

Analysis of Pressure Rise During Internal Arc Faults in Switchgear

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ABSTRACT

Switchgear include devices that play an important role in operations such as electric circuit switching and power measuring and monitoring, and IEC standards stipulate safety performance criteria regarding arc discharge (internal arc faults) in switchgear. Fuji Electric has developed an analysis technology for predicting pressure rise and pressure discharge performance during internal arc faults in order to design safe switchgear. By incorporating a pressure loss model in the vicinity of devices that discharge pressure and an arc model derived from the results of actual device testing, we have been able to implement highly accurate analysis. We have developed IEC standard compliant switchgear based on this analysis technology.

1. Introduction

In power reception and distribution facilities that connect power systems and power equipment, switchgear contains important devices responsible for electric circuit switching and power measuring and monitoring. To switchgear for overseas markets, an IEC standard (IEC 62271-200) applies. This standard contains enhanced approaches to safe structures such as classification relating to protection of people in the surrounding areas during failure and maintenance. It provides, among others, for safety performance against arc discharges (internal arc faults) in switchgear. If an internal arc fault occurs, energy supply from the arc heats up the atmospheric gas in the switchgear, and this causes the internal pressure to rise along with the increase in gas temperature. If the housing of the switchgear cannot withstand the pressure rise, the hot gas that has leaked out may make contact with people in the vicinity, developing into a critical accident. Accordingly, together with interlock technology that prevents internal arc faults in switchgear, it is important to have technology for venting hot gas in switchgear to the outside in the unlikely event of internal arc faults.

This paper describes analysis technology for predicting the pressure rise and pressure relief performance during internal arc faults as technology for designing safe switchgear.

2. Analysis Method

If an internal arc fault occurs, the following operations take place to prevent damage to the housing of the switchgear.

- (a) Internal pressure rise due to arc energy (heating energy)
- (b) Activation of the pressure relief device at the specified pressure
- (c) Venting of hot gas via the pressure relief device
- (d) Decrease of the pressure in the switchgear

Accordingly, the pressure rise value during internal arc faults must be predicted for designing the housing and pressure relief device. Specifically, it is necessary to predict the correlation between the arc energy generated and the internal pressure rise, and predict the operating performance of the pressure relief device.

To predict the arc energy, circuit analysis should be conducted that considers the relationships between the system voltage and impedance and between the short circuit current and arc voltage generated. An arc voltage is a potential difference generated between the 2 ends of an arc, and it causes a pressure rise in the switchgear. At the same time, it limits the current that flows through the system in the event of failure because it provides a back electromotive force against the system voltage. This arc voltage constantly changes according to the arc length, electrode material and current flowing into the arc, which makes it important to estimate it with accuracy.

Meanwhile, to predict the pressure relief performance in the switchgear, the mass flow rate of the hot gas that blows out must be determined by solving thermo-fluid equations. However, an internal arc fault may heat the gas around the arc to a high temperature of a few hundred to a few thousand K and ionization and dissociation may occur in the process, and this can cause the gas density and specific heat to vary in a nonlinear manner. The gas pressure, in particular, greatly depends on the gas density. For that reason, the nonlinear behavior of the property values of the gas must be taken into consideration. As shown in Fig.

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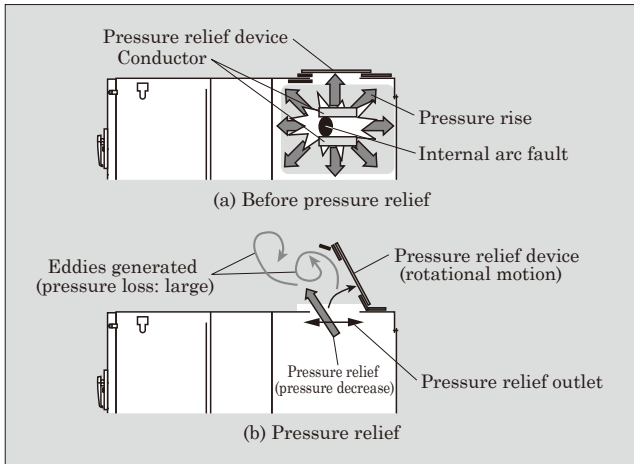


Fig.1 Operation of pressure relief device

1, the pressure relief device involves rotational motion at the time of pressure relief and the hot gas flows to the periphery and generates unsteady eddies. These may contribute to pressure loss. This makes it difficult to predict the pressure loss in the periphery of the pressure relief device.

