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CALCULATION OF PRESSURE RISE AND ENERGY OF HOT GASES DUE TO HIGH ENERGY ARCING FAULTS IN THE METAL-CLAD SWITCHGEAR

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Abstract. This paper presents the 3-D CFD calculation results of the pressure rise due to the High Energy Arcing Faults (HEAFs) in the metal-clad switchgears. The calculations were performed considering the came-off of the roof panel that was observed in the arc tests. The calculated pressure development approximately agreed with the measured one. Furthermore, the energy of hot gases exhausted from the broken roof panel was calculated to investigate the thermal effect of hot gases.

Keywords: switchgear, internal arc, pressure rise, energy of hot gases.

1. Introduction

High Energy Arcing Faults (HEAFs) can be caused by the failure within electrical installations due to either a defect or an exceptional service condition or maloperation [1]. The HEAFs lead to the temperature rise and the pressure rise in the installations and then the exhausting of hot gases from the installations. As a result, the successive fire incident owing to the ignition of flammable materials may occur inside and/or outside the installations.

In Japan, the Tohoku District-off the Pacific Ocean Earthquake attacked the Onagawa Nuclear Power Station of Tohoku Electric Power Co., Inc. on March 11, 2011 and the successive fire incident due to the HEAFs occurred in the electrical cabinet. In order to clarify the pressure rise in the non-arc proof electrical cabinets due to HEAFs and understand the critical condition for the successive fire occurrence in the cabinets, a series of 3-phase internal arc tests with 6.9 kV switchgears were performed [2]. In the tests, the arc current I_{arc} was around 20 kA, the arcing duration tarc was 0.1–2 s, and the electric arc energy W_{arc} was 3–45 MJ.

In this paper, the calculations of the pressure rise due to the HEAF in the switchgear were carried out using a CFD (Computational Fluid Dynamics) method. The calculated pressure rise was compared with the measured one. The propagation of the hot gases in the switchgear and the energy of the hot gases exhausted from the switchgear through the broken roof panel were also investigated.

2. Calculation method and conditions

In the 3-D calculations, a CFD program (CFD-ACE+) was applied to solve the full set of basic hydrodynamic equations (i.e., conservation equations of mass, momentum and energy). Those conservation equations in terms of partial differential equations were solved at each location in the switchgear iteratively, while the energy input, a portion of the arc energy, was set locally. The general form of the conservation equations can be written as:

$$\frac{\partial}{\partial t}(\rho\,\phi) + \nabla\cdot(\rho\,\mathbf{v}\,\phi) = \nabla\cdot(\Gamma\,\nabla\,\phi) + S \qquad (1)$$

where ϕ represents the conserved variables under consideration, ρ the gas density, $\mathbf{v}$ the gas velocity, Γ the transport coefficient of ϕ and S the source term for ϕ [3].

Figure 1 shows the schematic drawing of the switchgear used in the tests. The switchgear has two cable compartments (CCs), a bus compartment (BC) and two circuit-breaker compartments (CBCs). The compartments are separated by the metal plates. For the ventilation in the switchgear, the metal plates of the rear wall as well as the metal plates between the CC and BC have some rectangular slits. Figure 2 shows the sketch of the upper CC considered in the calculations. The volume of the CC was 1.31 m^3. In order to simplify the calculations, the pressure and the temperature of the outside of the upper CC were 0.1 MPa and 293 K, respectively. As the arc was ignited in the upper CC, the energy input W_{input} was applied locally in the CC. W_{input} was given as k_p times W_{arc}. k_p is a fraction of the W_{arc} leading to the pressure rise. k_p changes depending on the arc current and the arcing electrode material, e.g. k_p decreases from 0.6 to 0.53 gradually with increasing arc current from 1 kA to 12.5 kA in the case of copper electrodes [4]. The values of k_p estimated in other publication [5] is in the same range as those mentioned above. When estimating the values of k_p, the energy balance

