APPLICATION OF SIMPLIFIED MODEL FOR THE CALCULATION OF THE PRESSURE RISE IN MV SWITCHGEAR DUE TO INTERNAL ARC FAULT

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ABSTRACT

This paper describes a simplified mathematical model for the calculation of the pressure rise in switchgear due to an internal arcing fault and outlines few applications where it can be used. This approach has been developed and validated by CIGRE A3.24 Working group "Tools for Simulating Internal Arcs"

INTRODUCTION

CIGRE A3.24 Working group was formed in 2009 and it will complete its work and publish the technical brochure ***"Tools for simulation of effects of Internal Fault in MV and HV Switchgear"*** in 2013. The goal of this working group was to assess the calculation methods and software tools that could be used to simulate the effects of an internal arcing fault in MV and HV switchgear.

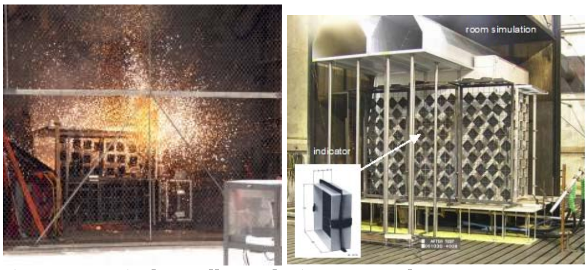


Figure 1: Typical Installaton during Internal Arc Tests

The motivation for this work was multifaceted:

- To provide methods for pressure rise calculations and allow benchmarking with performed tests
- To reduce the number of internal arc tests for environmental reasons by improving the design process (Figure 1)
- To verify design modifications by simulations
- To replace SF6 with air in testing with proper consideration of the differences

This paper focuses on calculations of the pressure rise as result of an internal arc fault. First, the equations of the mathematical model are provided. Then, two applications of the simplified model are discussed

a) Prediction of the pressure rise in a similar design. This is useful to reduce the number of type tests on design modifications.
b) Prediction of the pressure rise when the gas type is changed from SF_6 to air. Once the test has been done with an air-filled volume, the tool is able to predict pressure rise in the SF_6-filled switchgear. This is useful for manufacturers following IEC 62271-200 [1] guidance replacing SF_6 by air for internal arc tests.

OVERVIEW OF THE SIMPLIFIED MODEL FOR THE PRESSURE RISE CALCULATIONS

Over the last three years, CIGRE WG A3.24 has developed a simplified numerical model for the calculation of the pressure rise in a MV or HV switchgear compartment due to internal arc faults and checked this model against about 70 tests performed with either air, SF_6 or N_2 filled switchgear. The size of the analyzed compartment volumes varied between 0.005 m^3 and 1.2 m^3, the fault current between 12 kA and 63 kA and the fault duration between 10 ms and 1.2 s.

The simplified mathematical model assumes uniform pressure and temperature distributions in analysed compartments. Despite important physical simplifications, it shows a good agreement between test results and calculations, provided that the arc energy can be measured or estimated. This is obvious from Figure 2 representing the deviation between calculated and measured maximum pressure in all test cases where relevant data are available. For most of the cases (93%) the agreement is within 10%.

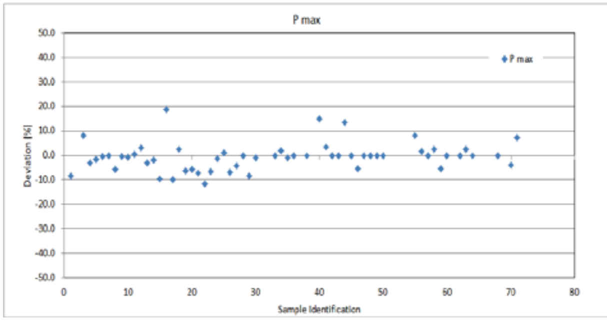


Figure 2: *Deviation between tested and calculated maximum pressure for test cases collected by CIGRE A3.24 Working group.*

Figure 3 shows schematically the test arrangement consisting of arc compartment, exhaust compartment, and installation room or environment (V_1, V_2, and V_3 respectively).

