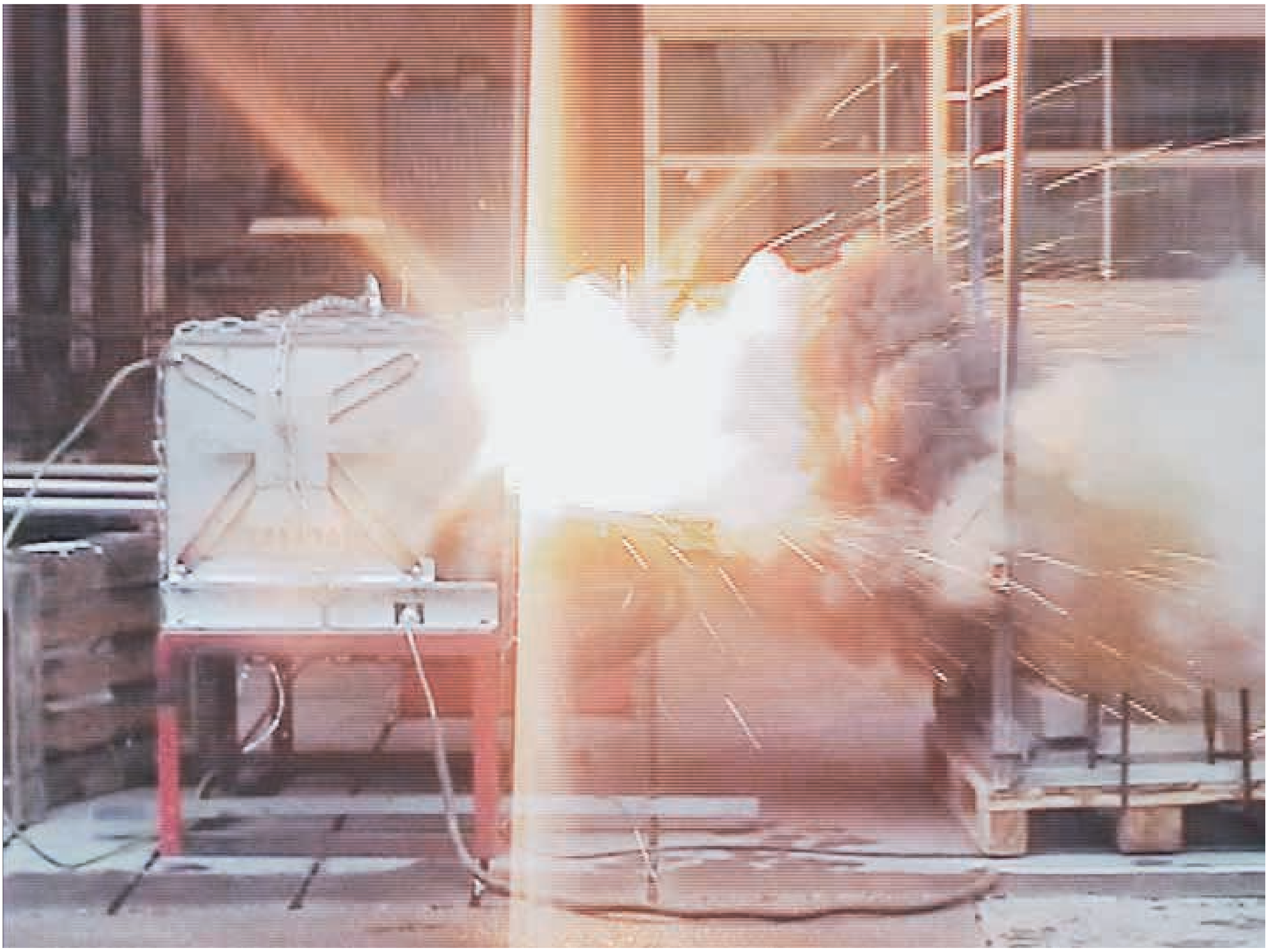
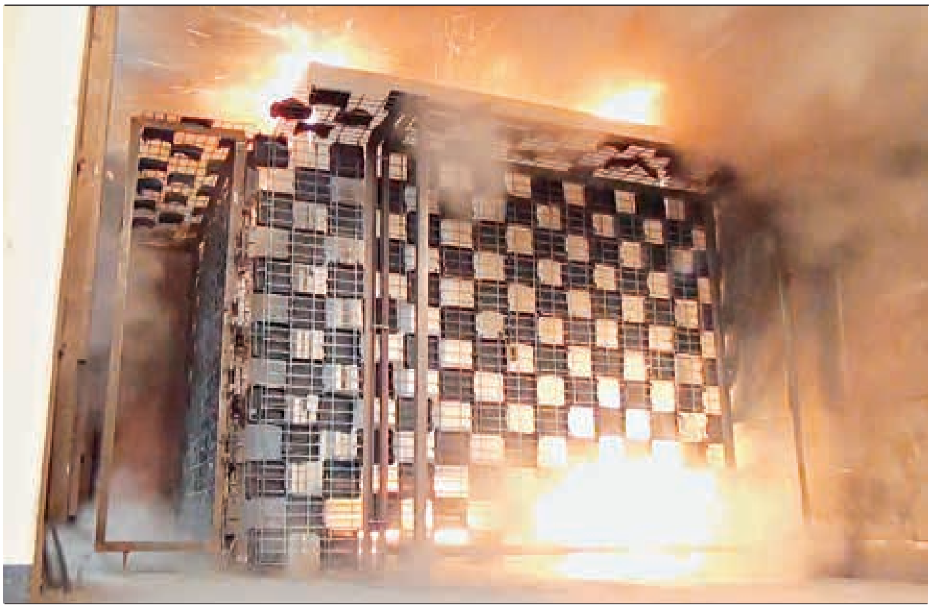


