Conductance Diagnostics in Hot Gas Ejected from a Molded Case Circuit Breaker during High Current Arc Interruption

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A probe method is described for measuring conductance of hot gas ejected from a molded case circuit breaker during arc interruption process. Two steel rods of 1mm diameter were adopted as probing electrodes, then being located near to an exhaust hole of the hot gas. Ratio of a current passing through gap between the probing electrodes to a voltage across them gives an apparent conductance of the hot gas. Net conductance was estimated from the apparent value with consideration of cool gas layer near to the probing electrode surface. The net conductance $g_{net}$ proved to increase markedly from 0.6 to 2.3mS by a factor of 4 with a rise of a peak value $I_{peak}$ of an arc current from 6.5 to 8.8kA. The electrical conductivity $\sigma$ was then estimated from $g_{net}$ by taking into consideration of the effective cross-section of the measurement area of the probe method. The electrical conductivity $\sigma$ was found to grow from 0.071 to 0.27 S/m with increasing $I_{peak}$. Above results suggest that the probe method is much more useful as means of assessing the ejected hot gas.

Key words: Hot gas, Conductance, Probe method, Molded case circuit breaker

1. Introduction

A molded case circuit breaker(MCCB) in a low-voltage distribution system ejects hot gas through an exhaust hole during high current arc interruption. In the three-phase circuit, MCCB's quenching chambers are arranged so close in parallel that short-circuit passages can form between adjacent columns of the ejected hot gas. This may lead to serious short-circuit fault at source-side terminals of the MCCB[1,2]. The hot gas with high conductance seems to enhance the possibility of occurrence of the short-circuit fault at source-side terminals. However, few papers have reported the conductance of the hot gas ejected from the MCCB.

Firstly, this paper describes a probe method for measuring the conductance of the hot gas ejected from the MCCB. Two steel rods of 1mm diameter are adopted as probing electrodes and then are located near to the exhaust hole. A series of interruption tests were carried out to measure time variation of the conductance of the hot gas by means of the probe method. The conductance obtained by the probe method is, however, only an apparent conductance between the probes. This is because the probing electrodes are surrounded by thin cool gas layer[3]. By subtracting the low conductance of the cool gas layer from the apparent conductance, we get net conductance of the ejected hot gas. The magnitude of the net conductance proves to increase markedly with a rise of a peak value of a prospective breaking current. Throughout all experiments, the hot gas temperature in the gap between the probing electrodes is also measured simultaneously by the spectroscopic observation technique. As a result, the probe method is found to be much more effective as means of assessing the ejected hot gas than the spectroscopic observation technique.

Secondly, the effective cross-section of the current flow area between the probing electrodes is approximately estimated by using electric field analysis. By using the effective cross-section, electrical conductivity of the ejected hot gas is then derived. The probe method proves to be successful in determining the electrical conductivity of the ejected hot gas.
2. Probe Method

<2.1> Molded Case Circuit Breaker And Breaking Test

The adopted MCCB has a rated voltage of a.c. 110Vrms and a rated interrupting current of 7kApeak. The MCCB has an rectangular exhaust hole of 13mm in length and 3mm in width. Figure 1 shows experimental setup for measuring the conductance of the hot gas ejected from the MCCB. A breaking current with a frequency of 50Hz was supplied to the MCCB from a 1,955µF capacitor bank through both a 5.7mH reactor and a step-down transformer. A peak value of the prospective breaking current was adjusted in the range of 12.3-17.3kApeak. Such a large overrated current was intentionally supplied in order to force the MCCB into ejecting sufficient hot gas. For each peak value of the prospective breaking current, the actual peak value of the current decreased by a factor of about 0.5 during arc interruption, owing to the MCCB's current limiting action. As a result, the peak value Ipeak of the arc current was in the range of 6.5 to 8.8kApeak. In this experiment, after connecting a new MCCB to the current supply circuit, we carried out the breaking test three times for the same peak value of the arc current.

<2.2> Probe Circuit

We used two steel rods of 1mm diameter as probing electrodes, then placing them at a distance of 5mm away from the exhaust hole of the MCCB. The corners of the probing electrode was planed off with the radius of curvature of 0.05mm. The gap length between the probing electrodes was adjusted to be 3mm. A d.c. voltage of 100V was applied between the two probing electrodes with a series resistance of 1,000Ω, as illustrated in the upper part of Fig.1. Voltages $\mathcal{V}_h$, $\mathcal{V}_l$ and $\mathcal{V}_i$ in the probe circuit are measured to the ground. This is because the ejected hot gas itself has some electric potential to the ground. The time variation in the voltages $\mathcal{V}_h$, $\mathcal{V}_l$ and $\mathcal{V}_i$ were recorded with digital waveform memory units.

