SMALL SCALE ARC FAULT TESTING OF MEDIUM VOLTAGE SWITCHGEAR

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ABSTRACT

Arc fault tests of medium voltage switchgear have been performed with reduced volume and arc energy. This has been done in order to investigate if small scale experiments can be used to predict the pressure build-up during full scale arc fault test. Between 40 and 50 % of the arc energy was transferred to the gas in both small scale and full scale tests. The results show that it is reasonable to assume that small scale testing down to 10 % can be used to predict the pressure rise in a full scale test with a single phase arc with about 10 % precision. However, the scaling method of the arc energy seems to be important.

INTRODUCTION

Internal arc faults in medium voltage (MV) metal-enclosed switchgear have low frequency of occurrence. However, the large amount of energy released within a short period of time may have severe consequences on electrical installation buildings and personnel. Thus, the internal arc fault classification (IAC) and the experimental method to verify it (annex AA in [1]) play an important role in improving the quality and safety of switchgear. IAC tests during a development project require several weeks for each test loop and the costs are significant. The access to a lab able to perform small scale tests are easier compared to a high power lab. Performing small scale tests will increase the probability of passing the IAC test and development time and cost will be reduced.

In literature, not much is found on small scale internal arc fault testing. Daalder et al [2] made two different model test set-ups with a single phase arc to simulate the pressure rise due to a three phase arc fault in a MV transformer substation. It was found difficult to simulate practical conditions by small scale model tests.

In this study, a simple prototype is made by igniting a single phase arc inside a cubic container, which in the following is denoted as “arc compartment”. The energy of the arc is transferred to its surroundings, and a fraction of the energy goes to heating the enclosed gas, giving a pressure rise in the arc compartment. The main objective of this work is to see if small scale model experiments can be used to predict the pressure build-up in full-scale tests.

BACKGROUND

The state of the gas is given by the pressure and the temperature, which are considered to be uniform inside the arc compartment. Energy from the arc gives an increase in gas temperature, ΔT. Assuming ideal gas and that the pressure rise, Δp, is only due to the increase in gas temperature, the energy needed for this is

$$Q_{in}(t) = c_V m \Delta T(t) = \frac{V}{\kappa - 1}\Delta p(t) \quad (1)$$

where c_V is the specific heat capacity at constant volume, m is the mass, V is the volume, and κ is the adiabatic index of the insulating gas. A temperature independent κ of 1.4 is used for simplicity. The arc energy is given by

$$W_{arc}(t) = \int_0^t i(\tau) u_{arc}(\tau) d\tau \quad (2)$$

where t is the time, and i and u_{arc} is the momentary test current and arc voltage, respectively. The fraction of the arc energy heating the gas is given by the thermal transfer coefficient, called the k_p-factor

$$k_p = \frac{Q_{in}}{W_{arc}} \quad (3)$$

The pressure rise while the arc compartment is closed is

$$\Delta p(t, t < t_{open}) = \frac{k_p(\kappa - 1)}{V} W_{arc}(t) \quad (4)$$

where t_{open} is the time when the pressure relief opens. k_p is a measure of the slope of the pressure rise and is determined by comparing equation (4) with measured pressure rise from experiments. For small scale tests to be successful, the k_p-factor should be the same as for the full scale tests.

Heat conduction and radiation not absorbed by the gas will increase the temperature of the metal enclosure and the electrodes. Melting and evaporation of electrode material will affect the pressure rise.

EXPERIMENTAL

Today's MV metal-enclosed switchgear uses SF_6 as insulating gas. For environmental reasons, IEC Standards (subclause 6.106.3 in [1]) however, recommend to replace SF_6 with air for the purpose of internal arc fault testing. In this study, air at atmospheric pressure was considered as the insulation gas.

The arc compartments were cubes made of 4 mm thick welded steel plates. The electrode arrangement was linear with a gap, *g*, as seen in Figure 1a. A single phase arc was ignited in the gap by means of an ignition wire. The rod electrodes were made of copper (Cu) or aluminium (Al), and were 20 mm in diameter. One test was performed with reduced diameter to observe the influence of the electrode diameter. When the pressure reached a critical value, a pressure relief disc opened to allow gas exhaust into the surroundings. Figure 1b shows the outside front view of the compartment with a pressure relief disc with an opening pressure at 1.6 bar relative. The area of the pressure relief opening was not scaled, i.e. the pressure decrease in the small scale tests will not be comparable to the full scale tests.