Feeling the pressure

Simulating pressure rise in switchgear installation rooms

EDGAR DULLNI, PAWEL WOJCIK, TOMASZ BLESZYNSKI – An internal arc fault is an unintentional discharge of electrical energy in switchgear. During the fault, short-circuit currents flow between phases and to ground. The arc heats the filling gas in the switchgear enclosure – either SF_6 or air, resulting in pressure rise. The incidence of a fault is very rare, but when it happens it may seriously damage the electrical equipment and the building and may even endanger personnel. It is only possible to evaluate the pressure rise in a building by calculation. Nevertheless, calculations should be substantiated by special tests allowing the measurement of external pressure rise. ABB has developed a calculation program that is easy to use by developers of switchgear and civil construction engineers.

1 Internal arc in switchgear during an arc fault test in the laboratory



Pressure rises stress switchgear enclosures mechanically. In order to avoid rupture, a relief device opens at defined pressure. The fault arc produces hot gas, which has to be directed in a controlled manner into the environment. Most often, exhaust channels are placed on top of the switchgear. These channels often possess a hatch or absorber at the end, where the hot gas is cooled down before it leaves the channel.

Standards eg, IEC 62271-200 [1] require switchgear to be safe for operating personnel, even if an internal arc occurs → 1. Type tests not only verify that the switchgear enclosure withstands the pressure, but also prove that hot gases are directed away from personnel. IEC 61936-1 [2] requires that the building design shall take into account the pressure rise due to these exhaust gases. Switchgear arc fault tests do not cover this aspect, since the installation room is simulated by two perpendicular walls and ceiling, which do not present a gas-tight room allowing room pressure measurement. Therefore it is only possible to evaluate the pressure rise in a building by calculation. Another application for the calculation program is to simulate the pressure rise for different filling gases, ie, SF_6 and air. For validation, tests were conducted together with RWTH Aachen and TÜV Nord Systems GmbH.

Title picture
Image captured from a high speed video showing the controlled exhaust of hot gasses from medium voltage switchgear during an internal arc test. ABB software calculates the observed pressure development inside the switchgear and in the installation room.

Equations in the calculation program

Gas pressure in an enclosure depends on gas temperature, in accordance with the ideal gas law. Mass balance equations consider mass flow out of the enclosure. Compartments are represented by their effective volumes (components subtracted) and pressure relief areas in between. Gas properties such as the specific heat capacities are independent of temperature and uniform all over the volume [3].

