Arc Simulation Technology

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ABSTRACT

With distribution, switching and control equipment components, finding a way to predict and control the behavior of the arc generated by contact switching is an important technological challenge. Fuji Electric has developed arc simulation technology that couples thermal fluid analysis with electromagnetic field analysis for further miniaturization of components, improvement of performance and accommodation of direct current devices. The arc simulation technology makes it possible to use structure of an actual device to visualize its behavior or arc for quantitative evaluation of gas flow and electromagnetic force.

1. Introduction

For power distribution, switching and control equipment components, predicting and controlling arc behavior generated by switching contacts is an important technological concern. Fuji Electric has been committed to the improvement of interruption characteristics by making effective use of numerical analysis technologies, such as current limiting interruption simulation technology combining electromagnetic field analysis and circuit analysis, gas flow analysis technology for molded-case circuit-breakers based on thermo-fluid analysis, and prediction of arc behavior by electromagnetic field analysis(1).

Interruption by an electric distribution device is a phenomenon that continues for only several milliseconds, and the current and the voltage waveforms are the only information obtained through measurement. Although pressure and temperature can be observed by making a special test sample and even arc behavior can be measured through a high-speed camera by setting a window in the interruption section, it is difficult to measure them with the product in its original shape. Arc behavior depends on the pressure or gas flow at the time of arc generation or on the Lorentz force produced in the arc. These factors are governed by the structure or material of the case, the material or switching speed of the contact, or the grid structure. To conduct a more in-depth study at the stage of development, Fuji Electric endeavored to develop simulation technology capable of quantitatively evaluating all of these factors and visually reproducing arc behavior.

This paper outlines the effort in the arc simulation technology combining thermo-fluid analysis and electromagnetic field analysis and its application to products.

2. Arc Simulation Method

2.1 Calculation method

An arc is the phenomenon in which a gas as hot as several thousand to several tens of thousands of degrees is ionized and becomes conductive; the temperature rises as a result of self-heating induced by the current, and a charged state is consequently maintained.

To accurately reproduce this phenomenon, arcs must be handled at the level of electrically charged particles, such as electrons and ions. In the simulation presented herein, the arc phenomenon is calculated using the physical properties of a plasma-state gas and a general-purpose thermo-fluid analysis program (STAR-CCM+*1). However, the force working on the plasma-state gas consists of electromagnetic force induced by flowing current in addition to the pressure and heat generation that can be calculated by thermo-fluid analysis.

Thus, Fuji Electric created a program designed to calculate the magnetic field from the current density based on the Biot-Savart law, and reproduced arc behavior by applying Lorentz force induced by the interaction between the current and the magnetic field etc. to the fluid element (see Fig. 1).

The equation for calculating the magnetic field based on the Biot-Savart law is shown below.

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*1: STAR-CCM+: Trademark or registered trademark of CD-adapco.

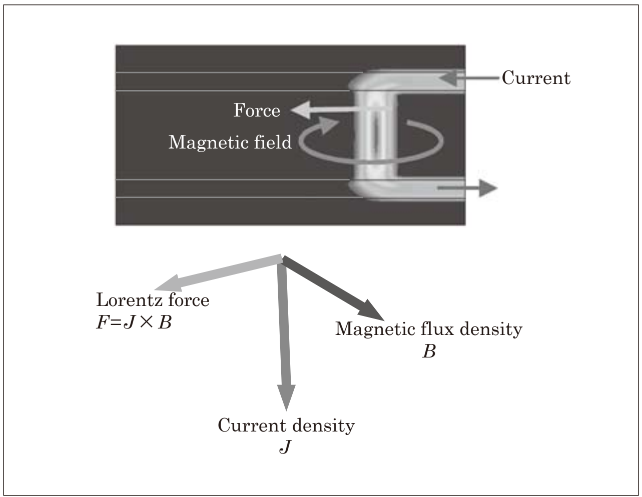

Fig.1 Calculation of Lorentz force

$$B(r)=\frac{\mu_0}{4\pi}\int_{r'\neq r}\frac{J(r')(r-r')}{|r-r'|^3}dV' \quad \cdots\cdots (1)$$

B : Magnetic flux density vector
J : Current density vector
r : Position vector
V : Cell volume
μ_0 : Magnetic permeability of vacuum

If Equation (1) is applied as it is, calculation time will increase in proportion to the square of the number of cells. For this reason, the calculation is sped up by excluding minute current cells from the integration range.

