Electromagnetic Force Analyzed Results on Switchgear of Disconnector for Overevoltage Protector

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Abstract: - A disconnector for overvoltage protector (OVP) is equipment which intercepts a circuit safely, when OVP breaks down in short circuit mode. As a disconnector, a Circuit Breaker (CB) is normally used. When a large current such as a lightning surge flows, switchgear of CB comes floating according to the electromagnetic force generated by large current which flows into a switchgear. The function of OVP is spoiled by this influence. If the problem which the switchgear comes floating can be solved, even when a large lightning surge flows through it, electrical aparatus can be protected by OVP.We have been analyzing this switchgear floating mechanisms using finit element method. This paper presents a way of preventing switchgear floating.

Key-Words: - circuit breaker, lightning surge current, switch floating, current density, electromagnetic force

1 Introduction

This paper presents an electromagnetic force analyzed results on switchgear of disconnector for overvoltage protector. A disconnector for an overvoltage protector is equipment that disconnects a circuit when the overvoltage protector may fail in a short circuit mode [1] . The disconnector and the overvoltage protector are connected in series. Therefore a disconnector should conduct a current generated by lightning and block a current from a commercial power supply. A fuse or a circuit breaker is normaly used as a disconnector. However there are problems with both methods. A fuse is not recyclable once it goes out. Even a circuit breaker is resetable, a lightning surge current causes a swichgear of circuit breaker to open unnecessary. This malfunction caused by a lightning surge current prevents the overvoltage protective function which eliminates a lightning surge current into electrical aparatus. If the problem which a switchgear of circuit breaker comes floating can be solved, even when lightning surge current flows through it, electrical aparatus can be protected by the overvoltage protector. We have been analyzing this switchgear floating mechanisms using finite element method. In this paper, current density and electromagnetic force analysis of a switchgear are conducted.

2 Problem on Circuit Breaker type Disconnector

Fig. 1 is a configuration example of an overvoltage protection device combining the disconnectors and the overvoltage protectors[2]- [9]. A disconnector needs to be connected in series to an overvoltage protector and be instaled between an electric wire and an earth .

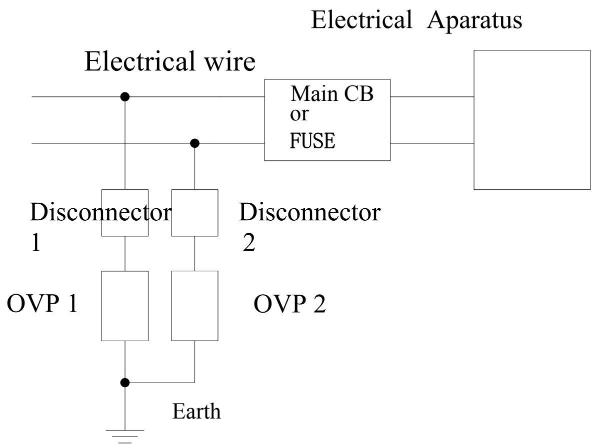


Fig.1 Configuration example of overvoltage protection device

A disconnector for an overvoltage protector is equipment that disconnects a circuit when the overvoltage protector may fail in a short circuit mode. Therefore a disconnector should conduct a current generated by lightning and block a current from a commercial power supply. However a lightning surge current causes a swichgear of circuit breaker to open unnecessary.

3 Technical data on analysis

We have been analyzing this switchgear floating mechanisms using finite element method .

Fig. 2 shows a waveform (temporal change) of the lightning surge current[10]-[13].

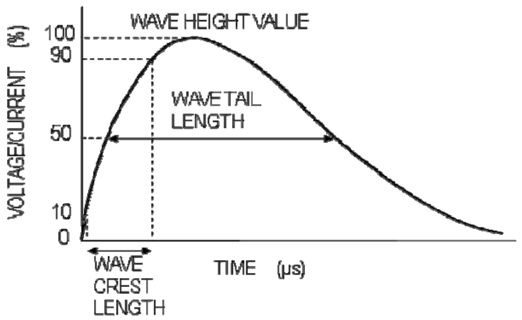


Fig. 2 Waveform of the lightning surge current

In the worst conditions, the maximum wave height current is about 50 kA. Wave creast length is sevral 10 μ seconds and the wave tail length is several 100 μ seconds (10/100μ s).

The current shown in Table 1 is flowed through each model. A numerical analysis of current density and electromagnetic force is conducted. Moreover, in electromagnetic force analysis, the power of the three dimensions is analyzed and it investigates what kind of power is working to each conductor of switchgear.