Some fraction – called thermal transfer coefficient k_p – of the fault arc power heats up the gas in the arc compartment:

$$Q_1 = k_p \cdot W_{el}$$

The electrical arc power is evaluated from measured currents and phase-to-ground voltages:

$$W_{el} = (u_R \cdot i_R + u_s \cdot i_s + u_T \cdot i_T)\, t$$

The measured voltages are not necessarily identical to the arc voltage, because a three-phase arc can burn between two phase conductors, but also to the grounded enclosure. The pressure calculation tool either imports measured phase-to-ground voltages from a formatted data file or applies an empirical average phase-to-ground voltage.

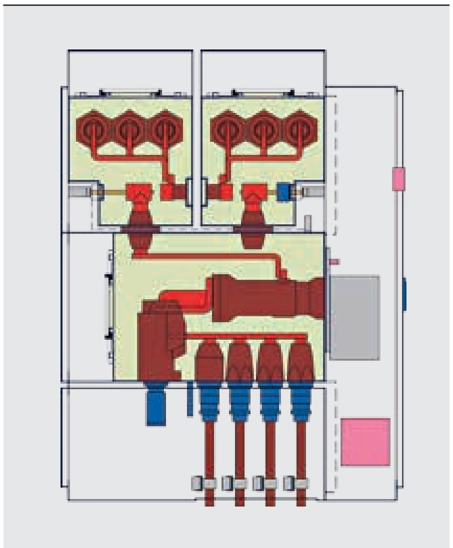
All time-dependent quantities in the Internal Arc Tool (IAT) are regarded before and after a time step Δt. The following equation shows the mass flow out of the arc compartment into the exhaust compartment:

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

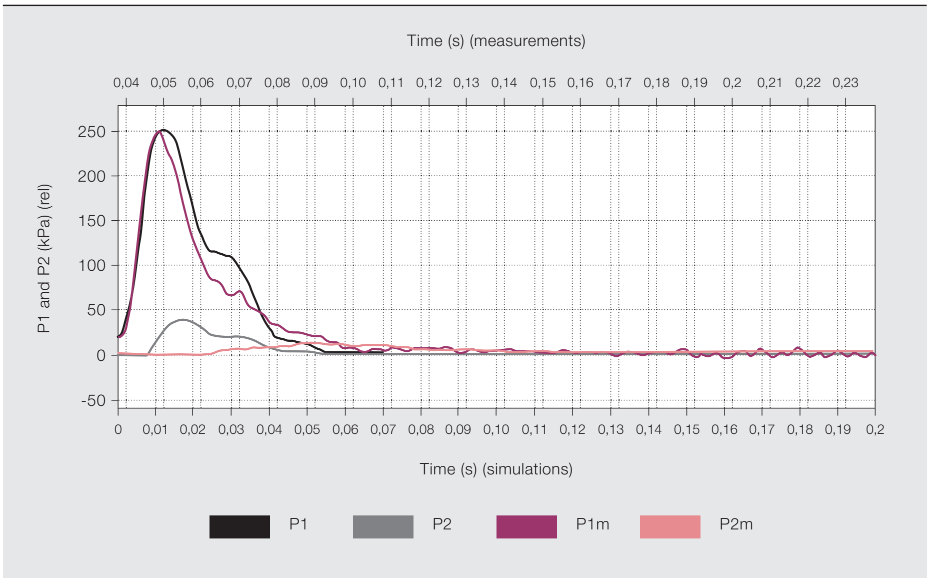
α_{12} is the efficiency of a relief device with area A_{12} and considers the contraction of gas flow through an opening with sharp edges (0.7 to 1.0), but also the flow reduction due to eg, a mesh or absorber. When the relief device opens, the mass Δm_{12} escapes from the volume per time step. $\rho 12$ and $w12$ stand for gas density and gas velocity inside the opening according to Bernoulli's law [3]. This mathematical approach allows for the calculation of the pressure rise in all involved volumes.

The accuracy of the calculation is limited by the applied simplifications. Because of the assumption of constant specific heat capacities, dissociation of gas molecules into fragments is not considered. This starts at 6,000 K in air and 2,000 K in SF_6. However, agreement with test results is obtained also for higher gas temperatures.