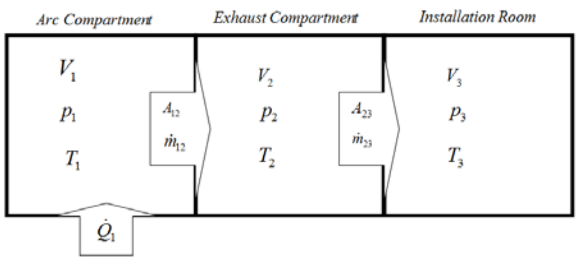


Figure 3: Principal arrangement and quantities used for pressure calculation

The arc, represented by the temporal development of energy input (Q_1), is initiated in V_1. A pressure relief opening (with cross-section A_{12}) connects arc and exhaust compartments. All openings between V_2 and V_3 are represented by one cross-section (A_{23}). When the pressure in the arc compartment (p_1) reaches the response pressure, the relief device opens and gas flows into the exhaust compartment and the installation room or environment.

The type of insulating gas in each volume is characterized by the corresponding heat capacity ratio (κ_i) and the specific gas constant ($R_{S,i}$); i=1, 2. The initial state of the gas is defined by pressure and temperature. While volume V_1 may be filled with air or SF_6, volumes V_2 and V_3 were filled with air in most cases.

The simplified model uses the equations for ideal gas, conservation of energy and mass flow through orifices. The equations (1) to (5) represent it [2, 3].

$$Q_1 = k_p W_{el} \tag{1}$$

The heat transfer coefficient k_p determines the fraction of the electrical energy (W_{el}) which contribute to the pressure rise in the arc compartment [4, 5, 6].

The gas relative parameters (such as κ, R_S and k_p) are assumed to be constant in the simplified model. The enhanced model may consider these parameters dependent on gas density.

In order to provide a numerical method for the calculation, the time dependent quantities are regarded for a time step Δt. The mass flow from compartment V_1 to compartment V_2 is given by:

$$\Delta m_{12} = \alpha_{12} A_{12} \rho_{12} w_{12} \Delta t \tag{2}$$

where α_{12} is the discharge coefficient, which considers contraction of the gas flow through the area A_{12}. ρ_{12} and w_{12} are the gas density and gas velocity in the orifice, which results from Bernoulli's equation. A similar equation describes the mass flow from V_2 into V_3. The change of mass in V_2 per time step is calculated as the difference between incoming mass (m_{12}) and outgoing mass (m_{23}).

$$\Delta m_2 = \Delta m_{12} - \Delta m_{23} \tag{3}$$

The temperature change in the arc compartment during time step Δt is determined by the difference of energy input by the arc and energy loss due to gas flow out of the compartment.

$$\Delta T_1 = \frac{\Delta Q_1 - \Delta m_{12}(c_{p1} - c_{v1})T_1}{m_1 c_{v1}} \tag{4}$$

where c_{p1} and c_{v1} are the specific heat capacities at constant pressure and constant volume respectively and T_1 is the temperature in V_1,. The pressure in V_1 at time t follows from the ideal gas law.

$$p_1 = \frac{(\kappa_1 - 1)}{V_1} m_1 c_{v1} T_1 \tag{5}$$

The simplified model can be used to roughly evaluate the pressure rise in arc and exhaust compartments in typical MV and HV switchgear. However, it also has some limitations:

- Does not calculate spatial differences in pressure inside the volumes
- Is not applicable when the relief opening is large in relation to the compartment volume
- Is not reliable when gas temperature exceeds 2000K for SF_6 and 6000K for air
- Neglects mixtures of air and SF_6

APPLICATION OF THE SIMPLIFIED MODEL

Simplified model can be used to predict the pressure rise in case of the design modifications (using interpolation between known test results). When calculating the pressure rise with the simplified model, the following steps should be taken to ensure consistent and reliable predictions:

1) Model (simplify) the switchgear geometry

Determine the size and volumes as depicted in Figure 2. This is illustrated in two examples shown in Table 1. In the first example, the switchgear tank is modeled with a single arcing volume and a rupture disc, whereas in the second example, the switchgear is modeled with two volumes (arc and exhaust compartments) and a rupture disc in-between. In both examples it is assumed that V_3>1000 m³.

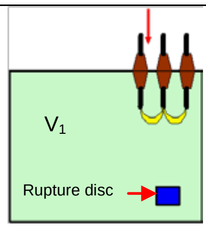
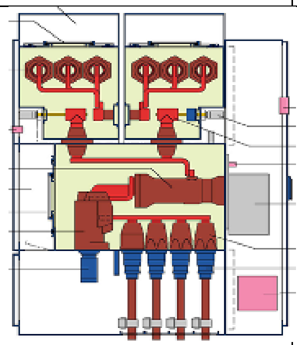
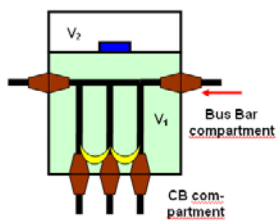
#	Switchgear	Simplified geometry
1		
2		

Table 1: ***Examples of simplified geometry of switchgear***

2) Collect data from internal arc tests

The volumes are determined by the geometric volume of the compartments without the volume of the built-in components. Relief openings are represented by effective areas, i.e. the geometric cross-section of the opening diminished by the area of frames, slats, grills etc. The opening of the relief device occurs instantaneously at the given (static) response pressure. The initial filling pressure is as recorded in the test report. Phase-to-ground voltage is the average of measured voltage over the whole arc duration. The current course is evaluated considering a DC time constant of 45 ms.