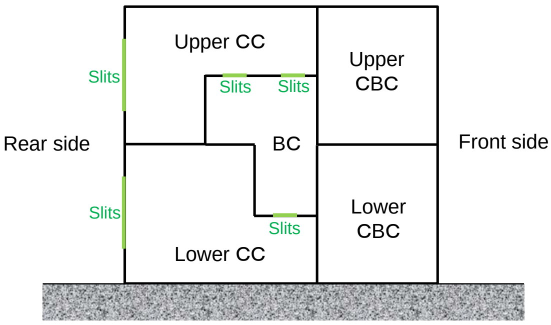

Figure 1. Lateral view of the compartments in the switchgear [8]. [CC: Cable compartment, BC: Bus compartment, CBC: Circuit-breaker compartment]

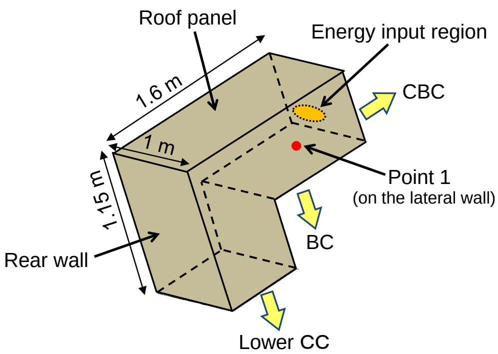

Figure 2. Geometrical arrangement considered in the calculations (upper CC). [8]

in the closed container was investigated [4–7], where the "input" energy in the container was the electric arc energy and the energy of chemical reactions like oxidation of electrode vapor in the case of exothermal reactions. Conversely, the output energy in the container was the energy causing pressure rise in the container and the energy losses due to arc radiation energy and the energy portion for electrode melting and evaporation.

The pressure rise in the CC was measured at point 1 in the test. The gas inside was air with an initial pressure and temperature of 0.1 MPa and 293 K, respectively. I_{arc} was 21 kA, t_{arc} 0.1 s (100 ms), W_{arc} 3.1 MJ, the current frequency 50 Hz. k_p was taken as 0.53, because the arcing electrode material was copper in the tests, and k_p did not change so much when the arc current increased from 4 kA to 12.5 kA [4]. The metal plate with the slits was simply considered as a medium of gas flow resistance and of heat resistance/capacitance in the same way as in [9]. The walls of the CC were assumed to be adiabatic, because the arcing duration was short (0.1 s), and the

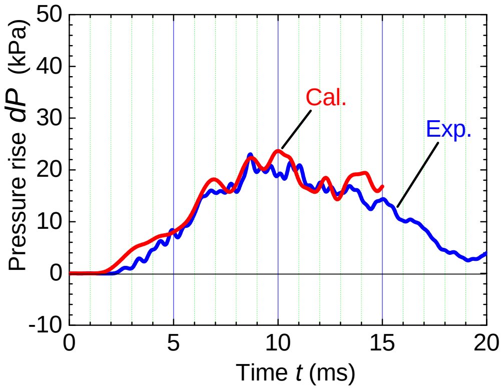

Figure 3. Calculation and experimental pressure developments at point 1 in the upper CC.

CC was embedded in ambient air, which was a good heat-insulating medium.

During the test, the tightening bolts of the roof panel of the upper CC broke owing to the pressure rise in the CC and the roof panel came off. In the calculations, it was assumed that a part of the roof panel began to open when the pressure rise reached about 5 kPa, which was estimated using the ultimate tensile strength (420 N/mm^2) and the cross-sectional area (14.2 mm^2) of the bolt, and the area of the roof panel. In our previous paper [8], as a first step, the opened area of the roof panel was constant (0.064 m^2). In this paper, the opened area increased gradually (0.036–0.295 m^2) with time by considering the motion of the roof panel. The opened area was estimated by using the following method. Supposing that the roof panel is rigid and the roof panel comes off with the rear eyebolts as the supporting points, the motion of the roof panel due to the internal pressure rise in the upper CC was calculated by using the motion equation. The gap between the roof panel and the upper CC was calculated, and then the opened area of the roof panel was estimated by using the gap area.

3. Calculation results

3.1. Pressure rise

Figure 3 shows the calculated and measured pressure developments of point 1 in the CC. The measured pressure rise dP increased and reached the maximum value of about 23 kPa at time t of about 8.7 ms, and dP showed a tendency to decrease although the arc continued to burn in the CC. In this paper, the calculation was carried out until $t = 15$ ms, where dP decreased gradually. The calculated pressure development agreed well with the measured one.

