INTERNAL ARCS: PRESSURE RISE VERSUS COOLING METHODS IN AIR INSULATED MV SWITCHGEAR

Yvette PETERMAN-GUNTHER, Eaton – The Netherlands, Yvettepeterman-gunther@eaton.com
Gerard SCHOONENBERG, Eaton – The Netherlands, gerardschoonenberg@eaton.com
Johan DE JONG, Eaton – The Netherlands, johandejong@eaton.com

ABSTRACT

When considering internal arcs in switchgear, prevention should be the main approach, both at the design stage and in service. Protection in case an internal arc does occur is step two. The protection approach consists of reducing the effects of internal arcing. In the current market this protection approach focuses mainly on reducing the arcing duration, prescribing protective wear for the operator, and/or leading the hot gases away from persons present at dedicated locations around the switchgear.

However, the impact of internal arcs, like pressure rise on the surrounding switchgear room, is generally not covered by the standards. Only IEC 62271-202 considers also the pressure rise for the closed substation with the optional IAC-B test.

This paper focusses on the pressure rise outside the switchgear. After a simple theoretical approach also specific internal arc tests are discussed both during

- *type testing of various prefabricated substations with its several intermediate compartments, like a cable cellar, plus the generally applied energy absorbers used for cooling the hot gases and*
- *more fundamental tests where the influence of arc energy absorbers integrated in several switchgears was studied.*

Main objective of these studies was to come to an optimal configuration to reduce the room-pressure. It turned out that the "rules of thumb" are sufficient in practice as indication what to expect regarding the room pressure in case of internal arcs.

INTRODUCTION

When planning a switchgear in a room, the customer could encounter several issues when internal arcing has to be addressed; except for protection from burning for persons, either by switchgear design or by protective clothing, also possible toxic effects, fire propagation and mechanical aspects of the switchgear room should be taken into account.

Over the years a lot of papers have been written about internal arcs. Several of them also addressed the pressure rise in the switchgear room [1,2,3,4]. Although elaborate calculation and simulation programs exist, up to very time consuming Computational Fluid Dynamics (CFD), this paper comes to easy rules of thumb, based on calculation and subsequent tests.

To further enlarge the passive protection by design in order to diminish the effects of internal arcs, several types of arc energy absorbers are distinguished: one consists of several layers of perforated metal plates or expanded metal, as generally applied in prefabricated transformer substations. Other known types of arc energy absorbers are a set (labyrinth) of metal plates and ceramic honeycomb blocks. All three types were investigated over the years by the authors. Especially the ceramic blocks turned out to be a promising means to reduce the pressure rise in the switchgear room, when an internal arc in the switchgear occurs. Therefore the paper concentrates on the tests with these ceramic absorbers (cooling blocks).

Tests with several arcing currents in the 10-20kA range for MV applications are described. The related pressures were measured during various tests both with fundamental and with type testing.

TREATMENT OF ARCS IN STANDARDS

The (international) standards developed in different ways regarding requirements for internal arcing. Relevant standards and reports with their specific focus are:

IEC 62271-200 for MV metal-enclosed switchgear, addresses Internal Arc Classification (IAC) as an optional specification. IAC is demonstrated by standardised tests based on a dielectric breakdown between phases in closed MV compartments, during normal operation. Explosion of internal components is not dealt with and tests with air are considered to be representative for SF6 switchgear. Two types of indicator material are prescribed: for operators at 30 cm distance and for general public at 10 cm distance from the switchgear. Both types of indicators discolour at a glow wire temperature of 300 ºC where at 500 ºC, the 40 g/mm^2 indicator burns through the fabric in 3 s and the 150 g/mm^2 indicator discolours at a glow wire in 23 s.

So only direct burning aspects are addressed for people at a specific distance from the switchgear, other distances and hazards like toxic effects from dust, smoke, SF6 residuals, ear damage etc. are not treated.

IEC 62271-202 for MV/LV substations, excludes arcs in the transformer and in the LV section. An Ad hoc Workgroup within IEC concluded recently that investments on the LV side are best to be put on improving the IP grade of the LV. The IAC specification is optional and only related to the MV part. IAC can be declared for operator protection (grade A) and general public protection (grade B, test with closed door).

