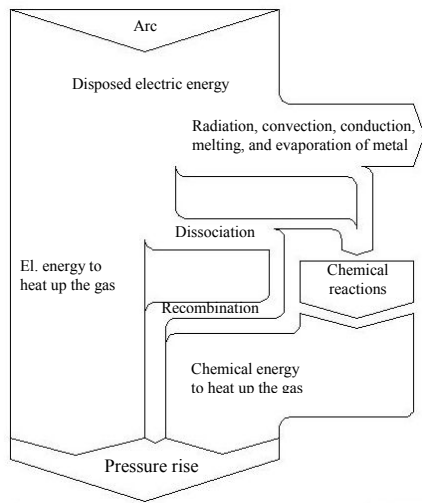


Figure 4 Energy/pressure development when an arc is burning between aluminium electrodes in SF₆ [7]

Figure 5 indicates an empirical linear approximation between normalized arc energy and pressure rise with different electrode materials in SF₆. This figure is based on results from previous experiments with arc fault tests in SF₆ with aluminium-, copper-, or iron electrodes. Pressure rise regarding to the aluminium electrodes in Figure 5 is appr. the same as the outcome of a theoretical curve if one assume that all electric input power were transferred to the gas. However this is not quite true. Experiments with burning arcs between copper- or steel electrodes show that the pressure rise is appr. 50 %. These observations indicate that only about half of the transferred electric energy is directly attached to the temperature rise in the SF₆ gas. The rest is due to the fact that there is a chemical reaction i.e. the formation of AlF₃. These reactions are as previous mentioned strong exothermal reactions and compensate more or less for the “energy loss” to the environment.

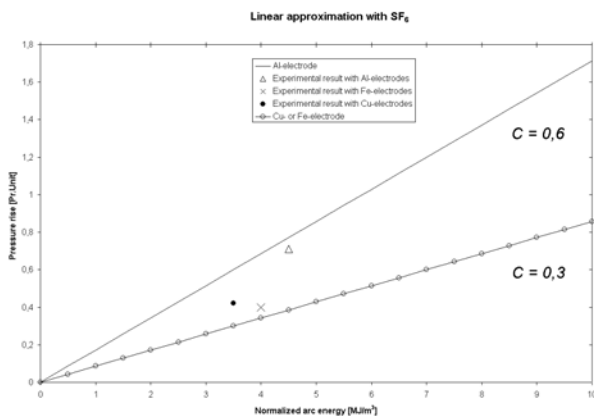


Figure 5 Pressure rise as a function of input volumetric arc energy in SF₆ with different electrode materials

Figure 5 indicates that the observed tests described in this paper are roughly correlating with the empirical curve for pressure rise with this type of electrode materials in SF₆.

In cases with air the linear correlation between pressure rise and normalized arc energy has a different characteristic. By using experimental results from air the factor C can be estimated to 0,95 as seen in Figure 6. This is a slightly higher value than for cases with SF₆. One reason for this is due to the higher observed opening pressure with air with the same energy amount put into the system, contra SF₆.

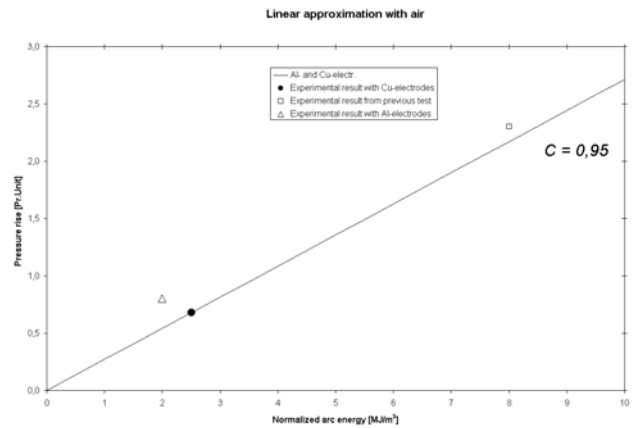


Figure 6 Pressure rise as a function of input volumetric arc energy in air with Al and Cu electrodes [4]

Figure 6 indicates that there is also a linear correlation between pressure rise and normalized arc energy with burning arcs in air. It was observed some higher pressure rise when the arc was burning on aluminium electrodes. These may arise from the theory of some small ongoing exothermal reactions with evaporated aluminium and dissociated air. Previous tests with air show that this estimate harmonizes even with different pressures and normalized arc energy.

SHARE OF ENERGY AND TEMPERATURE IN THE GAS FLOW

In order to light up the similarity with the measured temperature (at 1m) and the theoretical temperature within the enclosure (based on the measured pressure), one has to take some assumptions: First one has to assume that ideal gas as a linear correlation is prevailing in both air and SF₆. One can consider the opening at the enclosure after the bursting event as a *Lavall nozzle*. If one assume isentropic flow (i.e. no shock), and sonic conditions in the minimum exit area equation 5 will be prevailing:

$$\frac{T_0}{T} = \left(\frac{p_0}{p} \right)^{\frac{\gamma-1}{\gamma}} \tag{Equation 5}$$

In use of the method described above the theoretical temperature in the gas for some of the tests were respectively 760 K for air and 725 K for SF₆. When using these calculated temperatures as start conditions (T₀) one can plot the equation above. Figure 7 indicates temperature as a function of the ratio between the pressure in the enclosure (p₀) and the ambient pressure (p).