The voltage and the current necessary to estimate the conductance of the hot gas was derived through simple data processing in the next way. When the ejected hot gas envelops the probing electrodes, a small amount of d.c. current $i_{probe}$ passes through the gap between the probing electrodes. The probe current $i_{probe}$ was obtained from the measured voltages of $\mathcal{V}_h$ and $\mathcal{V}_l$ follows:

$$i_{probe} = \frac{\mathcal{V}_h - \mathcal{V}_l}{1,000} \quad [A].$$ (1)

The subtraction of $\mathcal{V}_l$ from $\mathcal{V}_h$ leads to determination of the voltage $\mathcal{V}_{probe}$ between the probing electrodes:

$$\mathcal{V}_{probe} = \mathcal{V}_h - \mathcal{V}_l \quad [V].$$ (2)

The apparent conductance $g_{app}$ between the probing electrodes is determined by

$$g_{app} = \frac{i_{probe}}{\mathcal{V}_{probe}} \quad [S].$$ (3)

The reciprocal of eq.(3) gives the corresponding resistance as follows:

$$R_{app} = \frac{\mathcal{V}_{probe}}{i_{probe}} = \frac{1,000(\mathcal{V}_h - \mathcal{V}_l)}{\mathcal{V}_l - \mathcal{V}_h} \quad [\Omega].$$ (4)

However, the cool gas layer probably surrounds the probing electrode[3]. Thus, the resistance obtained from eq.(4) includes high resistance of the thin cool gas layer in vicinity of the surface of the probing electrodes. As described in detail later, other experiments enables us to find out that the cool gas layers near to the probing electrodes have resistance $R_{cool}$ of 500 Ω. Subtraction of $R_{cool}$ from $R_{app}$ enables us to derive net resistance of the ejected hot gas:

$$R_{net} = R_{app} - R_{cool} \quad [\Omega].$$ (5)

Finally, the net conductance of the ejected hot gas is derived from

$$g_{net} = \frac{1}{R_{net}} = \frac{1}{\frac{\mathcal{V}_{probe}}{i_{probe}} - R_{cool}} \quad [S].$$ (6)

<2.3> Temperature Measurement

Throughout the series of experiments, spectroscopic observation of the hot gas was simultaneously carried out at a position between the probing electrodes in order
to estimate the temperature of the ejected hot gas. Optical radiation from the hot gas was imaged by a lens system to an entrance slit of a monochromator. The monochromator has a multi-channel detector for observing simultaneously radiation intensities of three different wavelengths at the exit focal plane. At each wavelength, the radiation intensity of a spectral line was detected by a photomultiplier tube. The time variation in each signal of the radiation intensity was recorded with a digital wave-memory unit.

A lot of iron vapour is injected into the hot gas from deion plates [4] in MCCB. Use of the multi-channel detector permits the observation of two Fe atom spectral lines at the wavelengths of 431 and 443nm. However, these spectral lines overlap continuum[5]. Thus, the radiation intensities \( I_{431} \) and \( I_{443} \) measured at 431 and 443nm, respectively, with the detector include that of the continuum. Therefore, the radiation intensity \( I_{\text{cont}} \) of the continuum was simultaneously observed at the wavelength of 455nm with the multi-channel detector. At this wavelength, the continuum is free from overlapping the spectral lines. By subtracting \( I_{\text{cont}} \) from \( I_{431} \) and \( I_{443} \), we got net radiation intensities \( I_{\text{Fe}431} \) and \( I_{\text{Fe}443} \) of Fe atom spectral lines at the wavelengths of 431 and 443nm, respectively. On the assumption of the hot gas with local thermal equilibrium, two-lines method[6,7] was used to determine the hot gas temperature \( T \) from \( I_{\text{Fe}431} \) and \( I_{\text{Fe}443} \). In accordance with the two-line method, the temperature \( T \) was derived using the following equation[8]:

\[
T = \frac{W_2 - W_1}{k \left( \ln \frac{\mu_2 A_2 \lambda_2}{\mu_1 A_1 \lambda_1} - \ln \frac{\epsilon_2}{\epsilon_1} \right)} \quad [K], \quad (7)
\]

where subscripts 1 and 2 refer to the Fe atom spectral lines at the wavelengths of 431 and 443nm. Then \( W \) is the energy of the upper excited states, \( \mu \) is the statistical weight, \( A \) is the transition probability and \( \lambda \) is the wavelength. These emission constants are given by Fuhr and Bridges[9,10]. The difference between \( W_1 \) and \( W_2 \) is 1.6eV for these Fe atom spectral lines. The difference is large enough to estimate the hot gas temperature with high accuracy.

### 3. Conductance of Ejected Hot Gas

Figure 2 shows typical oscillograms obtained at the first breaking test for the arc current with 8.8kApeak. The top diagram represents waveforms of the actual arc current and the arc voltage across the MCCB, the second the net conductance \( g_{net} \) measured by the probe method.

A few milli-Siemens of conductance is detected during the period from 1 to 3msec. At 1.7msec, the conductance reaches a peak value of 2.7mS. The third and forth diagrams represent the radiation intensity of the spectral lines and the derived gas temperature, respectively. The radiation intensities of the spectral lines are detected during the longer period from 1 to 5 msec. The temperature of the hot gas reaches a peak level of 3,100K.
the arc currents. At each of the arc current, three new MCCB were used. For one MCCB, the breaking tests were performed three times for the same peak value $I_{\text{peak}}$ of the arc current. Figure 3 represents the transient variation in the conductance for various $I_{\text{peak}}$ at the first breaking test. As seen in the figure, each conductance waveform has the peak. The time when the conductance reaches peak decreases from 2.2 to 1.6msec with increasing $I_{\text{peak}}$. Figure 4 shows the maximum magnitude of the net conductance $g_{\text{net}}$ as a function of the peak value $I_{\text{peak}}$ of the arc current. In this figure, the order of the breaking tests is taken as a parameter. Note that the maximum magnitude of the conductance $g_{\text{net}}$ increases markedly with a rise of $I_{\text{peak}}$ for each order of the breaking tests. Especially, for the first breaking test, $g_{\text{net}}$ grows most remarkably from 0.6mS to 2.3mS by a factor of 4 with increment of $I_{\text{peak}}$ from 6.5 to 8.8kApeak. As can be also seen from Fig.4 and Fig.5 that the conductance obtained by the probe method is much more useful as a means of assessing the hot gas ejected from the MCCB than the temperature measured by spectroscopic observation.

4. Resistance of cool gas layer

As mentioned in section 2.2, the thin cool gas layer surrounding the probing electrodes has the resistance $R_{\text{cool}}$ of 500Ω. The resistance $R_{\text{cool}}$ was estimated as described below.

The gap length $L$ between the probing electrodes was successively adjusted to be 2, 3, 5, 7 and 9mm. The shape and dimensions of the probing electrode for this experiment are the same as that mentioned in section 2.2. At each gap length, we measured the time variation in the apparent resistance $R_{\text{app}}$ between the probing electrodes for the arc current with 8.8kApeak. Oscillogram showed that waveform of $R_{\text{app}}$ had the minimum magnitude. Figure 6 indicates the minimum magnitude of $R_{\text{app}}$ as a function of the gap length $L$ for the first breaking test. As seen in Fig.6, $R_{\text{app}}$ decreases almost linearly with reducing $L$. The least square method enables us to draw a line through the plotted points.
Fig. 6 Apparent resistance as a function of gap length between probing electrodes for arc current with 8.8kApeak at the first breaking test

Extrapolating the line to L=0 permits estimation of a resistance at L=0. We regard the resistance at L=0 as that of the cool gas layer. This is because the cool gas layer probably has very thin thickness. The resistance $R_{cool}$ of the cool gas layer is estimated from Fig. 6 to be 500Ω for the first breaking test. The similar estimations were performed for the second and the third breaking tests. The cool gas layer for the second and the third breaking tests proved to have resistance $R_{cool}$ equal to that for the first breaking tests.