Figure 4 shows the 3-D pressure distribution in the CC. With time t, dP near the energy input region increased and the pressure wave propagated to another region, e.g. the rear of the CC. Also, the hot gases in the CC went out mainly through the opened area of

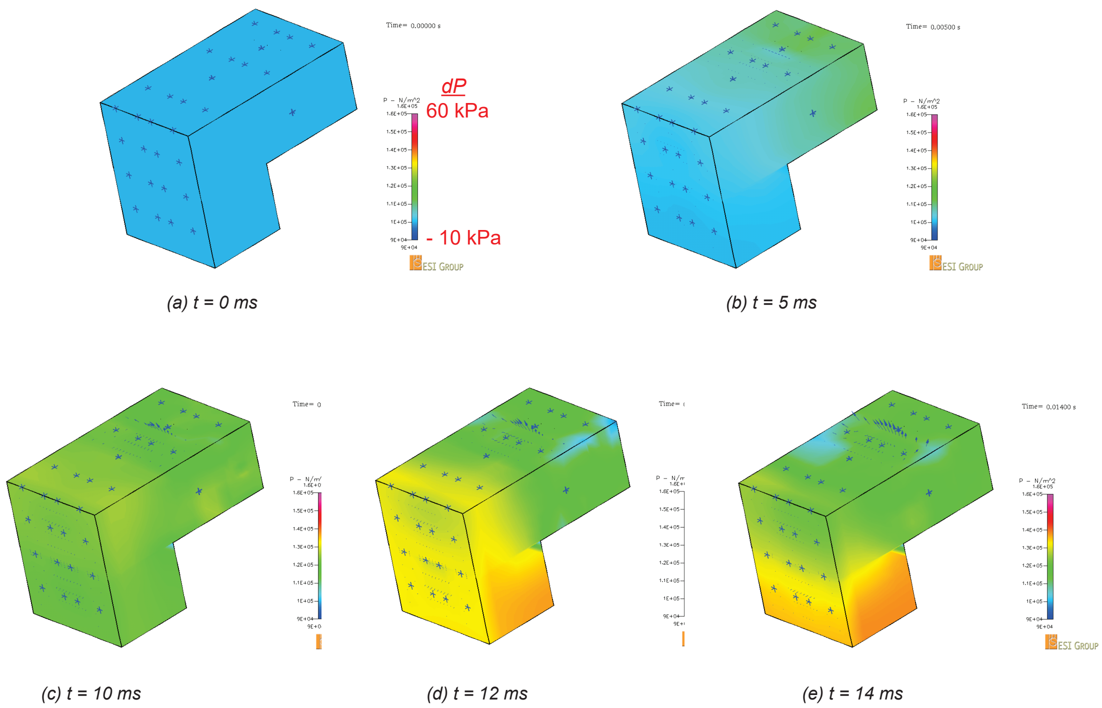

Figure 4. Time dependence of 3-D pressure distribution in the upper CC.

the roof panel after t of about 4.4 ms when dP of the roof panel reached about 5 kPa.

3.2. Energy of hot gases exhausted from roof panel

When investigating the thermal effect on personnel and flammable materials near the electrical equipment in which fault arcs occur, it is necessary to estimate the energy of hot gases exhausted from the equipment. In this section, the energy flow density EFD of hot gases exhausted from the opened area of the roof panel was calculated using the same method as in [10]. The energy flow density EFD of hot gases is given by

$$EFD = H_{ex}\, \rho_{ex}\, v_{ex} \tag{2}$$

where H_{ex}, ρ_{ex}, and v_{ex} are the specific enthalpy, gas density, and velocity of the gas at the exit of the opened area of the roof panel, respectively.

Figure 5 shows the energy flow density EFD of hot gases exhausted from the broken roof panel. EFD increased rapidly at time t of about 4.4 ms when the roof panel began to open owing to the pressure rise in the CC.