Volume of arc comp. (V_1)	0.27	m³
Volume of exhaust comp. (V_2)	0.58	m³
Volume of installation room (V_3)	>1000	m³
Initial filling pressure in V_1	120	kPa abs air
Initial filling pressure in V_2	100	kPa abs air
Area of the relief opening A_{12}	0.049	m²
Discharge coefficient of α_{12}	1.0	
Response pressure of relief device	220	kPa rel
Area of the opening A_{23}	0.195	m²
Short-circuit current	38.8	kA rms
Number of phases	3	
Averaged phase-to-ground voltage	250	V

Table 2: ***Data for Example #2 from Table 1***

3) Determine the coefficients k_p and α by comparison of calculation to test results.

The arc energy is determined from measured phase currents and phase-to-ground voltages:

$$\Delta W_{el} = (u_R i_R + u_S i_S + u_T i_T)\Delta t \qquad (6)$$

According to equation (1), the thermal energy of the arc leading to the pressure rise is determined by k_p, which results from adapting calculated to measured pressure rise (slope $\Delta p/\Delta t$ up to the response pressure of the relief device). Therefore, the measured and calculated pressure developments in the arc compartment displayed in Figure 4 are congruent in the rising part of the curves.

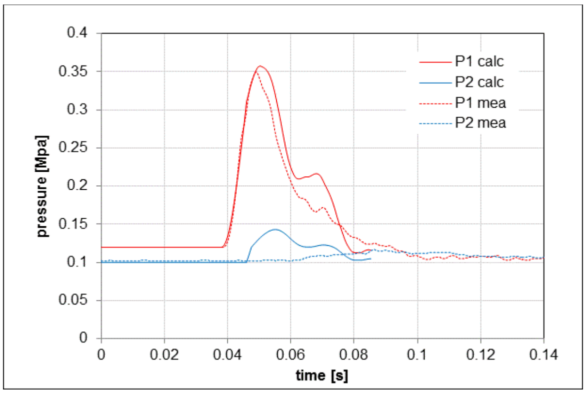


Figure 4: ***Calculated pressure development in V_1 (red line) and V_2 (blue line) for test example #2 from Table 1 in comparison with measurement (dotted lines)***

The discharge coefficient (α) is adjusted to fit as well as possible the measured pressure decay.

4) Predict the pressure rise with simplified model calculation

Figure 4 compares measured and calculated pressure curves for example #2. Coincidence in course and peak pressure is good for the arc compartment but less satisfactory for the exhaust compartment.

To illustrate the difference in the pressure development for different switchgear geometries, Figure 5 displays the calculated results for the volume V_1 increased by 50% keeping all other input values constant and for the area of the relief device A_{12} enlarged by 50%. The peak pressure determining the stress on the enclosure is in both cases lower than in the reference case.

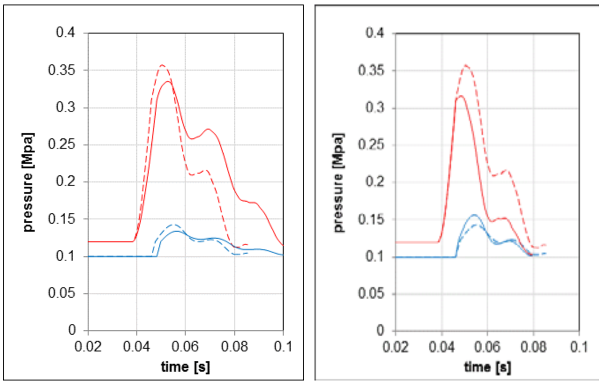


Figure 5: ***Calculated pressure curves corresponding to example #2 with volume V_1 (left) or relief area (right) increased each by 50%***

The difference in pressure course when replacing the filling gas SF_6 by air is noted from Figure 6. Here, the actual measured phase-to-ground voltage of 400 V and a best fit k_p of 0.76 have been applied to the same switchgear compartment. The peak pressure is smaller for SF_6; however, the gas stays longer in the compartment. The test with SF_6 also gives a lower peak pressure; however, the pressure drop is two times faster in test (noisy light lines in Fig. 6) than in simulation.