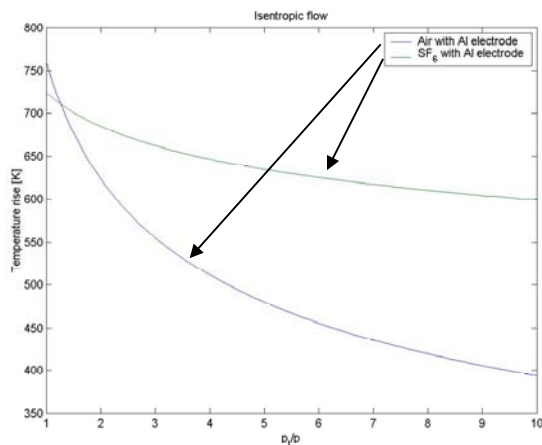


Figure 7 Isentropic flow in a Laval nozzle

Figure 7 indicates that hot air is more effectively cooled down than hot SF₆. The ambient pressure is in tests with SF₆ measured to about 20-30 kPa under pressure. If one assumes that this value is representative for tests with Al-electrodes in both air and SF₆, the pressure ratio (p_1/p_0) will be around 6-7. According to the upper curve in figure 7 the temperature in the gas-flow with SF₆ should be about 600-650 K. This corresponds quite well to the measured values in figure 8.

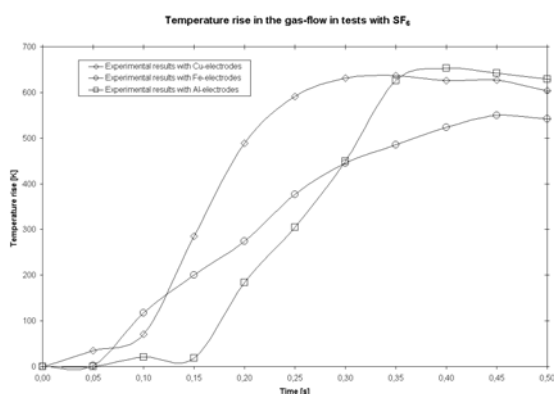


Figure 8 Temperature rise as a function of time in the gas-flow

In tests with air this assumptions did not agree very well. An explanation on this could be that air is so rapidly cooled down that with measuring the temperature at one meters distance, the assumption will not match. This means that in cases with air the temperature must be measured closer than one meter if the assumptions of isentropic flow in a Laval nozzle shall be a good approximation.

DIFFERENT OPENING PRESSURE WITH AIR VERSUS SF₆

There are mentioned in prevailing IEC standard, [4] that it will be a different pressure rise if the arc fault tests are carried out with air instead of SF₆. This phenomenon is also observed in tests done in connection with this paper. The opening pressure was measured to appr. 55 % higher with air than with SF₆ (at appr. same conditions). An explanation on this phenomenon can be that when an arc fault occurs there will break out shock waves that will spread out from the arc core.

The pressure waves spreads out in the volume with the speed of sound of the medium plus the velocity of flow within it. The velocity of flow can be higher in air than in SF₆. The size of the pressure wave is dependent on the energy behind. Dynamic pressure ($1/2 \cdot \rho \cdot v^2$) is translated into static pressure when it flows towards a wall and stops. This static pressure is what the pressure transducers in the tests actually measure. By that very fact that the bursting discs opens at the same time means that there are a more quickly pressure build up in air versus SF₆. On the other hand the density of SF₆ is almost 5 times greater than air. In practice this means that the velocity of flow must be almost 3 times greater in air versus SF₆ if the static pressure which the transducers measures shall be 50 % higher. There are attached a large uncertainty to this phenomenon with higher opening pressure in air versus SF₆. Additionally it can e.g. occur chemical reactions in both gases that could affect the pressure in any directions.

SIMULATIONS

In order to improve the understanding of the full-scale experiments there was worked out a model of the encapsulation. The pressure rises where simulated by means of Finite Element Method. It is assumed that the pressure rise is due to the increase of temperature. The method calculates the pressure rise without regard to any possible chemical reactions.