When handling the arc behavior of electric distribution devices, metallic vapor produced by contacts or grids, ablation gas generated by resin, and the effects of external magnetic fields induced by grids and magnets, must be taken into account in addition to the voltage drop characteristic in the sheath region close to the electrode.

2.2 Arc root model

In the portion where the arc comes into contact with the electrode (arc root), temperature and electric potential significantly vary, and complicated phenomena, such as electron discharge and absorption, occur. This portion is consequently brought into the non-equilibrium state (see Fig. 2), in which the local thermal equilibrium (LTE) assumption of the electrons and plasma temperatures being equal is not satisfied.

There is a method of describing the arc root as a non-equilibrium model taking into account the temperature of electrons, but we adopted a model designed to reduce the calculation workload[2]. With the voltage drop of the arc root defined as a function of the current density J, the electric conductivity of the arc root of thickness δ is derived, as shown in Equation (2).

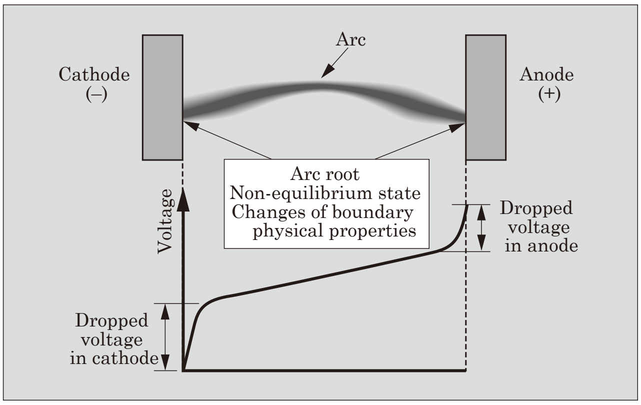

Fig.2 Voltage drop of arc root

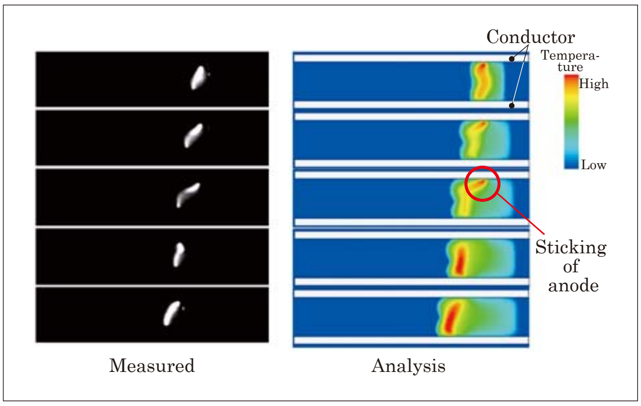

Fig.3 Inchworm movement of arc on parallel conductors

$$\sigma=\frac{\delta J}{E} \quad \cdots\cdots (2)$$

σ : Conductivity of arc root (S/m)
δ : Thickness of arc root (m)
J : Current density vector (A/m^2)
E : Dropped voltage (V)

A layer of mesh of thickness δ was placed on the surfaces of the electrodes and the grid. We caused a voltage drop of the electrodes and sticking of the anode by changing the characteristics of the cathode and anode sides of this arc model and successfully reproduced a phenomenon called inchworm moving (see Fig. 3).

2.3 External magnetic field (permanent magnet and magnetic body) model

Magnetic bodies such as permanent magnets and, grids generate external magnetic fields, and it is necessary to analyze these effects.

The magnetic field produced by the permanent magnet is calculated as an initial condition using the magnetic field calculation function of STAR-CCM+ in advance, and the external magnetic field is calculated by superimposing the magnetic field induced by the free current, which is obtained using Equation (1) over this magnetic field. Figure 4 shows the traveling state of the arc when permanent magnets are placed at a middle point on parallel conductors. It was verified