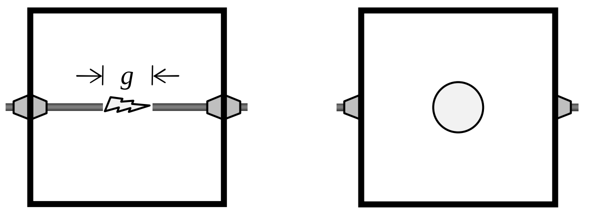

Figure 1. Arc compartment. (a) Inside view: Linear electrode arrangement with gap, g, and a single phase arc. (b) Outside front view: Pressure relief disc to allow gas exhaust into surroundings.

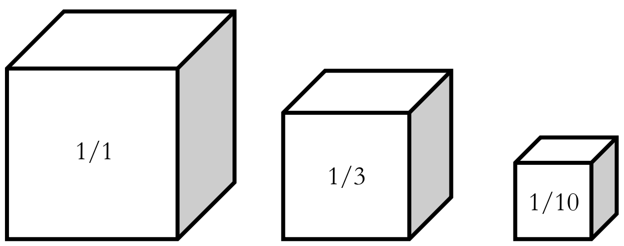

Figure 2. Arc compartment with three different volumes. Prototype (P) with a volume corresponding to a typical MV switchgear.

Scaling the volume

In this study, geometrically similarity was used for scaling the volume, i.e. all linear dimensions are proportional to the same scale factor, while all angles are preserved.

A prototype (P) of a medium voltage switchgear was build with a volume, V_P, of 0.343 m^3, corresponding a typical medium voltage switchgear. Two models were built with scaling factors of approximately 1/3 and 1/10 respectively, as illustrated in Figure 2. The model volumes are given by

$$V_{M1} \approx \frac{1}{3} V_P \tag{5}$$

$$V_{M2} \approx \frac{1}{10} V_P \tag{6}$$

where V_{M1} is the volume of model 1 (M1) and V_{M2} is the volume of model 2 (M2). Exact values for V_{M1} and V_{M2} are given in Table 1.

Scaling the arc energy

The electric arc has an explosive nature because the intense heat from the arc causes a sudden increase in temperature and pressure. In explosions, the blast effect is scaled by using the scaled volume

$$V^* = \frac{V}{W} \tag{7}$$

The scaling law implies that pressure, temperature, density, and velocity are unchanged through scaling, i.e. for the same value of V^* [3]. For V^* to be the same for the prototype and the models, the energy should be scaled with the same factor as the volume to give the same density of electric energy.

The arc duration was kept constant at 1 second which is popular for internal arc fault testing in Europe. The arc energy is given by equation (2), and can be scaled by scaling the test current and/or the arc voltage, i.e. by changing the test current and/or the electrode gap. Two different electrode gaps were used; 20 and 100 mm. The test current varied between 2 and 16 kA_{rms} at 50 Hz frequency. The currents were chosen as approximate values based on experience to give the wanted scaling of the arc energy. The current asymmetry peak factor was 2.3-2.5. 8 different tests were performed in total, and Table 1 summarizes the different test conditions.

According to criterion number 4 in subclause 6.106.5 in [1], one pass-fail criterion of internal arc tests is the ignition of cotton indicators positioned in the gas exhaust. The temperature in the gas exhaust was measured with a thermocouple placed 1 meter from the pressure relief opening. The gas exhaust was recorded by using a high speed camera. All tests were performed at NEFI High power laboratory in Skien, Norway.

Table 1. Experimental test conditions. V is the volume of the arc compartment, g is the electrode gap, d is the electrode diameter, and I_{rms} is the root mean square value of the test current.