Above estimations of $R_{cool}$ were made for the arc current with 8.8kApeak. However, $R_{cool}$ seems to be independent of the peak value of the arc current. The reason is given below. The cool gas layer is present between the ejected hot gas and the probing electrode. The hot gas has very much higher temperature than the cool gas layer. Thus, the temperature $T$ of the hot gas greatly affects the condition of the cool gas layer through the thermal conduction mechanism. However, remember from Fig. 5 that $T$ scarcely depends on $I_{peak}$ of the arc current in the range of 6.5 to 8.8kApeak. Consequently, the resistance $R_{cool}$ seems to be kept constant for $I_{peak}$.

5. Electrical Conductivity

5.1 Effective Cross Section of Measurement Area

It is effective to derive electrical conductivity $\sigma$ of the hot gas from the conductance $g_{net}$ obtained by the above-mentioned probe method. However, the determination of $\sigma$ from $g_{net}$ requires effective cross section of measurement area of the probe method. Thus, we calculated the effective cross section $S$ of the measurement area as described below.

The d.c. current passes through the gap space between the probing electrodes along lines of electric force. The electric field distribution in the direction perpendicular to the center axis of the probing electrodes was analyzed by the charge simulation method on the following conditions:

1. the diameter of the probing electrode is 1mm;
2. the corner of the probing electrode has the radius of curvature of 0.05mm;
3. the gap length between the probing electrodes is 3mm;
4. a voltage of 50V is applied across the probing electrodes;
5. the hot gas around the probing electrodes has a uniform electrical conductivity $\sigma$ at any position.

The actual hot gas ejected from the MCCB does not necessarily have the uniform electrical conductivity. Furthermore, the MCCB is located at the position of 5mm below the probing electrodes. Under this condition, it is extremely difficult to calculate the effective cross section $S$ of the measurement area with high accuracy. In the contrast to this, assuming the above term (5) facilitates the estimation of $S$. Thus, as the first trial, we approximately estimated $S$ with the assumption of term (5). Figure 7 shows the calculated electric field strength $E(r)$ at the mid point of the gap space as a function of the distance $r$ from the center axis of the probing electrodes. The electric field strength is 9.5V/mm at $r$=0. It decreases markedly with increase in the distance $r$, approaching to 0V/mm around $r$=10mm. The current
density \( j(r) \) passing through the gap is given by
\[
j(r) = \sigma E(r) \quad [\text{A/m}^2],
\]
where \( \sigma \) is the electrical conductivity of the hot gas. The infinite integral of \( 2\pi r j(r) \) gives the current \( I \) passing through the mid plane of the gap:
\[
I = \int_0^\infty 2\pi r \sigma E(r) \, dr
= 2\pi \sigma \int_0^\infty r E(r) \, dr \quad [\text{A}] .
\]
Substitution of the calculated values of \( E(r) \) into eq.(9) yields the following simple equation:
\[
I = 0.445 \sigma \quad [\text{A}] .
\]
This calculation result indicates that the total current of 0.445\( \sigma \)[A] passes through the uniform hot gas with the electrical conductivity of \( \sigma \) when the voltage of 50V is applied across the probing electrodes. The conductance of the hot gas is therefore expressed by
\[
g = \frac{I}{V} = \frac{0.445 \sigma}{50}
= 8.9 \times 10^{-3} \times \sigma \quad [\text{S}] .
\]
Using eq.(11), the effective cross section \( S \) of the measured area is thus calculated as follows:
\[
S = \frac{g \cdot L}{\sigma} = \frac{8.9 \times 10^{-3} \sigma}{\sigma} \times 3 \times 10^{-3}
= 26.7 \times 10^{-6} \quad [\text{m}^2]
= 26.7 \quad [\text{mm}^2] ,
\]
where \( L \) is the gap length between the probing electrodes. Consequently, the effective diameter of the measurement area is derived to be
\[
D = \sqrt{\frac{4S}{\pi}} = 5.83 \quad [\text{mm}] .
\]
Similar calculations were made for different voltages \( V_{\text{probe}} \). The effective diameters for different \( V_{\text{probe}} \) proved to be the same as that for \( V_{\text{probe}}=50\text{V} \).

Optical observation of the hot gas ejected from the MCCB were also performed from the direction parallel to the center axis of the probing electrodes. This optical observation enabled us to measure the width of the hot gas at the location of placing the probing electrode. The minimum requirement for confirming the validity of \( D \) is to show that the hot gas has the width larger than \( D \). The width of the hot gas was found from the optical observation to be above 20mm. This width is much larger than \( D \). This observation result indicates that the estimated \( D \) satisfies the minimum requirement.