We have built an analysis method that offers high accuracy for the pressure rise during internal arc faults by incorporating into numerical analysis the arc model and model of the pressure loss in the vicinity of the pressure relief device derived from the results of actual device testing.

2.1 Construction of arc model

An arc voltage can be represented as the sum of the positive column voltage shown in the first term and the electrode drop voltage shown in the second term in Equation (1). A positive column is the region between the electrodes where a strong light emission is observed.

$$V_{\text{arc}} = E_{\text{arc}}L_{\text{arc}} + V_{\text{con}} \quad (1)$$

$$E_{\text{arc}} = f(I_{\text{arc}}) \quad (2)$$

V_{arc} : Arc voltage (V)

E_{arc} : Arc electric field (V/m)

L_{arc} : Arc length (m)

V_{con} : Electrode drop voltage (V)

I_{arc} : Current flowing into the arc (A)

The electrode drop voltage, which is a voltage in the vicinity of the electrode generated when electrons and ions collide with the electrode, is a value specific to an electrode material. For copper used for power lines and bus bars of switchgear, the electrode drop voltage is 16.5 V⁽¹⁾. Meanwhile, the arc electric field that constitutes the positive column voltage depends on the current that flows into the arc (flowing current), as shown by Equation (2). Accordingly, Equations (1) and (2) can be used to determine the arc electric field experimentally by defining the arc length (distance between electrodes), flowing current and arc voltage.

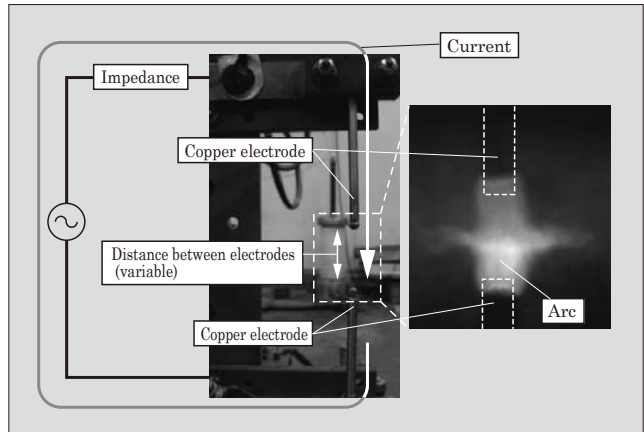


Fig.2 Basic test for arc electric field evaluation

Then, as shown in Fig. 2, we evaluated and obtained the current dependence of the arc electric field by basic testing for arc electric field evaluation. The following 2 test parameters were used.

○ Distance between electrodes L_{arc} : 2 to 20 mm

○ Flowing current I_{arc} : 1 to 10 kA

Figure 3 shows the results of measuring the arc voltage against the flowing current for different distances between electrodes. It indicates that, in the