Table 1 Current used for analysis

The kind of current	Maximum [kA]
AC50Hz	10
	50
Lightning surge 10/27μs	50

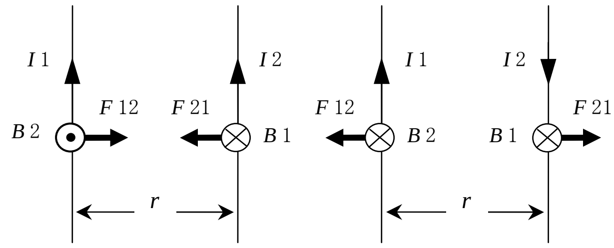
Although the maximum AC overcurrent which flows into a circuit at the time of a short circuit is about 10kA, in order to compare with the lightning surge current, both the current value of 10kA and 50kA (AC50Hz) are used . The characteristics of the various materials used for the analysis are shown in Table 2.

Table 2 Material characteristics

Material	The kind of material	Specific resistance [Ωm]	Density [kg/m^3]
Brass	Nonmagnetic material	6.30E-8	8560
Silver	Nonmagnetic material	2.08E-8	10500
Copper	Nonmagnetic material	2.23E-8	8900
Tungsten	Nonmagnetic material	7.30E-8	19300

4 Electromagnetic Force

The power produced by a current and a magnetic field is called Lorentz electromagnetic force as shown in Fig. 3, when current is flowing into two conductors, power of suction or restitution arises between conductors.



(a) suction (b) restitution

Fig.3 Power committed on parallel current

The electromagnetic force is obtained as folows.

From the law of Ampere, the current I and magnetic field H is expressed with the following formula

$$\oint_C \boldsymbol{H} \cdot d\boldsymbol{l} = I \quad (1)$$

$$|H| = \frac{I}{2\pi r} \quad (2)$$

The magnetic flux density B becomes the following formula.

$$|B| = \frac{\mu I}{2\pi r} \quad (3)$$

Moreover, current density i is expressed with the following formula.

$$I = \iint_S \boldsymbol{i} \cdot \boldsymbol{n} dS \quad (4)$$

$$|i| = \frac{I}{S} \qquad (5)$$

Power F is expressed with the following formula from the law of Fleming.

$$F = i \times B \qquad (6)$$

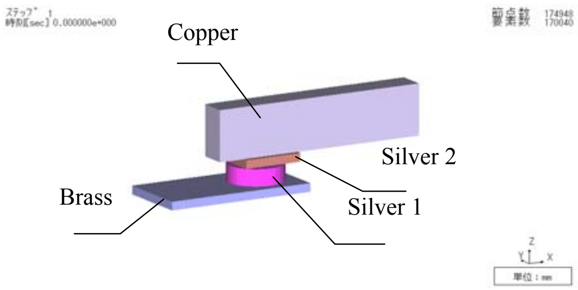
$$|F| = |i||B|\sin\theta \qquad (7)$$

$$|F| = \frac{\mu \sin\theta}{2\pi\, rS} I^2 \qquad (8)$$

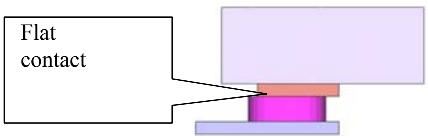
It is assumed that power becomes large in proportion to the square of a current value.

5 Analyzed Results on a conventional circuit breaker model

In conventional circuit breaker, when a lightning surge current flows, large electromagnetic force works in the switchgear. In order to investigate the characteristics of the electromagnetic force in each conductor when the lightning surge current flows, as shown in Fig.4, the electrode form of circuit breaker was modeled.



(a) 3 D model



(b) Cross section

Fig.4 Conventional circuit breaker model (Flat contact model)

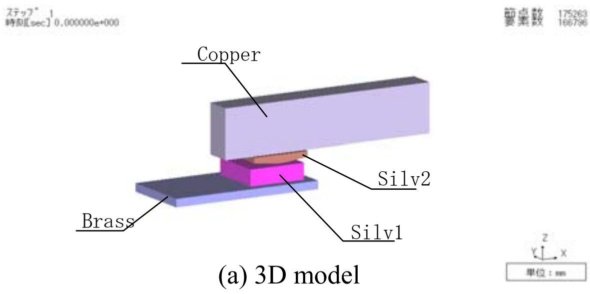
The size of the various materials used in the model of Fig. 4 is shown in Table 3.

Moreover, whenever the disconnector operates repeatedly, the contact surface of the silver 2 of a contact part will be roundish.

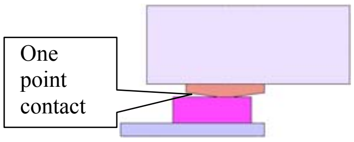
To estimate this effect, the contact surface of a switchgear having one point contact as shown in Fig. 5 was modeled.