IEC 62271-203 for HV GIS switchgear
The internal arc shall not propagate into adjacent gas compartments. Evidence of performance shall be demonstrated by the manufacturer when required by the user. Evidence can consist of a test or calculations based on test results performed on a similar design but of different size and shape and/or to other test parameters or a combination of both. The manufacturer is responsible for demonstrating the validity of extrapolation of test results for other currents and other sizes of enclosures.
IEC 61439 for LV switchgear assemblies simply states that internal flash-overs are prevented if the prescribed rules for clearances and creepage distances are fulfilled, and the tests for the specified short-circuit current were passed. IEC 61439 does not demand an internal arc test.
IEC/TR 61641 for testing Enclosed LV switchgear assemblies under conditions of arcing due to internal fault. In this technical report "arc free zones" are defined (Arc Ignition Protected Zones according to ed. 3), for which is stated that there's no need to test. Several classifications of performance are mentioned: Personal safety, assembly protection and limited continued operation. Compared to IEC 62271-200 extra criteria 6 en 7 regarding availability of the switchgear after an internal arc are defined.
IEEE C37.20.7 being aligned with the IEC 62271-200, although at testing the neutral of the supply has to be connected, where in IEC the neutral shall be floating.
The **IEEE 1584** standard for performing Arc Flash Calculations was initiated by the Petroleum and Chemical Industry. Arc flash hazard analyses should result in fact based quantification of the hazard in terms of thermal energy. Direct exposure to open arcs is addressed. The Arc Flash Safety approach is traditionally based on calculations, but design verification by testing is now also under discussion. The calculations result in a prescribed set of Personnel Protective Equipment (PPE) and are used primarily in the LV industrial applications, but are also emerging in the LV Utility networks and in the MV. Requirements for the flame resistant material performance and garment design are prescribed in **IEC 61482-2**, while the 2 ways of testing protective clothing are treated in IEC 61482-1-1 and -1-2.
IEC 61482-1-1 determines the incident Energy by the open arc test (International method) to come to the Arc Thermal Protective Value ATPV or Breakopen Threshold Energy BTE (E_{BT50})
IEC 61482-1-2 deals with the simulation of defined scenarios by the box test in order to come to the arc protection class 1 or 2.
The calculated PPE Category is expressed as a specific range in cal/cm^2.
The American **NFPA 70E** standard requires risk assessment for arc flash hazard. European local codes and standards do not yet specifically address the risks of arc flash. Nevertheless a practical rule in NEN 3140, a local Dutch LV-standard, states that arc flash hazard should be evaluated if the installation is fed by a fuse size >25A or MCB >16A.
Cigré brochure 602 [4] describes tools and calculation methods for the simulation of the effects of internal arcs in switchgear. Although primarily focussed on the consequences of testing SF6 switchgear with air, also pressure rise in switchgear rooms is addressed in ch.6.

Resume International Standards and reports
Except for this Cigré 602 and IEC 62271-202, none of the standards deals with possible overpressure in the switchgear room, although this could be one of the issues the customer is facing when planning a switchgear in a room with no arc venting possibilities to the outside.

BASIC CALCULATIONS

When an internal arc occurs, a heat exchange with the surrounding gases will occur. To get an idea how the dependencies from the several variables act, a very fundamental approach, based on air is given.
At first an arc is considered in a single, closed volume, filled with air to come to a static pressure rise.
When the arc takes place inside a switchgear with pressure relief valves that open at a certain overpressure, also a peak pressure wave can be expected on the structure of the room. Both static and peak pressure rise are treated below.

Static pressure rise in room

The ideal gas law, p.V = n.R.T, predicts how the pressure p (Pa), volume V (m^3), and temperature T (K) of a gas depend upon the number of total moles n of all the gas-phase species.
The gas constant R = 8,3144 J.K^{-1}.mol^{-1}, being the product of the Bolzmann constant Kb and the Avogadro's number Na. The mass of dry air is 0,0288 kg. mol^{-1}.
When Energy E from a single arc is added to a single Volume, the temperature T will rise: $\Delta T = E / (cv . \rho . V) = U . I . t / (cv . \rho . V)$ with U the arc voltage, I the arc current, t the arc duration, cv the specific heat at constant volume and ρ the density; at 1,013 bar and 21 °C,
Cv= 722 J.kg^{-1}.K^{-1} and ρ=1,18 kg.m^{-3}

For a constant volume V the change of temperature will create a change of pressure. The ideal gas law turns into:
$\Delta p = n . R . \Delta T / V = (n . R / V) . U . I . t / (cv . \rho . V)$
$\Delta p = B . U . I . t / V$

The constant B = n . R / (cv . Mass) with Mass = ρ .V
Because Mass is also n . 28,8.10^{-3} (in kg) the result is
B = n . R /(cv . n .0,0288) = 8,3144 /(722 . 0,0288) = 0,4

So the change of pressure can be expressed as
$\Delta p = 0,4. U . I . t / V$ for a single arc.