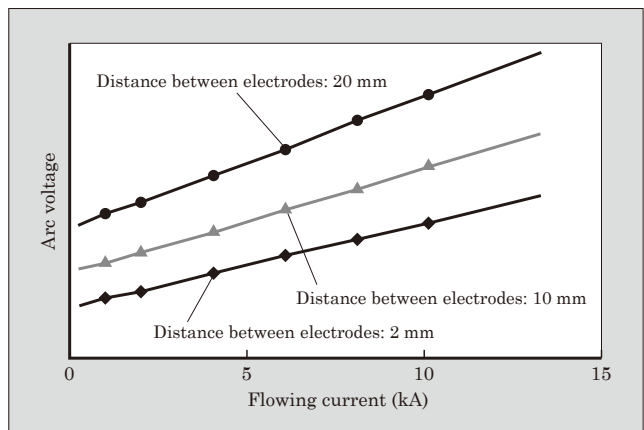


Fig.3 Relationship between flowing current and arc voltage

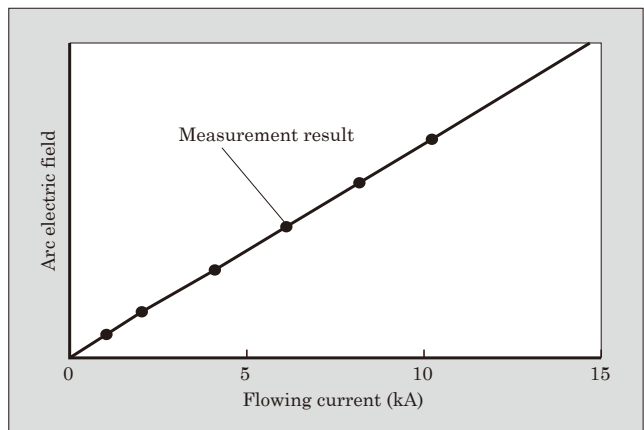


Fig.4 Relationship between flowing current and arc's electric field

current range that has been obtained, the arc voltage and flowing current are in a linear relationship. The relationship of the arc electric field with the flowing current calculated by using Equations (1) and (2) is shown in Fig. 4. It shows that the arc electric field and the flowing voltage are also in a linear relationship. Based on this finding, we used linear approximation to formulate the arc electric field against the flowing current and incorporated it into the arc model built for circuit analysis.

2.2 Simplified thermo-fluid analysis method

For thermo-fluid analysis, the finite volume method is generally used. The atmospheric gas in the switchgear is air (compressible viscous fluid) and, at the time as pressure relief operation, eddies are generated in the vicinity of the pressure relief device due to the viscosity and a pressure loss is generated by the change (rapid reduction and rapid expansion) in the flow channel's cross-sectional area of the opening. In addition, the pressure relief device is subject to a change in angle over time due to the rotational motion. For that reason, the pressure loss is unsteady. In order to predict this change in the pressure loss, it is necessary to solve fluid equations that allow for the shape of the pressure relief device changing over time. Unsteady coupled analysis of fluid in a structure involving a shape change requires a large amount of computation time and was difficult to apply to actual design of components of switchgear, which are individually designed.

The simplified thermo-fluid analysis method that has been developed is aimed to realize both reduced computation time and ensured analytical precision and built as a finite volume heat dissipation fluid analysis method specialized in prediction of pressure rises during internal arc faults by measuring the behavior during pressure relief operation, which involves high computational load, and reflecting the results to analysis. This method has 3 characteristics:

- (1) Element breakdown with rectangular parallelepiped meshes

In order to simulate a general 3D shape of switchgear composed of rectangles, rectangular parallelepiped meshes have been used to break down the elements.

- (2) Accommodation of nonlinearity of property values

When an internal arc fault occurs, property values related to pressure and temperature (density, specific heat and thermal conductivity) become nonlinear due to ionization and dissociation of the gas. The constructed method accommodates this nonlinearity and rapid change in the pressure, etc. due to ionization and dissociation can be solved with high accuracy.

- (3) Analysis of pressure relief portion with ensured accuracy

In order to allow for pressure losses due to viscosity in the vicinity of the pressure relief device, we

measured the relationships that the opening area, rotation angle and pressure loss of the pressure relief device have with the flow speed of the gas that passes through the pressure relief outlet in the basic test. We then incorporated the results into the analysis. This has made it possible to analyze the pressure relief portion with ensured accuracy and reduced the computational load.

2.3 Obtaining pressure-loss characteristics in the vicinity of pressure relief device

To obtain the pressure-loss characteristics in the vicinity of the pressure relief device, we used a pressure vessel equipped with a pressure relief device to conduct a basic test (see Fig. 5). For the test, the pressure vessel was filled with pressurized air from a high-pressure cylinder and the pressure was relieved by pulling out the movable lever. We used a pressure sensor to measure the pressure loss in the vicinity of the pressure relief device during pressure relief and the estimated outlet speed of the gas vented to the outside of the vessel from the pressure change. We also determined the change in rotation angle of the pressure relief device by using a high-speed camera.

As the test parameters, the opening area of the pressure relief outlet, maximum rotation angle of the pressure relief device and the filling pressure for the pressure vessel were used and their relationships with the pressure loss were evaluated.