Test no.	Arc comp.	V [m^3]	Electr. material	g [mm]	d [mm]	I_{rms} [kA]
1	P	0.343	Cu	100	20	15.3
2	P	0.343	Al	100	20	15.5
3	M1	0.118	Cu	100	20	6.75
4	M1	0.118	Cu	100	14	6.75
5	M1	0.118	Al	100	20	7.16
6	M1	0.118	Cu	20	20	10.1
7	M2	0.0359	Cu	100	20	2.03
8	M2	0.0359	Cu	20	20	4.01

RESULTS AND DISCUSSION

The resulting arc energy for each test is listed in Table 2. The column marked $W_{arc}/W_{arc,P}$ shows the scaling factor of the arc energy until $t = t_{open}$. The measured mass losses of the electrodes, Δm, are also listed in the table. From Table 2 it is clear that V^* is not equal for all tests, but confined into a narrow range. For Cu-electrodes, the mean value of V^* is 1.17 m^3/MJ with a standard deviation of 8.1 %.

Table 2. W_{arc} is the arc energy when pressure relief disc opened, V is the scaled volume, Δm is the total mass loss of the electrodes, and k_p is the thermal transfer coefficient.*

Test no.	W_{arc} [kJ]	$W_{arc}/W_{arc,P}$	V^* [m^3/MJ]	Δm [g]	k_p
1	284	1.0	1.21	258	0.46
2	296	1.0	1.16	176	0.44
3	98.9	0.35	1.19	112	0.47
4	113	0.40	1.05	102	0.41
5	90.8	0.31	1.30	76	0.50
6	105	0.37	1.13	188	0.41
7	28.6	0.10	1.26	18	0.50
8	34.9	0.12	1.03	66	0.40

Figure 3 shows the measured pressure rise inside the arc compartment when using Cu-electrodes. It can be seen that model tests with 100 mm gap gave a steeper pressure rise compared to the prototype, while model tests with 20 mm gap gave a slower rise. Model M1 and M2 gave approximately the same slope for the same electrode gap.

The measured pressure rise inside the arc compartment with Al-electrodes is given in Figure 4. As for Cu-electrodes, the pressure rise is steeper in the model test compared to the prototype.

The curves of the pressure rise in Figure 3 and 4 have steps that are a combined result of the 50 Hz frequency and the current asymmetry. The pressure started to decrease immediately after bursting of the pressure relief disc.

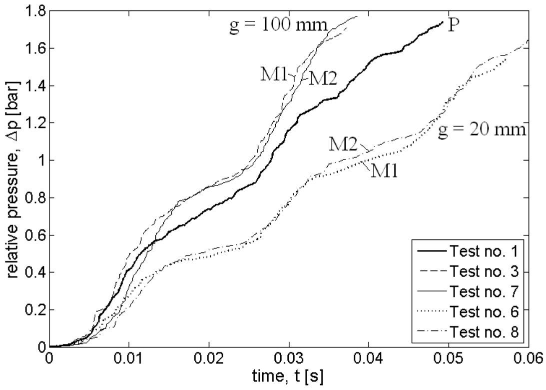

Figure 3. Measured pressure rise inside arc compartment as a function of time with Cu-electrodes.

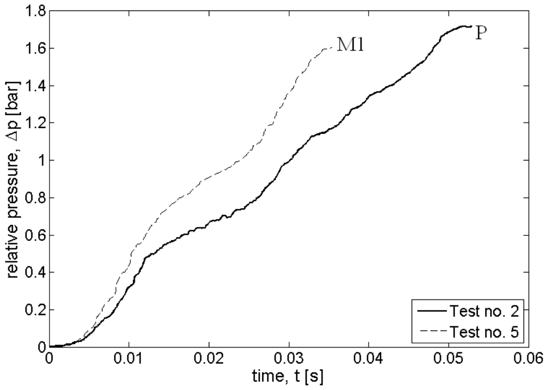

Figure 4. Measured pressure rise inside arc compartment as a function of time with Al-electrodes.

The k_p-factor is calculated by comparing equation (4) with the measured pressure rise, and finding the k_p-factor that best fits the measured values up to t_{open} by least squared method. k_p is found to be between 0.40 and 0.50 for all tests. The results are listed in Table 2, and plotted in Figure 5 as a function of the volume.

The electrode gap seems to be an important factor when scaling. For 100 mm electrode gap, a somewhat higher k_p-factor was found in the model tests compared with the prototype. For M1 the value is 2 % higher, and M2 10 % higher. As observed and reported in [4] and [5], less energy goes to melting and vaporization for lower currents, leaving more energy available for pressure build-up.