Because a 3 phase arc consists of 2 parallel arcs, changing 6 times per power frequency period [Kindler], a 3-phase arc will create only 50% of the energy, expected for 3 independent single phase arcs of the same current, so **Δp = 0,6. U.I.t / V**

The arc voltage U is dependent on length. Assuming 40 V cathode drop plus 25 V/cm along the arc length, where the arc length can be estimated as an average on 150% of phase distance. For Medium Voltage switchgear up to 24 kV the average arc voltage U can be set at 500 V as a good approximation in air.

In theoretical considerations a factor kp is generally defined [4], considering that not all electrical energy is transferred into pressure rise (kp varies from 0,2 to 0,8), thus reducing the pressure rise.
Measurements in literature in a single volume [5] state a reduction factor between the theoretical 'ideal' and measured pressure value of 0,07 should be applied, a.o. due to the kp factor. Another effect for introducing a lower pressure rise in the switchgear room is the encapsulation effect of the arc by the switchgear from which the overpressure is released into the room via a small relief area (volume in a volume with a restricted area to equalize pressures).

Taking 500 V as an average arc voltage, expressing Δp in bar (1 bar = 10^5 Pa) and I in kA then the constant in the formula for pressure rise for a 3-phase arc in MV switchgear would be 0,07 . 0,6 . 500 .10^3 /10^5 = 0,21 with the 0,07 reduction factor. Internal arc tests on Xiria, as described further on, demonstrate that 0,25 would be more accurate in the formula for the static pressure rise at 3-phase arcing in a MV switchgear: **Δp = 0,25. I.t / V** with Δp (Bar), I (kA), t (s) and the free air volume V (m^3)

Peak pressure rise on walls and ceiling

The pressure relief of a switchgear compartment opens at an overpressure P_0 (Bar), then a peak dynamic pressure wave enters the switchgear room. This peak wave can be estimated with a relatively simple rule of thumb in case no damping provisions are foreseen, see figure [1]:
Calculate the area of the pressure relief opening as a circle with radius r_f(m). Consider P_0 to expand in the switchgear room as a hemi-sphere; then the pressure peak will decline with the square of the distance. It doubles at the wall because of a 'bounce back'. Assume the width of the pressure peak is 4 ms, the speed of travel 300 m.s^{-1}, and consider the circle of the hemisphere on the wall that can be 'fed' by the pressure wave in this 4 ms. The centre point is the shortest distance x to the wall, seen from the pressure relief opening. The distance to the outer circle on the wall will be x+z with z being 4ms*300m/s = 1,2m.
The force F (kN) = $400.\pi.P_0.r_f^2.\ln\{(x+z)/x\}$ on this wall area of $\pi.(z^2+2.x.z)$. The max force on the 1m^2 area on the wall is **F_1 (kN) = $400.\pi.P_0.r_f^2.\ln\{\sqrt{(x^2+1/\pi)}/x\}$**
with related pressure (in mBar) F_1*10.
Example: at 0,7m distance, the pressure relief of 0,25m^2 (r_f=0,28m) opens at 0,4 Bar overpressure;
F_1= $400.\pi.0,4.0,28^2.\ln\{\sqrt{(0,7^2+1/\pi)}/0,7\}$ = 9,9 kN.
With damping, e.g. by absorbers, a reduction factor could be applied.

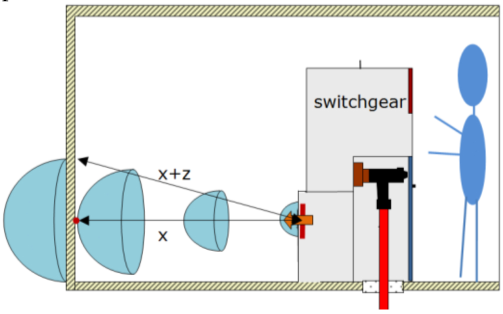

Fig [1]: local pressure wave

TESTRESULTS

Multiple internal arc tests have been performed over the years by the authors. From fundamental investigation tests till type tests according to IEC 62271-200 and -202.