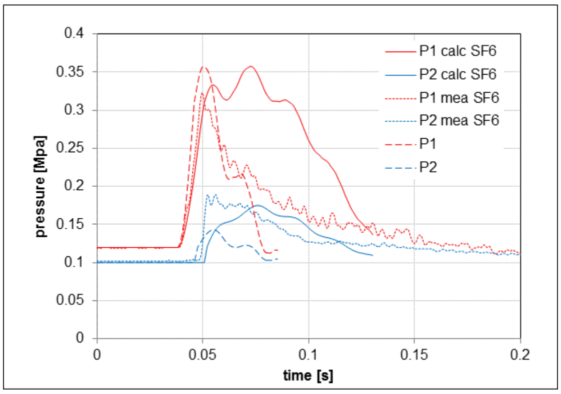


Figure 6: ***Calculated pressure development corresponding to example #2 with air (dashed line) and SF6 (solid line); dotted line shows measured pressure for SF6.***

5) Perform sensitivity analysis of the model

In order to determine the behaviour of the model, the sensitivity study consists in the evaluation of the pressure for several test cases with varying input parameters. Figure 7 presents the sensitivity of the pressure on the opening area for example #2 (color curves). The bold black curves represent the reference pressure course (0.049 m²). The arc and exhaust volume pressures are shown (solid and dashed lines respectively). The simulation for air is based on SF6 setting, with only κ and R_s changed.

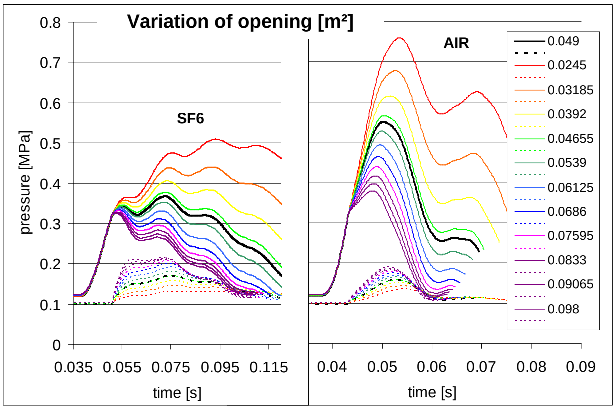


Figure 7: ***Sensitivity of the pressure on arc compartment opening area.***

In Figure 7, the SF6 reference curve corresponds to the P1-calc-SF6 from figure 6. It can be concluded that in order to obtain a better agreement between simulated and measured pressure decay in Figure 6, one could enlarge the opening or, equivalently, increase α (compare the violet lowest line for 0.098 m²).

The sensitivity study reveals that there is a difference in simulation between slow and fast processes. The process is considered fast when the burst occurs within one power cycle. It depends on volume, operating pressure, arc energy and gas. The example discussed here is a fast process (t_{burst}≈10 ms). The slow processes in general are more predictable.

The sensitivity analysis allows also evaluating the impact of the lack of precision in collected data, including the switchgear geometry. The table 3 below lists the worst error for all test cases on peak pressure while the input parameters are varied by ± 10%.

Parameter	Peak press. error			
	Slow process		Fast process	
20% of variation	Air	SF6	Air	SF6
Arc power	14%	13%	18%	19%
Arc comp. volume	7%	3%	19%	19%
Arc comp. opening	13%	12%	15%	12%
Arc comp. burst press.	19%	19%	20%	10%
Arc comp. init temper.	6%	6%	8%	6%
Arc comp. init. press.	6%	6%	8%	15%
Exhaust comp. opening	0%	4%	10%	11%
Exhaust comp. temper.	0%	1%	2%	1%

Table 3: ***Variation of peak pressure (worst case)***

CONCLUSION

A3.24 WG findings suggest that simulations cannot replace type tests, but they could be used for interpolation between the known tests and make predictions of the pressure rise.

Attempts to reproduce by simulation the pressure courses measured directly inside the compartments during an internal arc fault test are successful **as long as the input arc energy is well known**. The maximal pressure can be simulated within a 10% deviation.

The comparison also indicates that most arrangements can be successfully simulated by applying common input parameters: the coefficient *kp* of 0.5 for air and 0.7 for SF_6, the discharge coefficients α between 0.7 and 1.0 and an approximated arc voltage determined from the distances between electrodes.

REFERENCES

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