2 Cross-section of ABB switchgear type ZX2 with arc initiated in busbar compartment and pressure relief into the channel on top

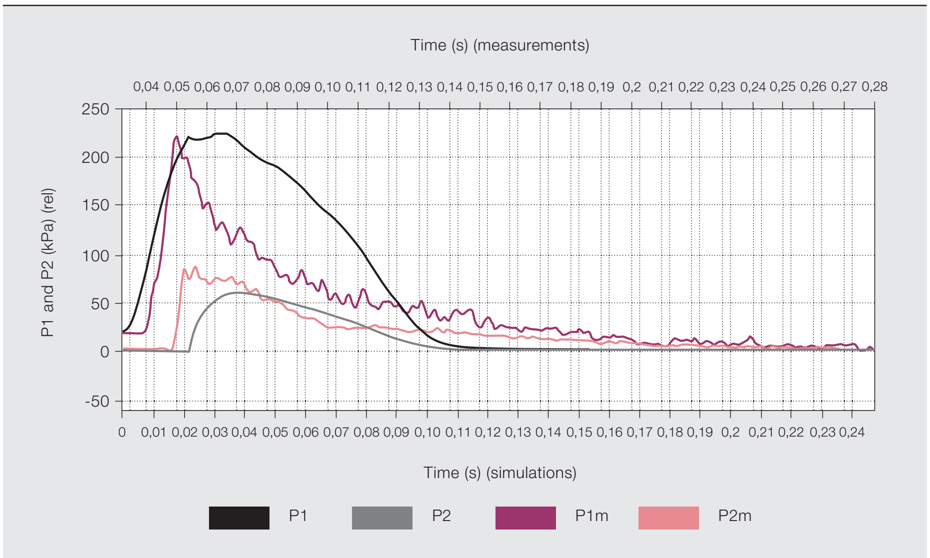


3 Comparison of calculated and measured pressure developments for an internal arc in ZX2 using air as filling gas (38 kA)



Type tests not only verify that the switchgear enclosure withstands the pressure, but also prove that hot gases are directed away from personnel.

4 Comparison of calculated and measured pressure developments for an internal arc in ZX2 using SF_6 as filling gas (35 kA)



If a considerable amount of gas flows out of the switchgear compartment, fewer and fewer gas molecules remain in it. If the heating fraction k_p of the arc energy stays constant in time, an ever increasing gas temperature would result, exceeding known arc temperatures of 20,000 K by far. This is not realistic and also generates numerical instabilities. To avoid this, the k_p is taken as density dependent [4]. This modification allows the extension of the calculation to longer fault durations and for calculating the pressure rise in the installation room.

Tool description

The proposed methodology was successfully implemented in the IAT simulation software at ABB's Simulation Tools Center (STC).[1]

The tool consists of two parts: graphical user interface (GUI) and solver. The solver was developed in Python and the user interface in Java. The main features delivered by the IAT GUI are:

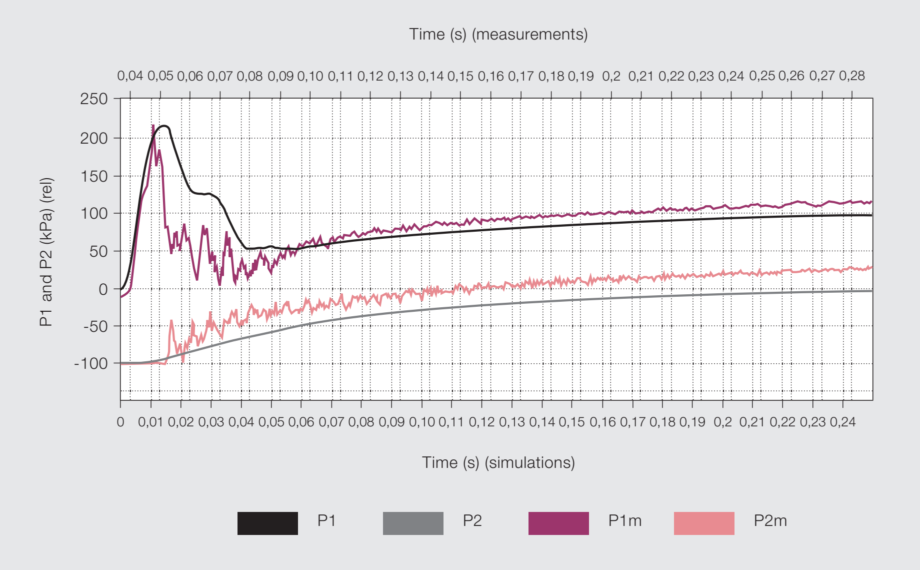
1) Set up model parameters
2) Run solver
3) Visualize results
4) Create report