Fundamental tests on controlled lab model

Test object
The basic blocks from Eaton's MV switchgear MMS were used for creating test objects, that include arc compartment, absorber channel, an extra control volume and an exhaust to the outside, as indicated in the figure [2]. The absorbers were applied in the absorber channel between the two compartments. The control volume, after the absorber channel simulates the switchgear installation room. Each compartment had the identical size of 500*600*600mm; each chimney has identical dimensions 150*150*300mm. Three types of ceramic arc energy absorbers with different number of tubes were tested: 13*13, 25*25 and 50*50 internal channels. The outer dimensions matches exactly the size of the chimney. The ceramic absorber is illustrated in figure [3]

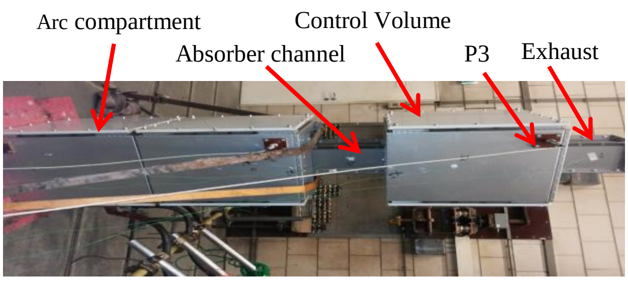

Figure [2]: controlled lab model

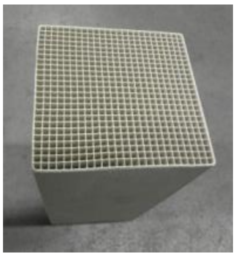

Figure [3]:ceramic honeycomb block

Test set ups

A series of tests was performed in the Prof. Ir. Damstra laboratory, Eaton Hengelo The Netherlands.

The test current was 10kA , the supply voltage 1.4kV, the arcing duration 530ms. The arc voltage 415V, 3 phase ignition through a thin copper wire. Besides the voltages, currents for each phase and arc energy are also the pressures measured through a data logger in the lab. The relative pressures inside of the arc compartment and the several buffer compartments in different locations were measured through the pressure transmitters.

Case	Arrangement	Notes
1	P1 P2 P3 A	Reference A: there is an control volume and channel after the first absorber channel, both channels are empty
2, 3, 4	P1 P2 P3 B	Same arrangement as A but the first channel filled with different absorbers
5	P1 P2 P3 C	Two identical chimneys as previous cases are in series, filled with two absorbers 50*50 inside
6	P1 P2 P3 D	Two identical chimneys same as previous cases, but in parallel, filled with two absorbers 50*50 inside
7	P1 P2 P4 P3 E	Same as arrangement C but with a small gap (room) in between the extra gas has a half size of the absorber channel

Figure [4]: different arrangements with ceramic arc energy absorbers

Arc tests performed with ceramic absorbers

There were different arrangements (cases) subjected to the test, listed in detail in Figure [4]. In order to make comparison between the different arrangements, a reference test was performed, test case 1 called reference A. This internal arc test was carried out without any absorber inside the absorber channel. The arrangements for the other test cases were the same, but they had ceramic absorbers inside the absorber channel in different layouts single, in series or parallel.

Test case 2, 3, 4 were done with arrangement B similar to reference A, but with a single ceramic absorbers inside of the chimney.

Test case 5 was done with arrangement C, an extended absorber channel was filled with two identical absorbers in series. Only one type of ceramic honeycomb absorber was tested, 50*50 channels.

Test case 6 was also done with arrangement D, a wider absorber channel was filled with two identical absorbers in parallel. Only one type of ceramic honeycomb absorber was tested, 50*50 channels.

Test case 7 was performed with arrangement E, almost similar to arrangement C, but with a small gap (room) in between the absorbers. The created volume was half a size of the absorber channel. Only one type of ceramic honeycomb absorber was tested 50*50 channels.

Test case	Arrangement	Number of tubes	Measured pressure peak P3 (mBar)	Compared with reference
1	A reference	1	250	357%
2	B single absorber	13x13	160	229%
3	B single absorber	25x25	114	163%
4	B single absorber	50x50	70	*100%*
5	C two absorbers in serie	50x50	60	*86%*
6	D two absorbers parallel	50x50	225	*321%*
7	E two in serie with gap	50x50	100	*143%*

Table [1]: different arrangements for test cases internal

Evaluation of tests with ceramic absorbers

The test results are summarized in table [1].

Firstly, a comparison between arrangement A and B with case 4 as a reference (highlighted green in table [1]) and case 1 (arrangement A). Without any absorber shows that the pressure in the control volume without any absorber 357% is compared to the pressure when a single absorber with 50x50 tubes is applied.

Secondly, a comparison between all arrangements B, shows that with a single block, the 50x50 tubes results in the lowest pressure behind the absorber; the block with 13x13 tubes comes to 229% compared to the block with 50x50 tubes and the block with 25x25 tubes results in 163%.

The pressure in the control volume behind the absorber decreases drastically due to the absorbers in our tests. This is because the absorbers can absorb much heat from the arc before the (hot) gases enter the compartments behind.