Figure 9 Geometrical model of test object

Figure 9 show that there are done assumptions of symmetry. This means that there are only done calculations at the one half of the test object. This is done in order to save calculation capacity. The energy being put into the system is taken directly from the measured power. With this model there are some assumptions that has to be taken into consideration. One must i.a. defines opening pressure of the bursting discs. The share of energy (W_{share}) that goes to pressure rise must also be defined. In previous experiments with air this part is estimated to be appr. 30 %. This proved that this value fitted quite well with the measured energy input of 25 % in that particular full-scale experiment. In conjunction with experiments done in this paper this parameter is estimated to 50-60 %. This share is estimated to fit the full-scale experiments with SF₆. With the following equation the fitted power as well as the share of energy factor was then used for the calculations:

$$dW = P(t) \cdot (1 - W_{share}) \cdot dt \tag{Equation 6}$$

Figures 10 to 12 show two curves, one simulated and one experimental. These figures indicates pressure rise as a function of time in tests with SF₆. The experimental results are the same as shown in Figure 2 but with other timescales.

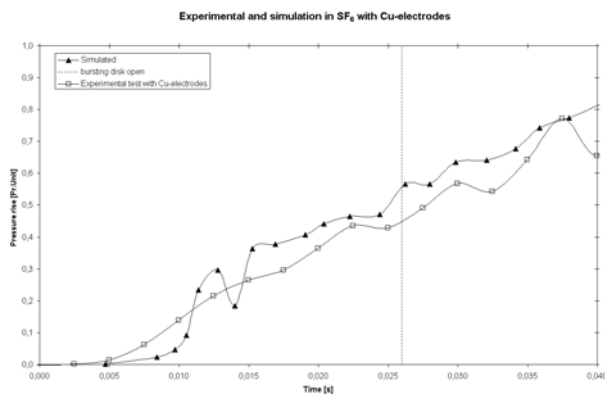


Figure 10 Measured and simulated pressure built up in SF₆ with Cu-electrodes

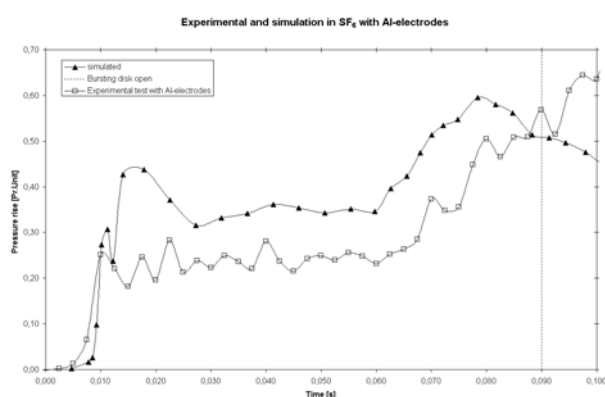


Figure 11 Measured and simulated pressure built up in SF₆ with Al-electrodes

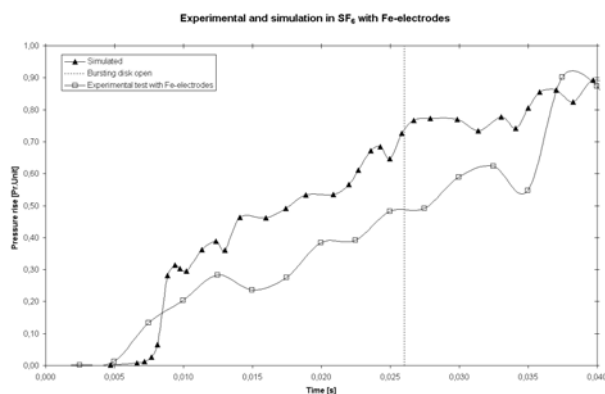


Figure 12 Measured and simulated pressure built up in SF₆ with Fe-electrodes

The comparison between experiments and simulations show that there was possible to set up an arc model and tune it in to the results. The limitation of these simulations are that with this model one can only calculate the pressure rise without regard to any possible reactions. This means that the simulations will not follow the measured curve when the reactions occur. It seems like the reactions occurs and have most impact on the pressure rise from about the time of pressure relief and ahead. The pressure rise is therefore only simulated into about opening time of the bursting discs.

CONCLUSIONS

These tests and simulations clearly indicate that there is a significant difference between internal arc fault testing of metal enclosed switchgear filled with air compared to SF₆. The main difference between testing of units filled with air versus SF₆ is the significant faster pressure increase in air. As a result of this and the fact that the bursting discs need a certain time to open, the pressure inside the test object will be higher at the time the bursting discs open when testing with air. The maximum pressure reached during a test with air however may be equal or lower than in SF₆ depending on dimensional parameters of bursting disc and encapsulation. Furthermore it is evident that there is a clear difference in the exhaust characteristics of SF₆ and air from an internal arc test. The air can be expected to have a higher initial velocity while cooling down much faster referred to travel distance from bursting disc openings compared to tests with switchgears filled with SF₆. This is highly relevant with respect to one of the main criteria of a standardised test – the potential ignition and following burning of flame indicators simulating operational personnel presence and safety.

The difference between testing units containing Aluminium parts where arcs may burn between should be treated even more carefully in respect of air versus SF₆ as gaseous insulation due to the exothermal reactions that occurs in a SF₆ atmosphere. Finally it can be disputed what should be the correct testing procedure.

It is the authors' opinion that there is no general answer to this as the most severe test condition may even differ between each of the different criteria that have to be passed for a standardised test.

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