Model parameters can be set directly or can be selected from a drop-down list and each parameter is validated. When the model is ready, the user is able to start the simulation. They are guided through the simulation setup by a simple wizard. Simulation time takes less than

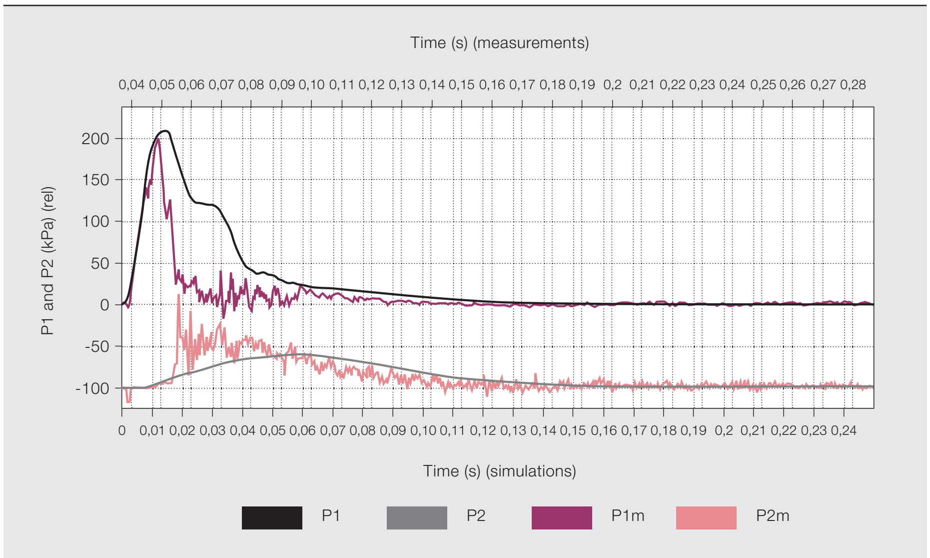
Footnote

1 See also → 7 on page 71 of *ABB Review* 3/2013.

5 Comparison of calculated and measured pressure developments for an arc in a test arrangement using an 8 m³ closed container (20 kA)



6 Pressure developments as in ➔ 5 with 0.3 m² relief opening (20 kA)



Simulation time takes less than 10 s for a maximum arc duration of 1 s on a laptop.

10 s for a maximum arc duration of 1 s on a laptop. The calculations are performed with a constant simulation time step of 0.05 ms. For comparison with tests, measurement data in proper format can be imported.

The following characteristics are drawn:
1) Pressures vs. time
2) Phase currents vs. time
3) Phase to ground voltages vs. time
4) Integrated arc power vs. time

Plots can be dynamically modified and no additional editor for visualization is needed. Examples are shown in ➔ 3 – 9.

Additionally, text files with simulation parameters (selected input and output values) and result data are generated.

Comparison of results

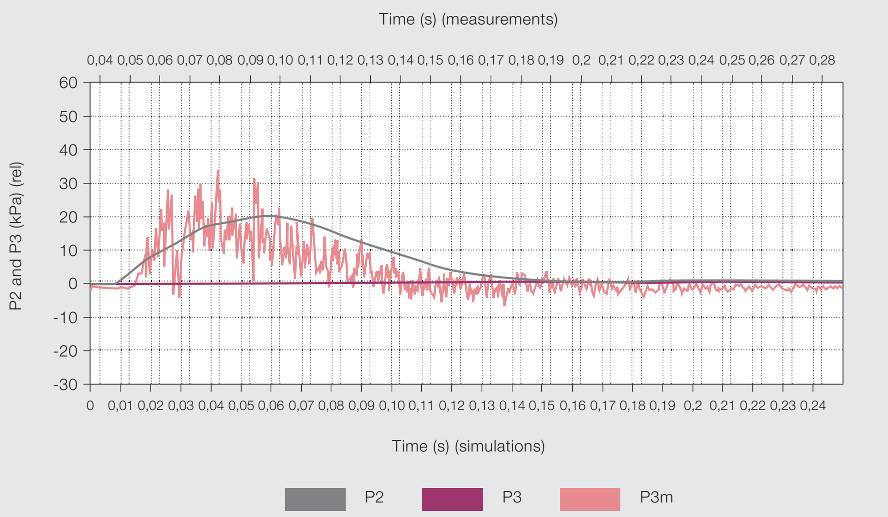
The IAT results were compared with results from tests obtained with ABB switchgear and specially designed experiments.