For 20 mm electrode gap, a lower k_p-value is measured. For M1 the value is 11 % lower, and M2 13 % lower. For the shorter gap, a higher energy fraction is taken by the arc roots where melting and vaporization of electrode material takes place. From before it is observed an increase in the electrode erosion for shorter gaps [5]. The effect can also be seen from measurements of Δm given in Table 2.

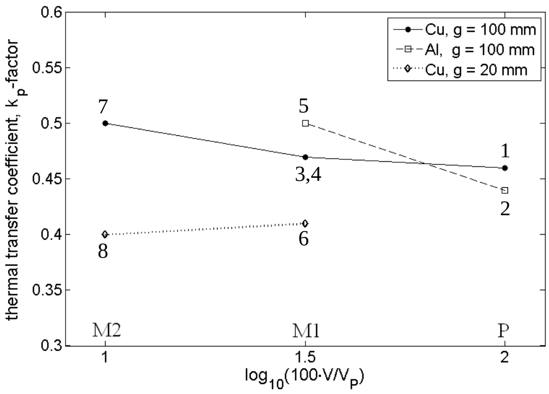

Figure 5. Thermal transfer coefficient, k_p-factor, as a function of arc compartment volume. Test numbers are indicated.

Test no. 4 was identical to test no. 3, but was performed with reduced diameter of the electrodes to reduce the fraction of arc energy conducted through the electrodes. However, a reduction in the k_p-value was observed, see Table 2. This is in agreement with observations made by Tanaka et al [6]. A lower k_p-value means that a smaller part of the arc energy was used for pressure build-up and more energy is lost to the surroundings. Due to thinner electrodes, the electrode gap increased more during the test, giving a longer arc, which may give rise to higher radiation losses. This is supported by temperature measurements of the enclosure, which was approximately 30 K higher for test no. 4 compared to test no. 3.

The temperature measured in the gas exhaust is given in Figure 6. For Cu-electrodes the prototype test and M1 reached a temperature of 360-380 K, while M2 only in the range of 300-310 K. From the video recordings, it is clear that the jet from the pressure relief openings did not reach the temperature sensor for M2 tests, which explains the lower temperature in Figure 6.

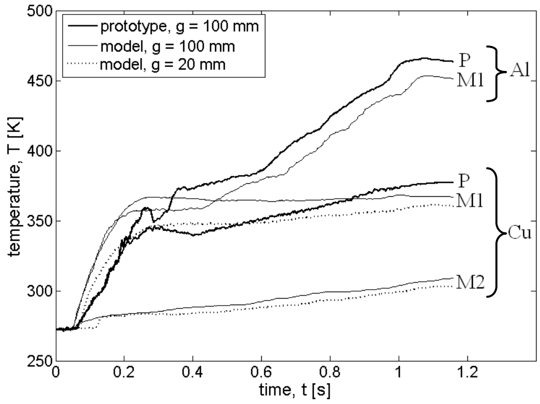

Figure 6. Measured temperature in the gas exhaust, 1 meter from the pressure relief disc.

For Al-electrodes, both P- and M1-tests ended up at a temperature of about 450-460 K. The temperature is almost 100 K higher than measured with Cu-electrodes.

Ignition of cotton indicators is not easy to scale. The energy flux on a large enough area on the indicator should be the same as for the full scale test. To achieve this, the position of the indicators should be adjusted according to the scaling factor and the size of the pressure relief opening.

CONCLUSION

Between 40 and 50 % of the arc energy was transferred to the gas in all tests reported in this study. The arc energy was scaled by two different methods; by reducing the test current and/or the electrode gap. The scaling method of the arc energy seems to be important. If the electrode gap is reduced too much, not enough energy will be transferred to the gas. Keeping the electrode gap and diameter constant, model 1 gave a thermal transfer factor only 2 % higher than the prototype test, while model 2 gave a value 10 % higher. Thus, small-scale arc fault testing with reduced volume and arc energy down to 10 % can be used to predict the pressure rise in a full-scale test with a single phase arc with about 10 % precision. It is important to note that a single phase arc can be regarded as a scaling of the real situation in internal arc fault testing of MV switchgear where the arc quickly will develop into a three-phase arc. The validity of such scaling still remains to be established.

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