Figure 6 shows the measured arc energy W_{arc} and the calculated energy W_{ex} of the exhausted hot gases. The energy W_{ex} increased gradually because both EFD and the opened area increased with time.

Figure 7 shows the ratio k_{ex} of W_{ex} to W_{arc}. The ratio k_{ex} increased approximately in proportion to the opened area A_{op} of the roof panel. This result suggests that the ratio k_{ex} can rise more as the opened area increases. It is necessary to consider the development

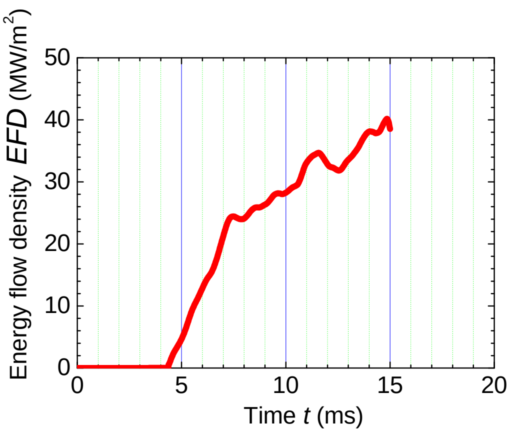

Figure 5. Calculated energy flow density of hot gases exhausted from the opened area of roof panel.

of the energy of hot gases exhausted from electrical equipment when investigating the thermal effect of hot gases on personnel and flammable materials near the equipment.

4. Conclusions

This paper described the 3-D CFD calculation results regarding the pressure rise due to HEAFs in the metal-clad switchgears and the energy of hot gases exhausted from the switchgears thorough the broken roof panel. The energy input took place locally in the upper cable compartment of the switchgear. The gas inside was air with an initial pressure of 0.1 MPa. The arc current I_{arc} was 21 kA, the t_{arc} 0.1 s (100 ms),

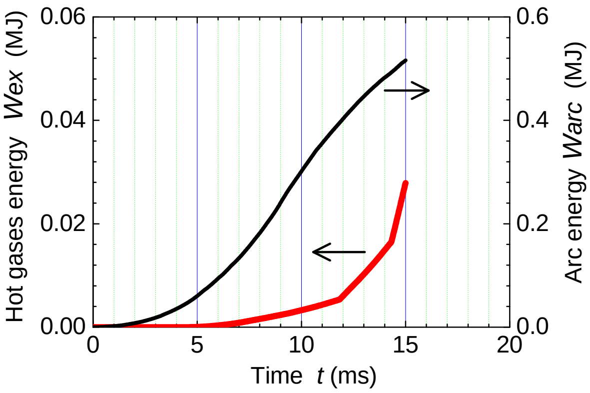

Figure 6. Calculated energy of the exhausted hot gases and measured arc energy.

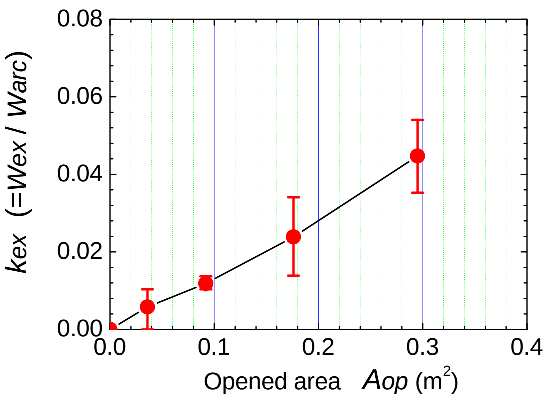

Figure 7. Dependence of the ratio $k_{ex} = (W_{ex}/W_{arc})$ on the opened area of roof panel.

W_{arc} 3.1 MJ. The calculations were performed considering the propagation of the hot gases from the cable compartment to the outside and the came-off of the compartment roof panel that was observed in the test. As a result, the calculated pressure developments of the cable compartment agreed well with the test results. In addition, the calculated energy of hot gases exhausted from the opened area of the roof panel increased gradually because both the energy flow density of hot gases and the opened area increased with time. The above properties of hot gases must be considered when investigating the thermal effect of hot gases on personnel and flammable materials near the switchgears.

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