The first comparison relates to gas-insulated switchgear (GIS) where the insulating gas SF_6 could be replaced by air. The cross-section of the ABB switchgear ZX2, where the arc was ignited in the busbar compartment, is shown in ➔ 2. The pressure relief device was a thin burst disc with an area of 0.049 m² opening into the channel on top at an over-pressure of 220 kPa. The fault current had a value of 39 kA and was applied for 1 s. The oscillograms show the time development of the calculated pressure in the arc compartment (black in oscillograms) and exhaust channel (gray in oscillograms), and the measured data (purple for the former, pink for the latter) up to 250 ms after arc ignition.

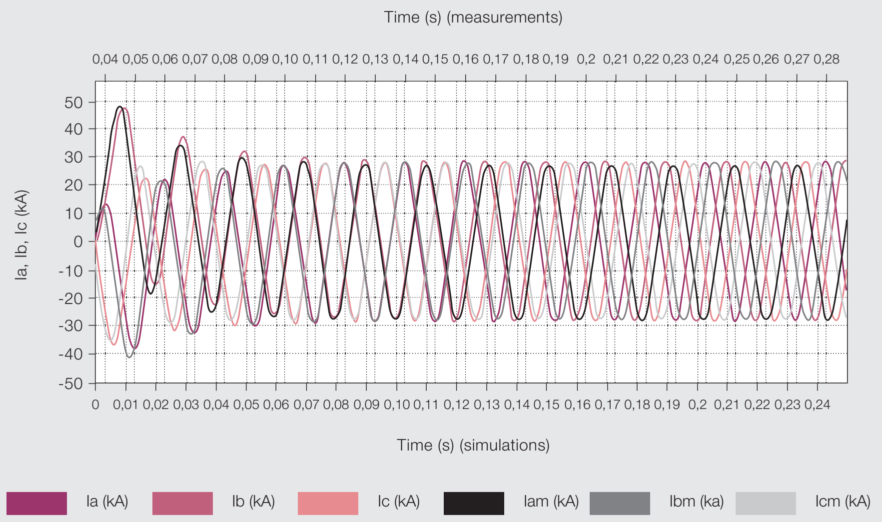
In ➔ 3, measurement and calculation of pressure rise, peak and drop in the arc compartment filled with air are in good agreement. k_p is taken as 0.5 in accordance with published data, and arc voltage (phase-to-ground) of 300 V is taken from test. The calculation of pressure in the exhaust channel shows less satisfying correlation with the test results due to travel time effects of the exhausted gas, which cannot be implemented in the IAT. For the filling gas SF_6 ➔ 4, the reproduction of the peak pressure is again good, but the drop of pressure after the opening of the relief disc is less satisfying. The calculation provides a longer residence time of the gas than observed in the test.

The exhaust of hot gas and subsequent pressure rise in a closed installation room were investigated in a special experiment.

7 Pressure in the container measured at another location than for ➔ 6



8 Measured and applied phase currents showing the initial asymmetry



k_p is taken as 0.75 consistent with publications, and arc voltage is 400 V according to tests.