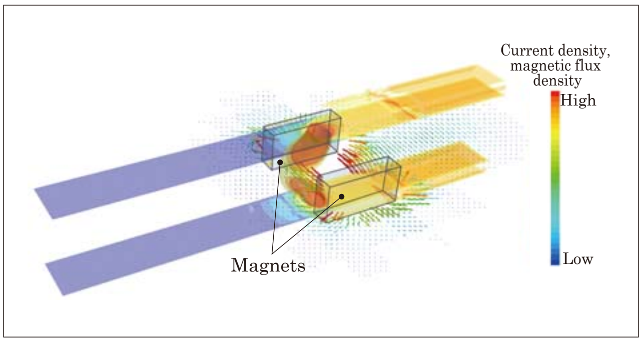

Fig.4 State of arc traveling when permanent magnets are placed

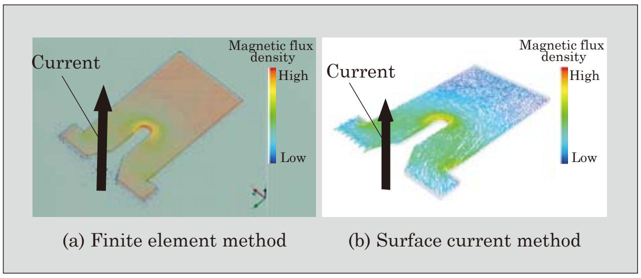

Fig.6 Magnetic field analysis results of grid

that the arc traveled at a speed equivalent to the measured actual speed by the effect of the magnetic field generated by the magnets.

In the case of grids and other magnetic bodies, magnetic field distribution, including magnetic bodies, must be calculated because they affect the magnetic field distribution and determine the driving force of the arc itself. As this calculation method, a method combining magnetic field analysis using the finite element method and the magnetic moment method are available, but we selected the surface current method[5] for its short calculation time (see Fig. 5).

The surface current method reproduces changes of the magnetic flux density due to a magnetic body by applying a virtual current (magnetizing current) to the surface of the magnetic body. A kind of boundary element method, this surface current method is linear analysis and cannot deal with the non-linear B-H characteristic or magnetic saturation but takes less time to calculate because it can reuse an LU-decomposed coefficient matrix. Thus, with this method, the magnetic flux density can be calculated using Equation (1), which is not generally available for magnetic bodies.

Figure 6 shows a comparison of magnetic field distribution induced by the current flowing near a grid between the finite element method and the surface current method. We obtained results from the surface current method that were equivalent to those produced by the finite element method with the aid of an elaborated element breakdown method and calculation algorithm.

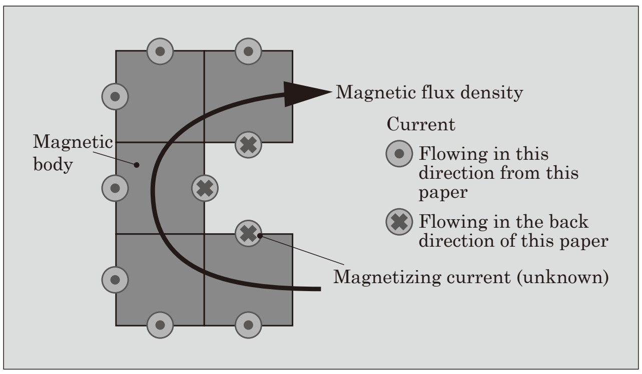

Fig.5 Surface current method model

2.4 Evaporative gas (ablation gas) generation model

One of the factors that greatly affect arc behavior is evaporative gas generated from contacts or the inside of the case.

As evaporative gas generation models, we simulated evaporation proportional to arc power and arc current and evaporation based on the panel heat transfer coefficient h_{arc}[3] of the arc, and verified that the evaporation model based on h_{arc} ensured relatively high calculation accuracy[4].

The evaporation model based on harc is set to generate evaporative gas (or pyrolysis gas in the case of resin) when the panel temperature T exceeds boiling point Tkof the adjacent solid substance in the fluid cell of the first layer of the wall surface. The evaporation rate m_k can be obtained from Equation (3).

$$m_k = \frac{h_{arc}(T - T_k)}{Q_k L} \quad \cdots\cdots (3)$$

m_k : Evaporation rate (kg/m^{3}s)
h_{arc} : Wall surface heat transfer coefficient of arc (W/m^{2}K)
Q_k : Sum of melting heat and evaporation heat (J/kg)
T : Wall surface temperature (K)
T_k : Boiling point of solid matter (K)
k : Type of solid substance
L : Thickness of wall surface layer (m)

The optimum value of harc was calculated based on various basic experiments, such as electrodes butting (see Fig. 7).