Another comparison can be made between arrangement B and C. The pressure in the arc compartment increases 19% with absorbers in series. The pressure in the control volume decreases to only 86% of case 4. This low effect of the second block is primarily due to the open chimney at the control volume to the outside world.

To compare the single with the parallel lay-out (case 6), the arrangements B and D are taken. The pressure in the arc compartment reduces with 16% when the absorbers are in parallel. The pressure in the control volume increases to 321% of case 4, so parallel blocks do not seem to be a good solution.

Test case 7 was done with arrangement E, almost similar to arrangement C, but with a small gap (space) in between the absorbers. Comparing case 7 with case 4, the pressure in the control volume increases to 143%. Comparing 2 absorbers in series with and without gap in between, the pressure in the control volume with the extra gap (case 7) was 67% higher. Thus the separation gap between the two absorbers has a negative impact on the pressure drops in the control volume. This result was not what was expected and more investigation is needed to explain.

Of course the introduction of the extra flow resistance due to the cooling blocks shall not lead to overstressing the switchgear compartments themselves; the pressure rise inside must stay in the withstand range of the switchgear compartments. The investigations concentrated on maximum cooling, so pressure reduction behind the absorbers, with the least internal pressure rise. By choosing the right layout of several cooling blocks, effective chimneys can be arranged. These chimneys decrease the expected overpressure in the switchgear installation room drastically, but give relatively low extra stress on the switchgear compartments themselves. Especially switchgear rooms in cellars, parking houses, tunnels, mines etc., where no or difficult to realize pressure relief to the outside world is foreseen, could benefit from these solutions, as well as older buildings.

Internal arc tests on Xiria

The IPH Laboratory in Berlin has a 77m^3 closed test bay, where room pressures can be registrated at internal arc testing of a switchgear. Several tests at IPH on Eaton's air insulated Xiria 24 kV RMU have been performed on standard lay-outs. The pressure relief discs open at appr. 1 Bar overpressure. The pressure in the room was measured 67 mBar at a 20kA-1s test. The constant in the theoretical formula for the static pressure rise is now 0,25.
67=0,25.20.1 / (77-1).

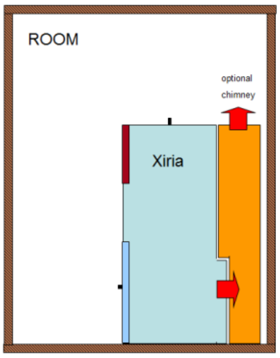

Fig [6]: air insulated Xiria 24kV RMU

Remark: The basic formula's in [4] put in an iterative program give as end pressure: 64 mBar, so in line with the rule of thumb above

With the for Xiria optional chimney, containing arc cooling ceramic blocks, a test was performed at 16 kA-1s. The room pressure dropped till 10,2 mBar, see fig. [7], where 0,25 . 16.1 / (77-1) = 54 mBar was theoretically expected when no chimney would be applied.

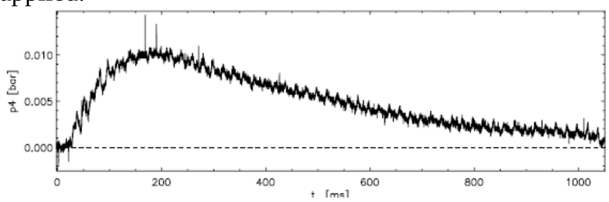

Fig [7]: room pressure measurement

So the pressure in the room was lowered to 20% of the value without the extra arc-cooling chimney.

Comparison several models with test results

The measured room pressure at internal arc tests performed at IPH are compared with the theoretical values, based on Eaton's rules of thumb and based on the calculation rules given in the [4], see table [2] (calculations performed without extra cooling of the arc).

Xiria RMU Air insulated		Test result IPH lab	Calculated:	
			Rule of thumb	Basics [4]
Ur IAC Ignition room	24 kV 20kA-1s 3-phase 77 m3	67 mBar	66 mBar	64 mBar
Ur IAC Ignition room	24 kV 16kA-1s 3-phase 77 m3	10 mBar (with chimney)	54 mBar	57 mBar

Table [2]: Comparison of models with test results

The results summarised in table [2] show that the several calculations are in line with the test results.

CONCLUSIONS

- The international standards that deal with internal arcs are far from complete in addressing internal arc aspects. Moreover they are not aligned with each other.
- The Eaton rules of thumb approach is a practical means to quickly assess expected overpressures in a switchgear room.
- By smart lay out of chimneys with ceramic honeycomb blocks, a drastic decrease of overpressure in the room can be attained
- Especially switchgear rooms where no or difficult to realize pressure relief to the outside world is foreseen, could benefit from these solutions

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