An example of pressure-loss characteristics obtained from the test results is shown in Fig. 6. The flow speed of the gas that flows out of the pressure relief outlet increases along with the rotation of the pressure relief device and reaches its peak at the maximum rotation angle (60° in Fig. 6). Subsequently, the flow speed decreases as the pressure in the vessel decreases. The process of decrease of the gas flow speed is nonlinear. However, it has been incorporated into analysis by simulating with an approximate curve derived from the pressure loss in the vicinity of the pressure relief outlet, maximum rotation angle of the

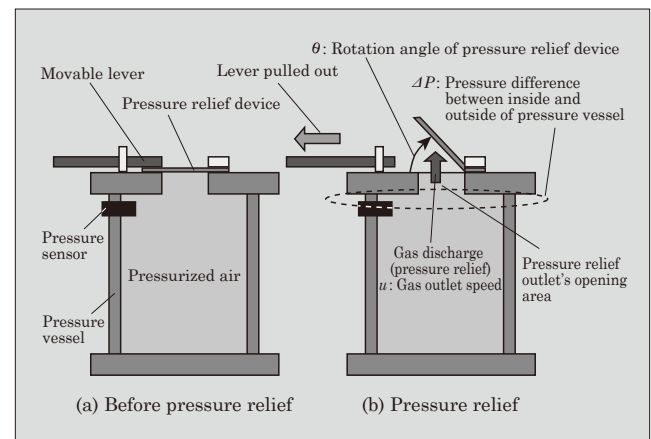


Fig.5 Outline of basic test for obtaining pressure loss characteristics in vicinity of pressure relief device

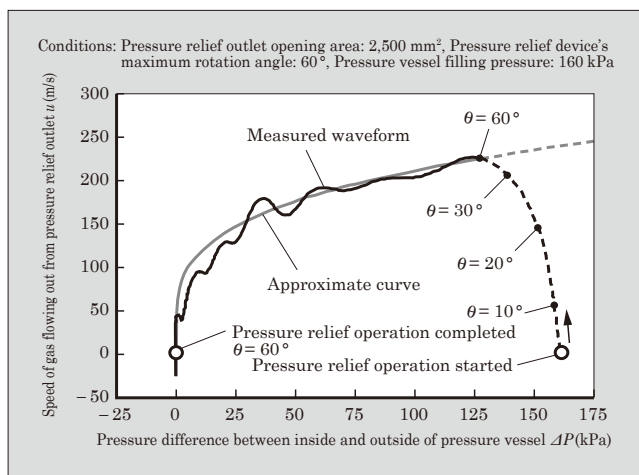


Fig.6 Example of pressure-loss characteristics in vicinity of pressure relief device

pressure relief device and opening area of the pressure relief outlet.

3. Analysis Results

To evaluate the validity of the analysis method developed, we conducted 2 tests for comparison with the analysis.

(1) Pressure decreasing process in pressure relief

For verifying the validity of the analytical precision in the pressure decreasing process that takes place during pressure relief, we made a comparison with the pressure relief test using the pressure vessel described above. Table 1 lists the test conditions. This test does not include heating of the gas (pressure rise) by arcing and is sufficient only for evaluating the validity of the model of the pressure loss in the vicinity of the pressure relief device incorporated into the analysis. Figure 7 shows a comparison between the results of measurement in the pressure-decreasing process during pressure relief and of the analysis. The pressure waveforms from the results of measurement and analysis show good correspondence with each other, which indicates that the analysis is capable of simulating the phenomenon that occurs during pressure relief. The volume of gas that passes through the pressure relief outlet is large when the opening area of the pressure relief outlet and the maximum rotation angle of the pressure relief device are large and the inertial

Table 1 Test conditions for pressure relief test using pressure vessel

Condition No.	Size of pressure relief outlet	Filling pressure of pressure vessel	Maximum rotation angle of pressure relief device
Test case 1	50 × 50 (mm)	200 kPa	30°
Test case 2	70 × 70 (mm)	200 kPa	60°
Test case 3	100 × 100 (mm)	75 kPa	90°