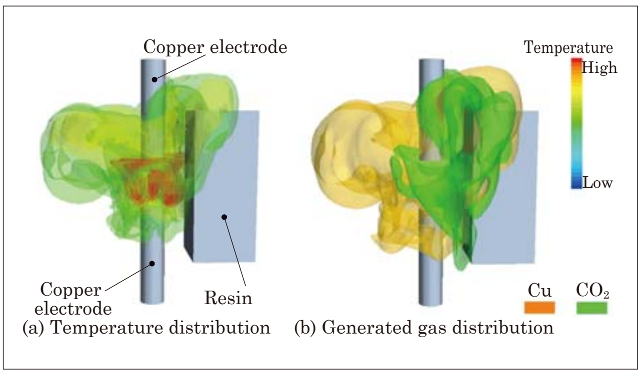

Fig.7 Example of arc simulation by electrodes butting

Evaporative gas will condense and returns to the liquid or solid state again if its temperature drops below the boiling point. When T was lower than the boiling point T_k of each material, the condensation rate was calculated using Equation (4) and set as the source term of the fluid cell.

$$n_k = Y_k R_c (T - T_k) \quad (4)$$

n_k: Condensation rate (kg/m^{3}s)
Y_k: Mass fraction
R_c: Condensation rate coefficient (kg/m^{3}sK)
T: Wall surface temperature (K)
T_k: Boiling point of solid matter (K)
k: Type of solid substance

In addition, the solid substance will absorb energy from the surroundings when it evaporates and reaches the temperature of the fluid cell, and will discharge the energy to the surroundings when it condenses. This relation was calculated using Equation (5) and set to the fluid cell.

$$S = -\sum_k (m_k + n_k) Q_k \quad (5)$$

S: Energy source term (W/m^3)
m_k: Evaporation rate (kg/m^{3}s)
n_k: Condensation rate (kg/m^{3}s)
Q_k: Sum of evaporation heat and melting heat (J/kg)
k: Type of solid substance

Simulations of arc behavior entail technical issues in addition to the above-mentioned concerns, such as physical property values and radiation models in the plasma (hot) state, the displacement of the mesh when moving the electrodes, and mesh subdivision. Arc simulations can be achieved by resolving these issues.

3. Application Examples of Arc Simulations

3.1 Arc simulation of circuit protector

A circuit protector is a circuit breaker combining an overcurrent protection function for protecting the circuits within equipment and a switch function for the equipment. It is compact in size but has a large breaking capacity of 2.5 kA (240 V AC). We performed an arc simulation to study whether a large-capacity interruption, including a grid, could be reproduced.