Table 3. Size of conventional model

Material	Y-axis breadth [mm]	X-axis length [mm]	Z-axis thickness [mm]	Radius [mm]
Brass	8.0	16.0	1.0	–
Silver1	–	–	2.0	3.0
Silver2	4.0	6.2	1.0	–
Copper	3.0	23.0	6.0	–



(a) 3D model



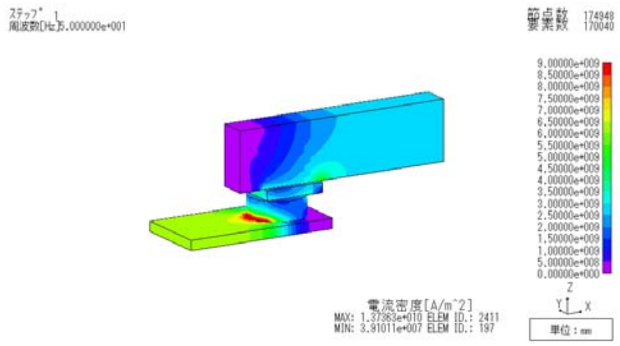
(b) Cross section

Fig.5 Conventional circuit breaker model (One point contact model)

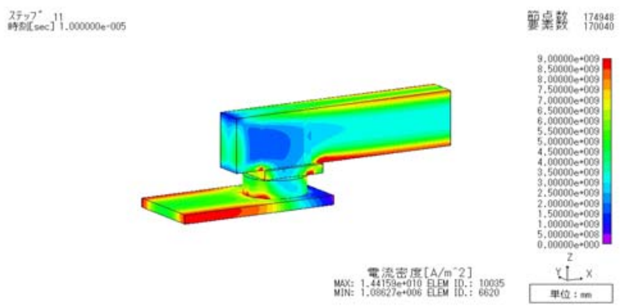
(1) Current density analysis

The analyzed results of current density, when both a 50Hz AC current and a lightning surge current flow into the conventional circuit breaker model, are shown in Fig.6.

When the current density of each conductor of the conventional circuit breaker model was seen, in the case of lightning surge current, compared with AC overcurrent, the frequency component was high and it became clear that the influence of a skin effect appears strongly.



(a) AC50kA(50Hz)



(b) Lightning surge 50kA(10/27μs)

Fig.6 Current density analyzed results
(Conventinal circuit breaker model)

Therefore, since the lightning surge current makes difficult to pass through in the central part of each conductor and much current is flowing through the outside of a conductor. From this, it is expected that the power generated by lightning surge current is stronger than that of AC overcurrent.

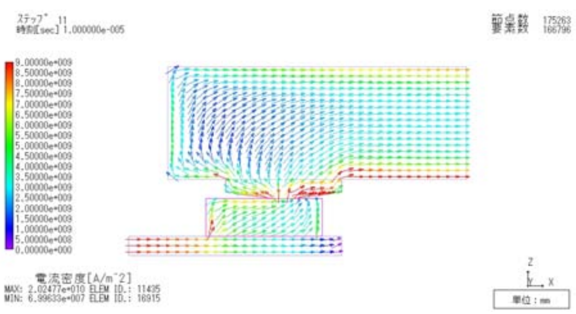


Fig. 7 Current vector (One point contact model)

The vector of the current density when lightning surge current flows into a point contact model is shown in Fig. 7. The result of Fig. 7 shows that current is concentrating at one point contact surface .

When the vector ingredient of current is decomposed as shown in Fig. 8 since current flows in and flows out of one point, big restitution will work at the contact point.

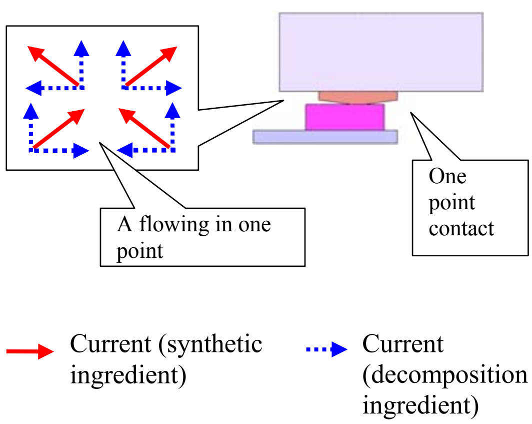


Fig. 8. Decomposition of current vector

(2) Electromagnetic force analyzed results

The electromagnetic force analyzed result of the direction of the Z-axis committed to a conventinal circuit breaker model when AC overcurrent flows is shown in Fig. 9 . Here, the Z-axis shows the top and bottom direction of the model.