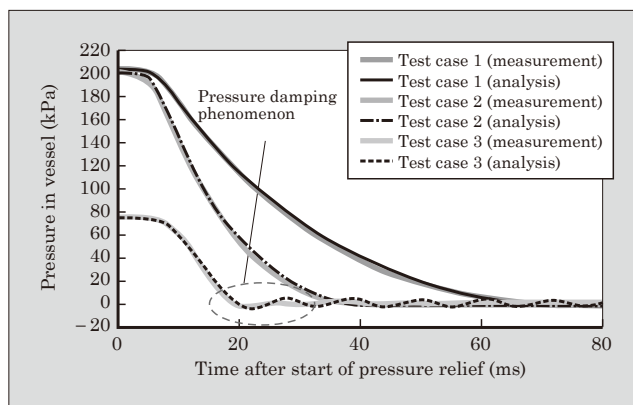


Fig.7 Comparison between results of measurement in pressure-decreasing process during pressure relief and of analysis

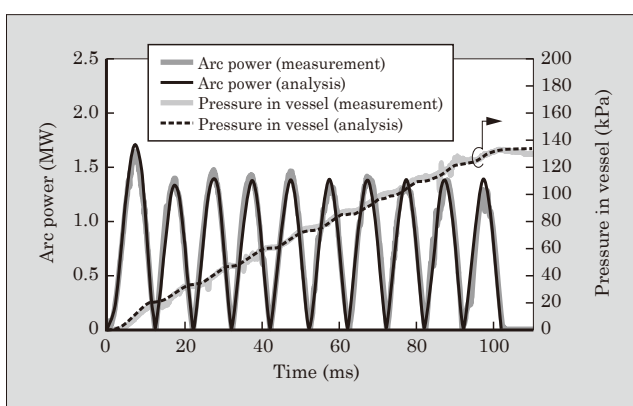


Fig.8 Comparison between results of measurement and analysis in pressure rising process during arcing

force of the gas flow causes a damping phenomenon around 0 kPa. It has been verified that the analysis simulates this phenomenon.

(2) Pressure-rising process during arcing

We wished to verify the validity of the analytical precision in the pressure-rising process that takes place when an arc is formed. Therefore, we sealed the pressure vessel and had an arc form in the pressure vessel to measure the actual pressure rise. The results were then compared with the analysis results. We calculated the results of the circuit analysis on the arc power and of the simplified thermo-fluid analysis using the calculated arc power as the input and compared them with the results of measurement for them respectively, which is shown in Fig. 8. Both the arc power and pressure waveforms show good correspondence with the measured values, which indicates that this analysis method is capable of simulating the phenomenon during a pressure rise.

4. Application to Switchgear Conforming to IEC Standard

By using the method of analyzing pressure rise during internal arc faults that has been developed, we

studied switchgear conforming to the IEC Standard. The analysis conditions used are the same as the test conditions for internal arc testing conforming to an international standard IEC 62271-200, as shown in Table 2. Figure 9 shows interphase arc power waveforms derived by circuit analysis. As a result of analysis, arc power has been found to peak immediately after the occurrence of an internal arc fault and decrease thereafter.

We next present the results of pressure analysis that uses as the input the arc power waveforms obtained by the circuit analysis. Figure 10 shows the shape of the switchgear analyzed and the result of analysis of pressure distribution immediately after arcing. As the figure indicates, pressure waves have been

Table 2 Internal arc test conditions for switchgear conforming to IEC Standard

Item	Condition
System voltage (RMS value)	11 kV
Short circuit current	18 kA
System frequency	50 Hz
Short circuit mode	3-phase short circuit