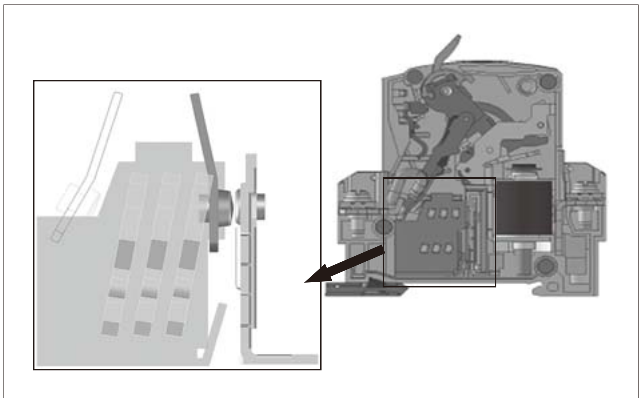
Fig.8 Structure of circuit protector

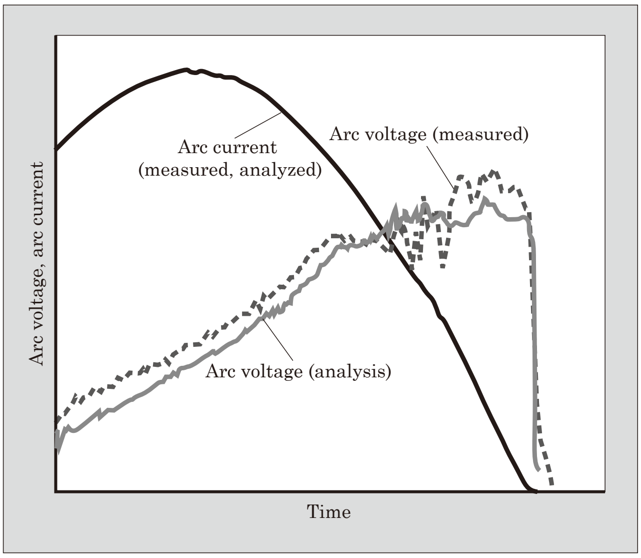

Fig.9 Arc current and arc voltage at the time of interruption

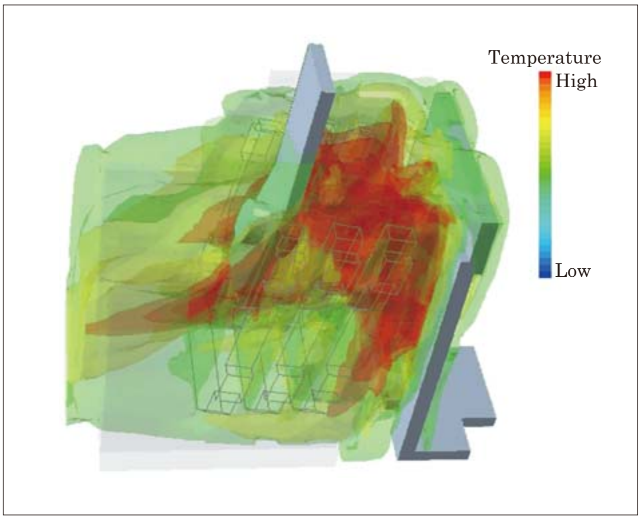

Fig.10 Arc simulation results of circuit protector

Figure 8 shows the structure of the circuit protector we adopted. We modeled the portion of the arc control device shown in the frame, and performed an arc simulation with an actually measured AC current as input. Figure 9 shows the arc current and the arc voltage in an interruption at 2.5 kA. The figure demonstrates good agreement between the calculated result of the arc voltage and the measured value. The state of the arc at the time of the interruption is shown in Fig. 10.

Arc simulations enable us to calculate temperature distribution, current density, gas flow rate, pressure, gas components, etc. in time sequence. Exhaust area, grid shape, arrangement, case rigidity, and other factors for the design of the arc control device can be studied based on the calculation results.

3.2 Arc simulation in DC interruption by molded-case circuit-breaker

A molded-case circuit-breaker protects a device connected to a distribution system from overcurrent. Recently, higher levels of DC current interruption have been required as DC transmission/distribution for photovoltaic power generation and data centers are diversifying and they work on higher voltages. This section describes an example of DC current interruption we studied.

Figure 11 shows an arc simulation model for molded-case circuit-breakers. In this simulation, the calculation was performed by inputting a definite DC voltage based on the test circuit.

Figure 12 shows a comparison between the measured and analyzed values of arc current and arc voltage when a DC current of 820 A was interrupted. Although the timing of arc commutation is slightly earlier, the analyzed values of both the current and the voltage are in good agreement with the measured values. The arc commutates from the moving contact to the arc runner and then moves to the grid. In response to it, the phenomenon of a temporary rise and subsequent drop of the arc voltage is observed with both the measured value and the simulation.