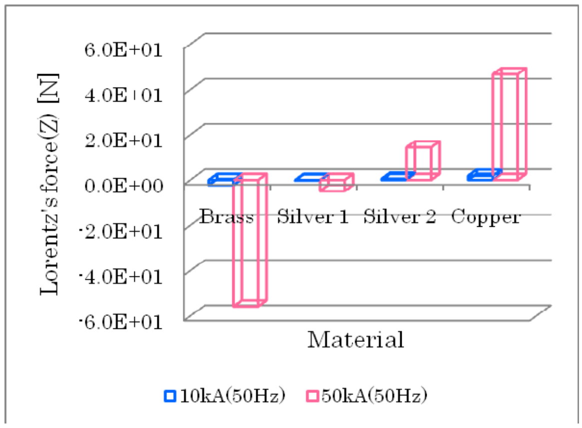


Fig.9. Electromagnetic force analyzed result of AC overcurrent
(Conventinal circuit breaker model)

When 50kA AC over-current flows into a disconnector, the power of being 25 times much worked to each conductor than that of 10kA AC overcurrent as the theorotical calcuration shown in fomura (8).

The electromagnetic force analyzed result in the direction of the Z-axis committed to the conventional circuit breaker model when lightning surge current flows is shown in Fig.10. Here, the Z-axis shows the top and bottom direction of the model.

When the direction of power which works each material was seen from the result of Fig.10, the below power worked to brass and silver 1, the above power worked to silver 2 and copper. And it became clear that the power working between conductors (brass, copper) is bigger than the power working a contact part (silver 1, silver 2).

In the case of conventional circuit breaker model having one point contact, the power is bigger than that of this flat contact model.

As these analysis results, it was proved that big power in the direction of the Z-axis of a switchgear make a contact point comes floating.

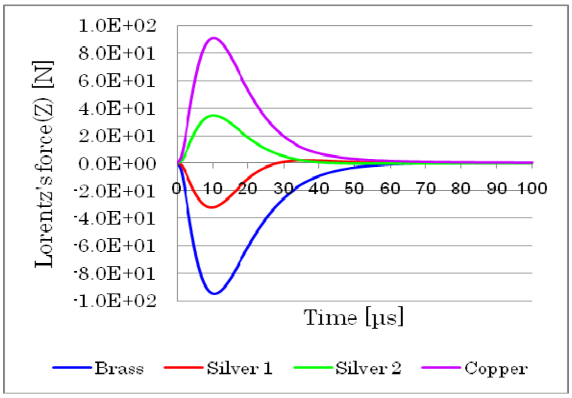


Fig.10 Electromagnetic force analyzed result of lightning surge current (Conventinal circuit breaker model)

Therefore switchgear floating problem based on the electromagnetic force in the direction of the Z-axis must be solved.

6 Improvement of terminal structure

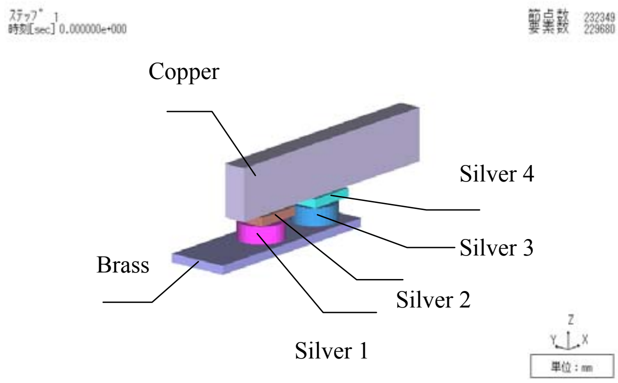
According to the principle of power which works on parallel current, the terminal structure of circuit breaker to be able to make current flows in the same direction is examined. When lightning surge current flows, restitution works in a contact part (silver 1, silver 2), but if strong suction simultaneously between conductors (brass, copper) can be worked, it will be considered that a switchgear stops floating [9].

(1) 2 point of contact form model

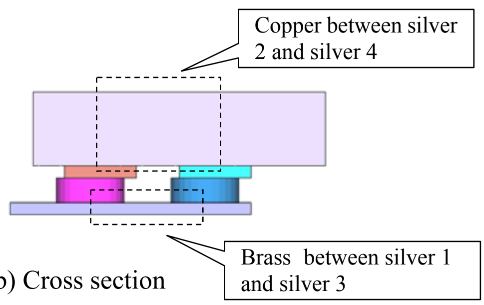
As shown in Fig.11, we considered the model having two switchgears. By setting a contact part to two, the current of the same direction flows into brass between silver 1 and silver 3 and copper between silver 2 and silver 4. Therefore, it is thought that switchgear floating problem can be solved. Material is the same that of conventinal circuit breaker model. The size of the materials used in the model of Fig. 11 is shown in Table 4. In addition, the distance between silver 1 and silver 3 was 10mm.