<5.2> Electrical Conductivity of Hot Gas
Determining the effective cross section \( S \) of the measurement area enables us to derive the electrical conductivity of the ejected hot gas from the net conductance using the following equation:
\[
\sigma = \frac{g_{\text{net}} L}{S} \quad [\text{S/m}] .
\]
As already described in chapter 3, the net conductance \( g_{\text{net}} \) increases markedly from 0.6 to 2.3mS with rise of \( I_{\text{peak}} \) from 6.5 to 8.8kApeak at the first breaking test. By using eq.(14), \( \sigma \) proved to rise from 0.071 to 0.27mS/m with increasing \( I_{\text{peak}} \).

In the similar manner, \( \sigma \) for the second and the third breaking tests were also estimated by eq.(14). In Fig.8, the electrical conductivity for all of breaking tests are plotted against the temperature measured by the spectroscopic observation. Figure 8 also shows four theoretical curves of the electrical conductivity as a function of the temperature in the high temperature air contaminated with iron vapour at a pressure of 0.1MPa[11]. On referring to a paper written by Amakawa et al.[11], we obtained the theoretical curves of the electrical conductivity. We assume a pressure at the measurement position to be 0.1MPa, because the probing electrodes were placed under the atmospheric condition. In Fig.8, iron vapour concentration \( X_{\text{Fe}} \) is taken as a parameter. The concentration \( X_{\text{Fe}} \) is defined as the ratio of the sum of the number densities of Fe, Fe' and Fe" to the sum of those all species except electrons. It should be noted from Fig.8 that almost all the plotted points are located between the theoretical curves for \( X_{\text{Fe}} \) of 0% and 100%. From the point of view, we can point out that the effective cross section \( S \) is correct and that
the probe method is capable of determining the electrical conductivity of the ejected hot gas. Furthermore, it is confirmed that the assumption (5) described earlier is valid, in other words, that hot gas has the uniform electrical conductivity at any position around the probing electrodes.

However, as shown in Fig.8, several of the plotted points lie in the region above the theoretical curve for $X_{Fe}=100\%$. This result seems to arise from an error of the theoretical value of the electrical conductivity for high temperature air contaminated with iron vapour[12]. The detailed explanations are given below. One of the numerical data required for the theoretical calculation of the electrical conductivity is the collision cross-section between the electron and the iron atom. The collision cross-section has an uncertainty within $\pm 30\%$
[13]. This uncertainty causes a high error on calculation of the electrical conductivity. The error of the electrical conductivity rises markedly with increasing the iron vapour concentration $X_{Fe}$ at the temperatures below 10,000K[12]. For instance, in case of $X_{Fe}=50\%$, the error is in the range of -20 to +40\% at 3,000K[12]. As a consequence, in Fig.8, several of the points lie in the region above the curve for $X_{Fe}=100\%$.

It can be also seen from Fig.8 that the points are positioned around the theoretical curves for higher concentration $X_{Fe}$ with a rise of the order of the breaking test. Judging from this fact, it seems that increase in the order of the breaking test causes $X_{Fe}$ to be raised, resulting in the electrical conductivity of the ejected hot gas. This iron vapour was supplied not from the probing electrodes but from the deion plates in the MCCB. After the breaking test, no variation was observed in either the shape of the probing electrode or the gap length between them.

6. Conclusion
The molded case circuit breaker ejects the hot gas with high electrical conductivity through the exhaust hole during arc interruption. Concerning a short-circuit fault through the hot gas at the source side terminals of MCCB, we investigated the conductance of the ejected hot gas. The conductance of the ejected hot gas was measured by the probe method. It was found that the conductance of the hot gas increased from 0.6 to 2.3mS with a rise of the peak value of the arc current from 6.5 to 8.8kApeak at the first order of the breaking test. The conductance obtained by the probe method also proved to be useful parameter for assessing the hot gas. The electrical conductivity was then estimated from the measured conductance by taking into account of the effective cross-section of the measurement area of the probe method. The probe method was successful in deriving the electrical conductivity of the hot gas. The electrical conductivity was found to be enlarged from 0.071S/m to 0.275S/m with increase in the peak value of the prospective breaking current from 6.5 to 8.8kApeak.

The hot gas with the high electrical conductivity probably causes the short-circuit fault to occur at source-side terminals of the MCCB.

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References

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