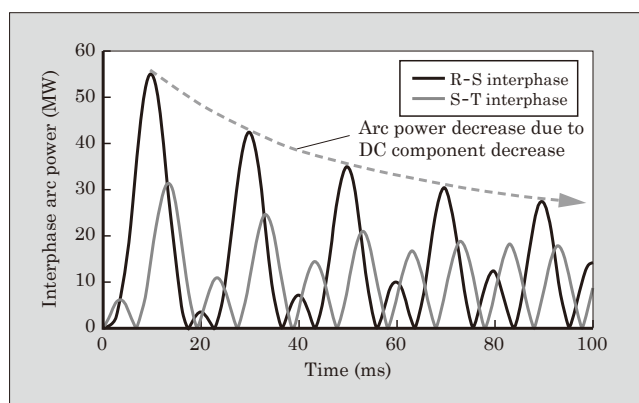


Fig.9 Results of analysis of interphase arc power generated

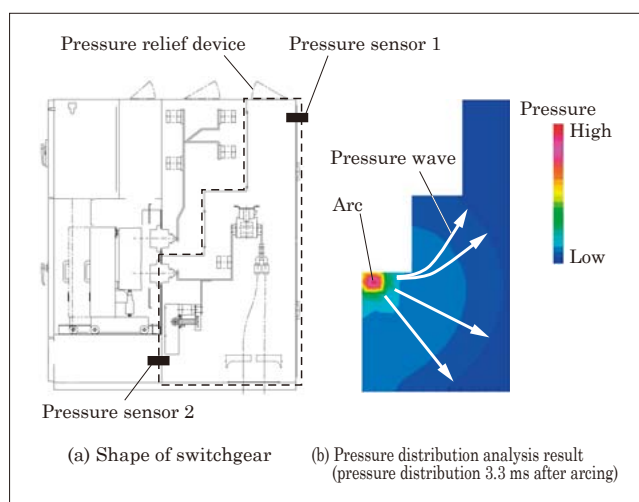


Fig.10 Shape of switchgear and result of pressure distribution analysis

found to propagate through the switchgear from the arc at the center.

Furthermore, we compared the results of analysis with the results of measurement for validity evaluation. Figure 11 shows the results of measurement by using pressure sensors located in the vicinity of the pressure relief device and arc respectively and results of analysis of pressure in the respective sensor locations.

The pressure during an internal arc fault is shown to continue to increase even after activation of the pressure relief device. This is because it takes a few ms before the pressure relief device reaches the maximum opened state after starting rotational motion. As shown in Fig. 11, the results of measurement and analysis show good correspondence and validity of the analysis method has been verified. In addition, this method has the analysis time reduced from the general-purpose thermo-fluid analysis method, which allows it to be applied to actual design.

In the development of switchgear shown in Fig. 12, we conducted structural analysis with the aforementioned analysis results used as the input data, thereby estimating the locations to be reinforced, which was fed back to the structural design. In this way, we have

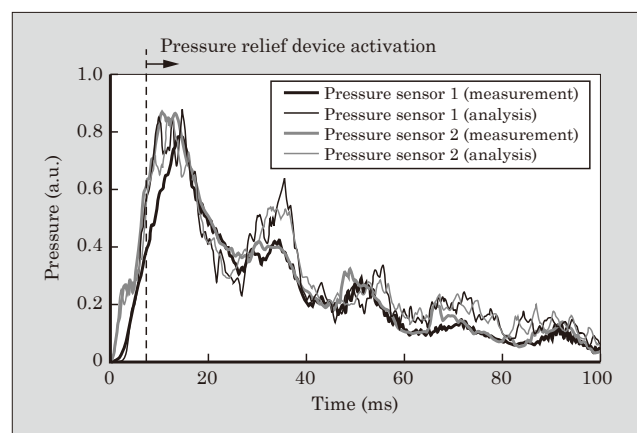


Fig.11 Comparison between pressure waveforms between different pressure sensor mounting locations



Fig.12 7.2-kV switchgear conforming to IEC Standards

completed the development of a product conforming to the IEC Standard.

5. Future Development

We have successfully predicted pressure rise during internal arc faults of switchgear by applying the analysis method described in this paper. This method also allows prediction of the flow speed, density and temperature of the hot gas flowing out of the pressure relief device and, in the future, we plan to study diffusion outside the switchgear of the hot gas after passing through the pressure relief device.

6. Postscript

This paper has presented analysis of pressure

rise during internal arc faults in switchgear. Power demand is expected to continue to increase overseas, especially in Asia, which involves addition and equipment replacement of switchgear estimated. Analysis technology (prediction technology) is required for designing safe power reception and distribution facilities and, schemes to satisfy computational speed requirements adequate for actual design are necessary. In the future, we intend to continue to work on the building of analysis technology in view of actual design of devices.

References

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