Table 4. Size of 2 point-of-contact form model

Material	Y-axis breadth [mm]	X-axis length [mm]	Z-axis thickness [mm]	Radius [mm]
Brass	8.0	26.0	1.0	-
Silver1	-	-	2.0	3.0
Silver2	4.0	6.2	1.0	-
Silver3	-	-	2.0	3.0
Silver4	4.0	6.2	1.0	-
Copper	3.0	33.0	6.0	-



(a) 3D model



(b) Cross section

Fig.11 2 point of contact form model

(2) 2 point of contact form tungsten model

When developing circuit breaker, it is also possible to use tungsten having larger specific resistance and melting point than silver as a material. Then, in the model of Fig.11, structure was left as it is, and the model which respectively changed the silver 1 and 2 of material into tungsten 1 and 2 was created. We also investigated the efects on both current and electromagnetic force change due to material dependence .

(3) Loop form model

As shown in Fig.12, we considered the model which improved brass forming loop. By making brass into loop form, the current of the same direction flows between brass (top) and copper. Although restitution works in brass (bottom) and copper simultaneously, suction works stronger because the distance of brass (top) and copper is nearer. Therefore, it is thought that switchgear floating problem can be solved.

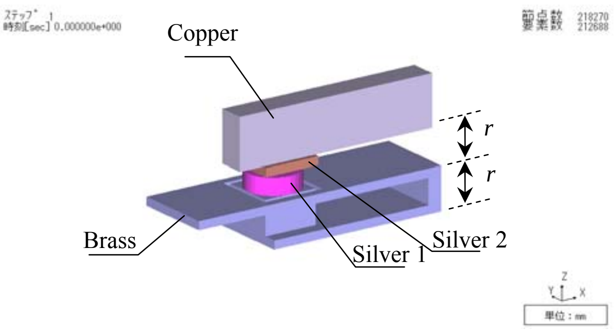


Fig.12 Loop form model

Table 5. Size of loop form model

Material	Y-axis breadth [mm]	X-axis length [mm]	Z-axis thickness [mm]	Radius [mm]
Brass top	9.0	29.0	1.0	-
Brass bottom	9.0	20.0	1.0	-
Silver1	-	-	2.0	3.0
Silver2	4.0	6.2	1.0	-
Copper	3.0	23.0	6.0	-

The size of the materials used in the model of Fig. 12 is shown in Table 5.

(4) Loop form depth model

In the model of Fig.12, the model which changed the depth distance between brass (top) and brass (bottom) twice was created. By increasing distance, the restitution which works between brass (bottom) and copper decreases and it is thought that the suction which works between brass (top) and copper increases compared with a loop form model.

7 Electromagnetic force analyzed results of advanced models

7.1 2 point of contact form model

(1) AC overcurrent analyzed result

The electromagnetic force analyzed result of the direction of the Z-axis committed to a 2 point of contact form model when AC overcurrent flows is shown in Fig.13.

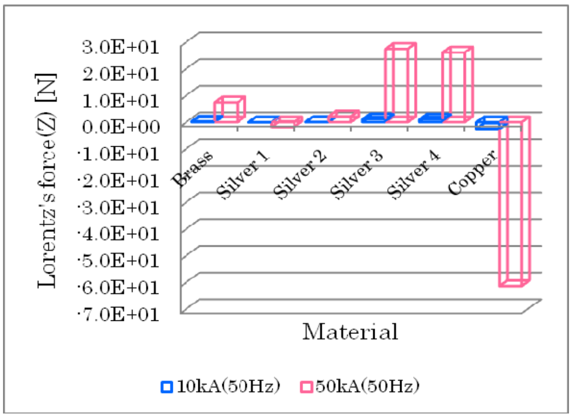


Fig.13 Electromagnetic force analyzed result of AC overcurrent (2 point of contact form model)

As the result of Fig.13, when the electromagnetic force of the contact parts (silver 1-4) was seen, restitution was working to silver 1 and silver 2, but both silver 3 and silver 4 was committing above power, and when seen only in the contact part, it became clear that restitution is not working. Moreover, when observed between conductors (brass, copper), since copper was working downward and brass was working upward, it became clear that suction was always working between brass and copper.

(2) Lightning surge current analyzed result

The electromagnetic force analyzed result in the direction of the Z-axis committed to a 2 point of contact form model when lightning surge current flows is shown in Fig.14.