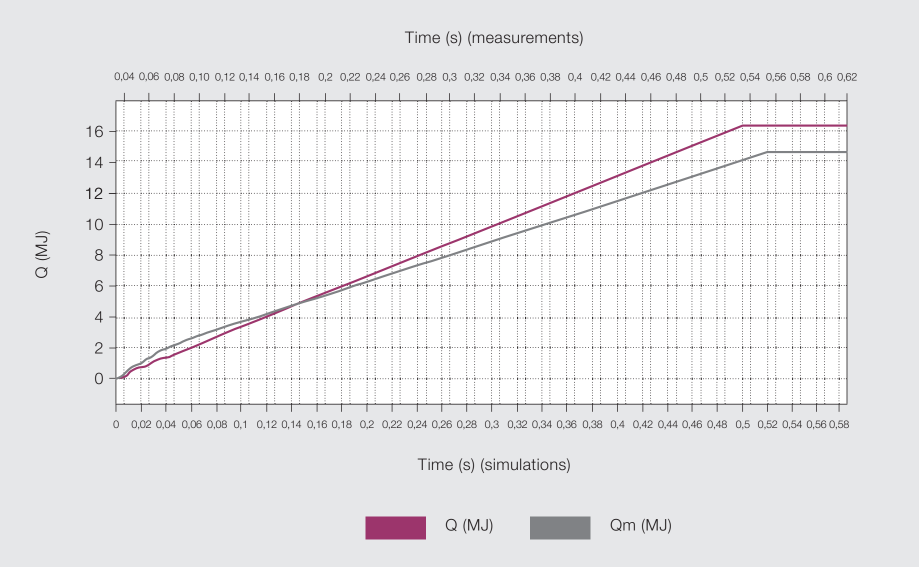
Many tests were recalculated. The inaccuracy in the peak pressure in the arc compartment is in the range of ±20 percent, mainly determined by the uncertainty of response pressure of the relief device. The drop of pressure after relief is simulated with an error of a factor of two. This is of no concern for the assessment of pressure withstand of the switchgear, since it is the peak pressure that is decisive.

The peak pressure in exhaust channels can also be calculated. However, the inaccuracy might be up to ±40 percent, which originates from the effects of pressure waves in elongated channels.

The exhaust of hot gas and subsequent pressure rise in a closed installation room were investigated in a special experiment [4]. The installation room was simulated by a gas-tight container of 8 m³. ➔ 5 shows pressures determined in test and calculations. The drop of pressure in the arc compartment, after response of the relief device, deviates from the measurement, but the saturation of the pressure rise in the container is simulated satisfactorily. This is due to the decrease of k_p implemented in the IAT in dependence of the decreasing gas density in the enclosed switchgear compartment. If the arc energy heats up the total container volume uniformly in time, as for a freely burning arc, the pressure would linearly rise to 345 kPa instead of the measured 154 and calculated 114 kPa.

The tool can calculate pressure rise in installation rooms with relief openings provided by, eg, windows or hatches.

9 Arc energy determined from the multiplication of phase-to-ground voltages and currents (purple from IAT; gray from measurement)



The internal arc simulation tool is a useful element to improve design efficiencies and increase safety, especially when it is impossible or impractical to carry out real-world testing.

The calculation tool implements the density dependence of k_p according to the following formula applied for $\rho(t) < \rho_c$:

$$k_p(t) = k_p \cdot c_0 \cdot (\rho(t)/\rho_0)^{0.5}$$

c_o is adapted to provide a continuous transition from the initial k_p. ρ_c is 1 percent of the normal gas density ρ_0 at 100 kPa for air and 20 percent for SF_6. Corresponding results were gained from the tests using SF_6 and air in a similar arrangement [4].

The tool can also calculate the pressure rise in installation rooms with relief openings provided by, eg, windows or hatches. → 6 shows a test result using the same 8 m³ container with a relief area of 0.3 m². The actual geometry of the installation room and the position of the relief opening and sensors cannot be considered in the IAT and will give deviations to reality. An example is the higher initial pressure in → 6 due to the direct stream of gas to the sensor. Another sensor positioned aside shows better agreement with the calculation → 7. Only computational fluid dynamics (CFD) may provide better results.

Estimated pressure

Within reasonable limits both peak pressures in the switchgear compartments and exhaust volumes match each other in test and simulation results. Inaccuracies are caused by the simplifications introduced in the tool (eg, ideal gas assumption and generic outflow function). The IAT can be used for simulation of the pressure effects of fault arcs in switchgear. The uncertainty in the prediction of the peak pressure is in the range of ±20 percent concerning the arc compartment. A reliable arc voltage is required determined from tests on similar switchgear. The tool can also be used to estimate the pressure rise in an exhaust volume or installation room with or without relief openings considering proper safety margins. The internal arc simulation tool is a useful element to improve design efficiencies and increase safety, especially when it is impossible or impractical to carry out real-world testing.

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[4] E. Dullni *et al.,* “Pressure rise in a switchroom due to internal arc in a switchboard,” Proceedings of the 6th International Symposium on Short-Circuit Currents in Power Systems, pp. 4.5.1 – 4.5.7, 1994.
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