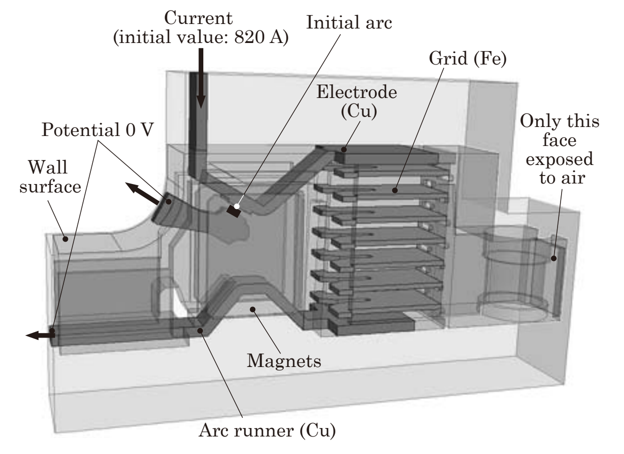

Fig.11 Arc analysis model for molded-case circuit-breakers

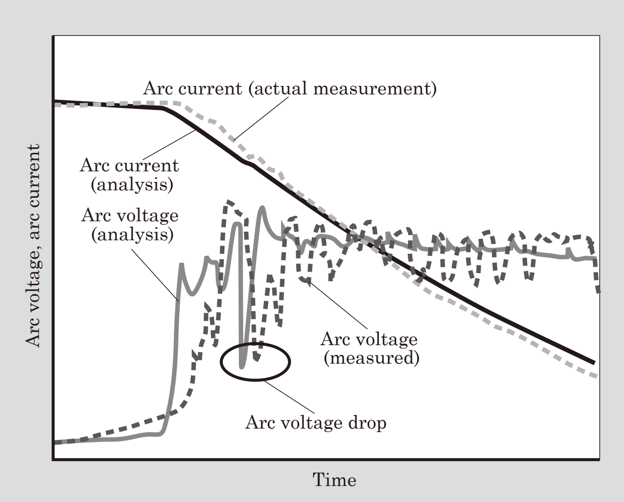

Fig.12 Arc current and arc voltage at the time of interruption of 820 A

The simulation results of the arc current density and the generated gas components at the time of the arc voltage drop are shown in Fig. 13. The arc current density indicates that the arc voltage decreased as a consequence of restriking the arc on the contact side after it reached the grid. Another finding is that the metallic vapor of copper with high conductivity commutated from the generated gas components to the contacts and the potential between the contacts consequently decreased, resulting in restriking of the arc.

As stated above, performing a simulation enables us to visually and quantitatively identify what phenomenon is manifested inside equipment. Simulations are effective in planning measures.

The arc produces high driving force at a large current because of the gas flow or Lorentz force but is low in driving force and may fail to move to the grid at a small current. As a solution to this problem, a magnetic body or permanent magnet is placed to promptly drive the arc. To verify the effect of a permanent magnet, we compared the results of arc simulations with and without a permanent magnet.

Figure 14 shows simulation results when 100 A was interrupted. It was verified that the driving of the arc stopped before the grid when permanent magnet

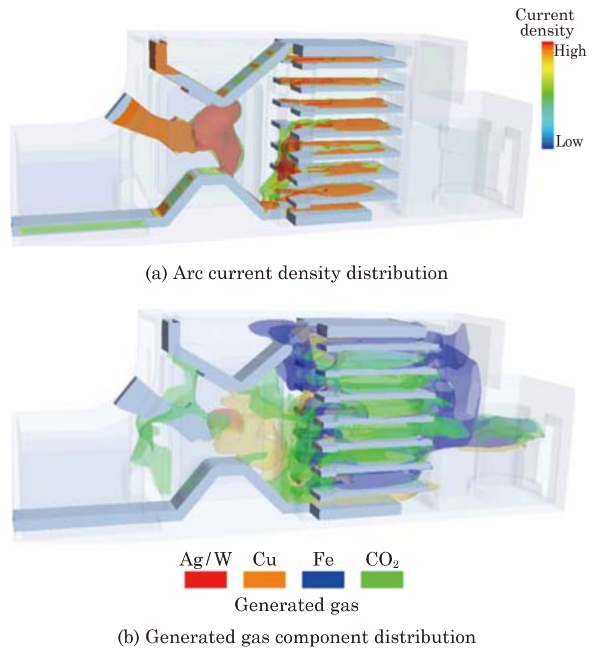

Fig.13 Simulation results of arc current density and generated gas components

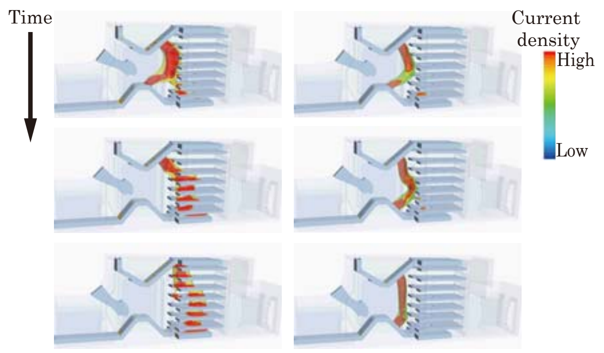

Fig.14 Simulation results at the time of interruption of 100 A

was not used, and a similar result was also obtained in an actual test.

4. Postscript

In this paper, we described simulation technology combining thermo-fluid analysis and electromagnetic field analysis for predicting and evaluating arc behavior. This technology made it possible to visualize arc behavior, which had not been visible, and quantitatively identify whether the behavior is induced by electromagnetic force or by a gas flow. In addition, with this technology we can arbitrarily set parameters to study, thus verify structures of unprecedented concepts without making prototypes. We are determined to further improve analysis accuracy and develop products of high performance and high quality through the application of this technology.

We would like to express our heartfelt thanks to Professor Yasunori Tanaka at Kanazawa University for the provision of various physical properties and advice to our analyses.

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