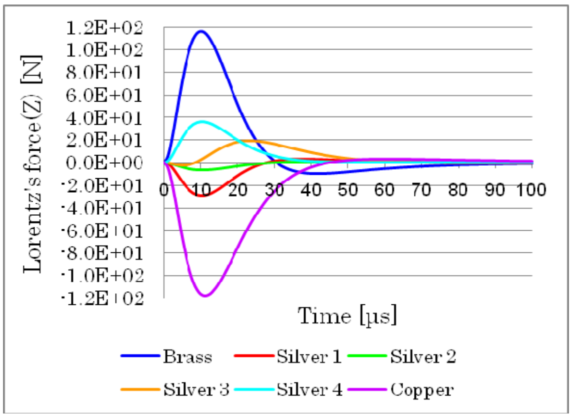


Fig.14 Electromagnetic force analyzed result of lightning surge current (2 point of contact form model)

As the result of Fig.14, change of the electromagnetic force with AC overcurrent was seen. In the case of AC overcurrent, when the contact parts (silver 1-4) was observed, below power committed only silver 1 and above power was working to silver 2, silver 3 and silver 4. On the other hand, in the case of lightning surge current, below power works to silver 1 and silver 2, and above power is working to silver 3 and silver 4.

Furthermore, like the case of AC overcurrent, when it observes between conductors (brass, copper), although brass shows above power and copper shows below power, it turns out that the degree of the power committed to brass is rising sharply compared with AC overcurrent. Therefore, strong suction will work between terminals if lightning surge current flows. If the same current value of 50kA compares, since still stronger power has arisen in the electrode part compared with AC overcurrent, it can be said that a 2 point of contact form model is a terminal structure which operating characteristic improves by the case of high frequency from a low frequency.

It became clear that a 2 point of contact form structure is much better than a conventional circuit breaker model.

7.2 2 point of contact form tungsten model

(1) AC overcurrent analyzed result

The electromagnetic force which works to a 2 point-of-contact form tungsten model, when an AC overcurrent flows and lightning surge current flows, is shown in Figs. 15 and 16 respectively.

Although all direction of power that works into each material from the result of Fig. 15 compared with a 2 point-of-contact model was the same, the current which flows into a front point of contact decreases, and the power committed to above brass under the influence which the current which flows into a back point of contact increased is large. Moreover, if the degree of the power which made a material change (silver 1 - tungsten 1 , and silver 2 - tungsten 2) is compared, the power committed to down of tungsten 1 is strong.

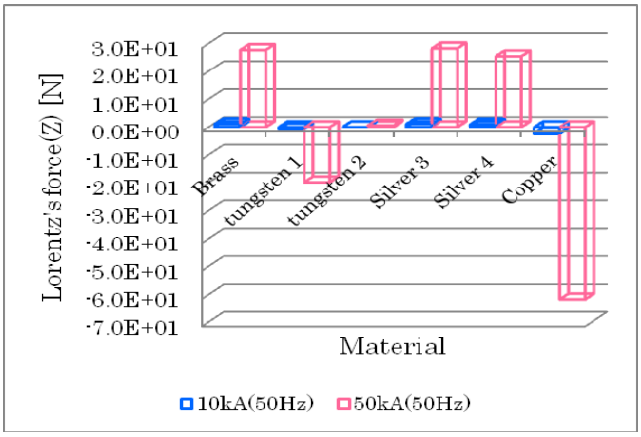


Fig. 15 Electromagnetic force analyzed result of AC overcurrent (2 point of contact form tungsten model)

(2) Lightning surge current analyzed result

The power committed to tungsten 1 compared with a 2 point-of-contact model increased from the result of Fig. 16, and the result which the power committed in copper is reducing slightly was obtained.

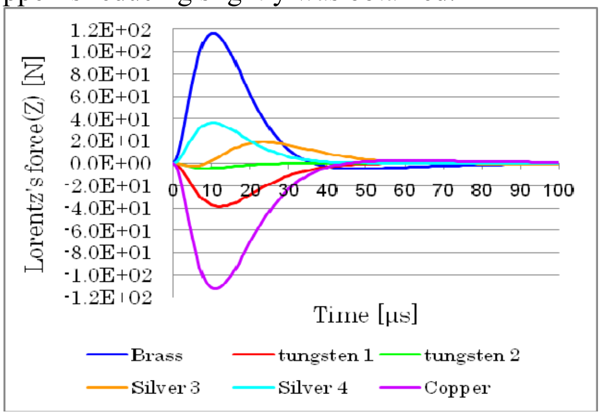


Fig. 16 Electromagnetic force analyzed result of lightning surge current (2 point of contact form tungsten model)

As compared with the 2 point of contact form model, the suction of AC10kA(50Hz) increased from the analysis result and since the suction of lightning surge current decreased, the result to which the operating characteristic of both current falls was obtained. Therefore, it became clear that it is better for using tungsten only for a front point of contact to avoid.

7.3 Loop form model

(1) AC overcurrent analyzed result

The electromagnetic force analyzed result in the direction of the Z-axis committed to a loop form model when AC overcurrent flows is shown in Fig.17. As the result of Fig.17, if the electromagnetic force of a contact part (silver 1, silver 2) is seen, below power works to silver 1 and above power works to silver 2 (restitution). On the other hand, if it observes between conductors (brass, copper), above power works to brass and below power works to copper (suction). Furthermore, when the size of power is compared, it turns out that the suction which works between conductors (brass, copper) is stronger than the restitution which works in a contact part (silver 1, silver 2).

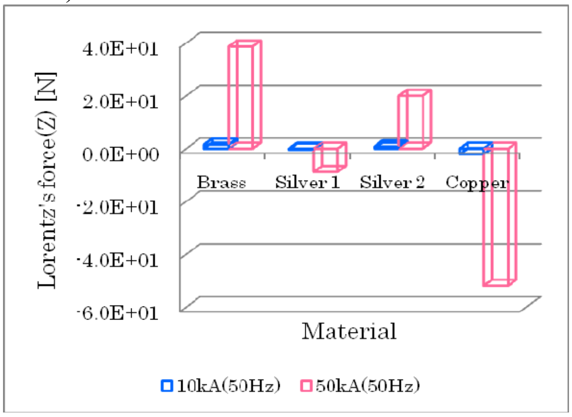


Fig.17 Electromagnetic force analyzed result of AC overcurrent (Loop form model)

(2) Lightning surge current analyzed result

The electromagnetic force analyzed result of the direction of the Z-axis committed to a loop form model when lightning surge current flows is shown in Fig.18. As the result of Fig.18, the direction and the degree of the power which work into each material as compared with AC overcurrent were similar. As mentioned above in lightning surge current, the suction which works between conductors (brass, copper) is stronger than the restitution which works in a contact part (silver 1, silver 2).

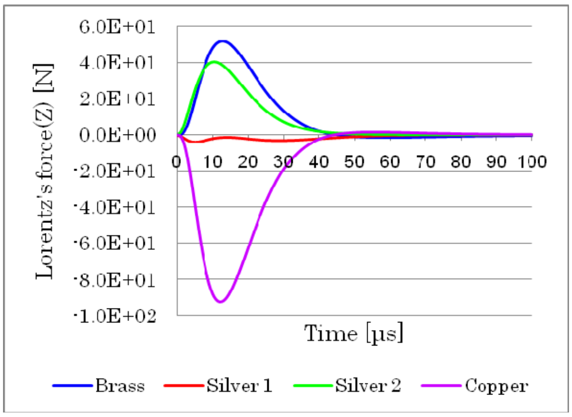


Fig.18 Electromagnetic force analyzed result of lightning surge current (Loop form model)

Therefore, strong suction works between terminals if lightning surge current flows. If the current value which is the same 50kA compares, since strong power has arisen in the electrode part although it is small compared with AC overcurrent, a loop form model is a terminal structure which bigger suction commits by the case of lightning surge current from AC overcurrent.

In the case of lightning surge current, since strong power is working compared with AC50kA (50Hz), it is expected that the point of contact of a switchgear does not intercept. It became clear that loop form model is much better than a conventional circuit breaker model.

7.4 Loop form depth model

(1) AC overcurrent analyzed result

The electromagnetic force analyzed result in the direction of the Z-axis committed to a loop form depth model when AC overcurrent flows is shown in Fig.19.

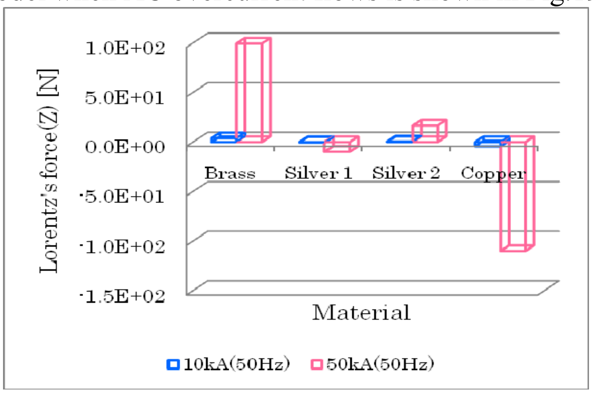


Fig.19 Electromagnetic forc analyzed result of AC overcurrent (Loop form depth model)

Although all direction of the power that works into each material from the result of Fig. 19 compared with a loop form model was the same, the degree of the power was different.

By increasing the depth distance between brass (top) and brass (bottom) twice, the restitution of the brass (bottom) and the copper became weak, and as a result, the power of suction of the whole brass and the copper became strong. It means thet an operating characteristic fell as compared with a loop form model in the case of AC over-current, because a disconnector should block a current from a commercial power supply.

(2) Lightning surge current analyzed result

The electromagnetic force analyzed result of the direction of the Z-axis committed to a loop form depth model when lightning surge current flows is shown in Fig.20. As the result of Fig.20, it turned out that the power of suction which works between the brass and the coper compared with a loop form model is going up remarkably. Since the suction of lightning surge current increased, as a result, the operating characteristic of lightning surge current improved.

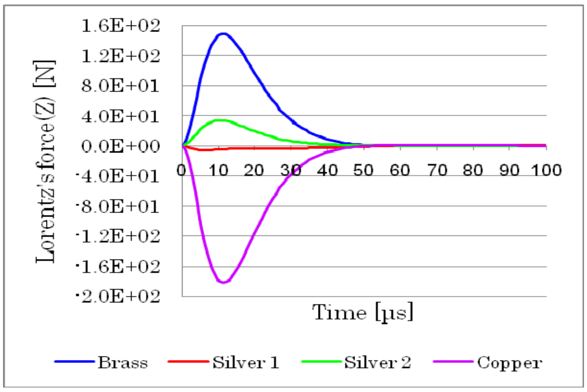


Fig. 20 Electromagnetic force analyzed result of lightning surge current (Loop form depth model)

Therefore, it became clear that the loop form depth model had the feature of both advantages and disadvantages. In the case of lightning surge current, the structure which suction between terminals as much as possible strongly commits is desirable, but the characteristics of AC overcurrent must be considered simultaneously.

8 Experimental Test Results

In order to claryfy the validity of the proposed methods, we tested them as shown in Fig. 21. Fig.22 shows one example of lightning surge waveform (class I, 10/350us) [8] in experiments.

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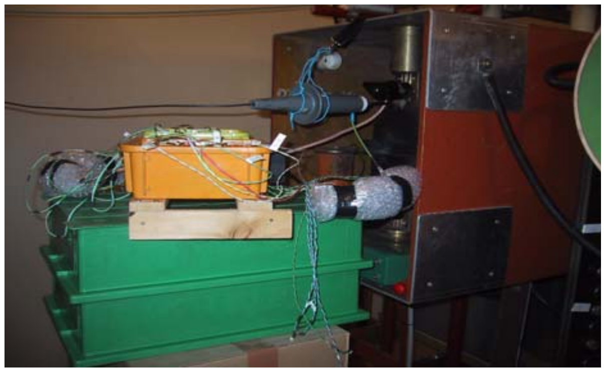

Fig. 21 Outlook of the experiment.

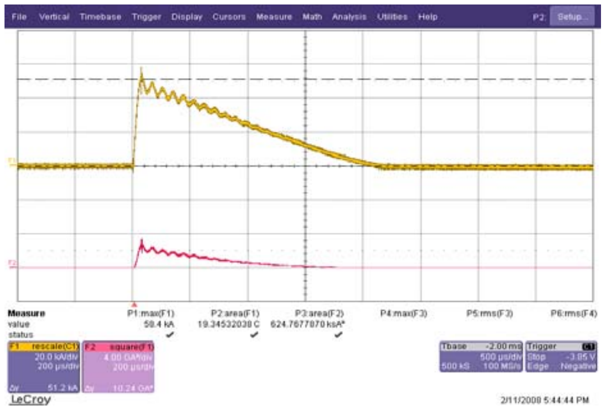

Fig. 22 Lightning Surge waveform used in experiments.

Based on the above simulation results, disconnector which used a 2 point of contact form model and a loop form model were developed for an experiment.

Table 6 shows the test results on operation performance of the various models under the condition of lighning surge current. The swichgear of conventional circuit breaker model could endure up to 15kA(10/350μs) . On the other hand, the swichgear of 2 point of contact form model could endure up to 40kA (10/350μs), and the swichgear of loop form model could endure up to 42kA (10/350μs). We found that proposed models obtained good test results.

Table 6 Operation performance of the various models

Disconnector	Experimental results [kA]	Desired value [kA]
Conventional circuit breaker model	15 (10/350μs)	50 (10/350μs)
2 point of contact form model	40 (10/350μs)	
Loop form model	42 (10/350μs)	

9 Conclusion

This paper presented an electromagnetic force analyzed results on switchgear of disconnector for overvoltage protector.

We summarized the evaluation results as shown in Table 7. It expresses with four-step evaluation of ◎ (very good), ○(good), △（so-so）and ×(bad).

Table 7 Comprehensive evaluation of various models

Disconnector	AC overcurrent	Lightning surge current	Comprehensive evaluation
Conventional circuit breaker model	◎	×	△
2 point of contact form model	○	◎	◎
2 point of contact form tungsten model	△	○	○
Loop form model	○	◎	◎
Loop form depth model	△	◎	○

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