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Analysis of Circuit Breaker Failures from Lightning Impulse Current

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Abstract—*Facilities such as base stations that are equipped with towers are frequently damaged by direct lightning strikes. A major type of such damage is the failure of low-voltage circuit breakers. There has been almost no consideration of the mode and mechanism of circuit breaker failure. Furthermore, there are no established standards for circuit breaker tolerance of impulse current or testing methods [1][2]. In this paper, we classify the mode of circuit breaker failure due to partial current of direct lightning strike and perform tests in which lightning current is applied to circuit breakers to evaluate the resistance to impulse currents.*

Keywords-Impulse current, lightning damage, Circuit breaker,

I. INTRODUCTION

Base stations equipped with towers and other such facilities are frequently subjected to direct lightning strikes. The most important damage from lightning is to the low-voltage circuit breakers of incoming panels, resulting in the inability to receive power from the commercial power grid.

To address that problem, we began an investigation of measures to prevent lightning damage to circuit breakers. To devise countermeasures, it is important to understand the electrical characteristics of circuit breakers related to the ability to withstand impulse currents. However, testing standards for circuit breakers do not specify requirements for impulse current tolerance.

We conducted tests to determine the ability of circuit breakers to withstand impulse currents which simulates the partial current of direct lightning strikes. In this paper, we analyze the failure mechanism and perform tests in which lightning current is applied to circuit breakers to evaluate the resistance to impulse currents.

II. MECHANISM OF CIRCUIT BREAKER FAILURE DUE TO LIGHTNING IMPULSE CURRENT

Facilities that are susceptible to circuit breaker damage from lightning tend to be among those listed below.

1) Low-voltage incoming facilities
2) Facilities equipped with a tower and cannot obtain a low contact resistance

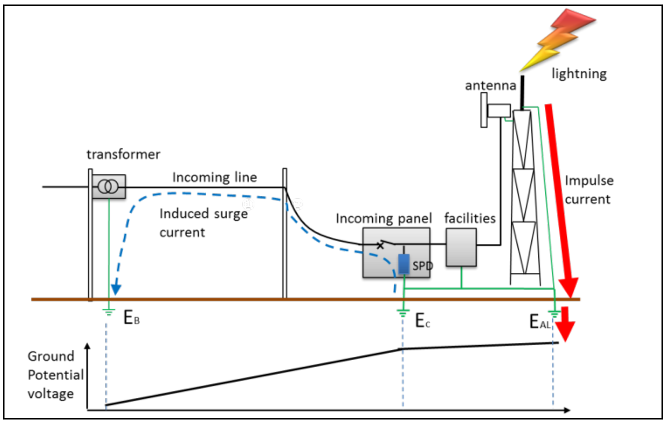

Fig.1 Surge current to power line due to direct lightning strike

The mechanism for circuit breaker damage when lightning strikes a tower directly is illustrated in Fig. 1. If the lightning strikes the lightning rod on the tower, the lightning current is conducted to the earth electrode (E_{AL}) via the down-conductors.

Depending on the current value and the earth resistance, the earth potential rises. The earth electrode for the building or facility (E_c) is connected to the E_{AL}, so the potential at E_c is about the same as at E_{AL}. The earth electrode of power line (E_B) and E_C are isolated at the T-T system, so a potential voltage difference between E_B and E_C arises during a lightning strike. Surge current from the high potential E_C through the SPD to the power line, and then to ground at E_B. In that case, a surge current flows through the circuit breaker. That surge has a very high energy, because it is a part of the current from the direct lightning strike, and that is what destroys the circuit breaker.

From analysis of the equipment problems, we can broadly classify circuit breaker failures as either open circuit failure mode or short circuit failure mode.

A. Open circuit failure mode

In the open circuit failure mode, the supply of power to the equipment is stopped. When the lightning surge current is small, the circuit breaker is only tripped; there is no abnormality in the outward appearance or function and recovery is possible by simply resetting the circuit breaker. When the lightning surge current is large, however, the circuit breaker case may be damaged with the contacts fusing and the conductive parts are exposed, so the circuit breaker cannot be reset. An example of open mode failure is shown in Fig. 2.

Open mode failures have the following features.

1) When the lightning surge current is relatively small, the circuit breaker can be reset as a temporary recovery measure.

2) If the circuit breaker is destroyed and conductors are exposed, there is danger of electrical shock.

3) Abnormalities are easily detected.

4) Because a power outage results, services are unavailable and urgent emergency response is required.

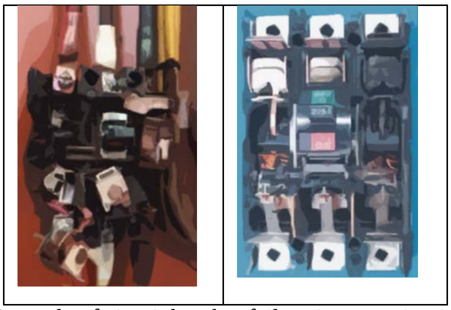

Fig. 2 Example of circuit breaker failure in open circuit mode

B. Short circuit failure mode

In the short circuit failure mode, the lightning surge current produces arcing between floating circuit breaker contacts. That results in abnormally high heat that fuses the contacts. When a short circuit mode failure occurs, the circuit breaker cannot open, so there is danger due to the loss of the overcurrent breaking function. An example of short circuit mode failure is shown in Fig. 3.

Short circuit mode failures have the following features.

1) No abnormal outer appearance and no power outage.

2) Circuit breaker abnormality is difficult to detect.

3) Because the circuit breaking and overcurrent interruption functions are lost, there is a risk of electrical fire when an equipment abnormality occurs.

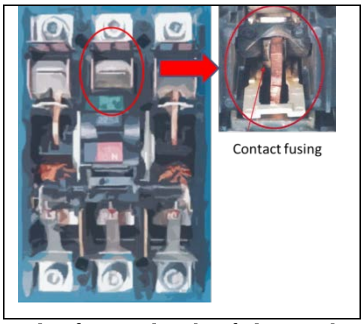

Fig. 3 Example of circuit breaker failure in short circuit mode

III. TEST FOR CIRCUIT BREAKER TOLERANCE OF IMPULSE CURRENT

An important point in preventing circuit breaker damage, as mentioned above, is confirming the amount of impulse current that flows to the circuit breaker. However, although the circuit breaker specifications include requirements and testing for impulse voltage, there is nothing for impulse current. It is therefore not possible to select circuit breakers according to their tolerance for lightning surge on the basis of the electrical characteristics listed in catalogs.

To deal with that problem, we performed tests of the ability to withstand lightning impulse current, focusing on circuit breakers that have a rated current of 140 A or less, which are used for low-voltage incoming facilities in Japan.

A. Test samples

The samples used in the tests were conventional circuit breakers from two different manufacturers and an electronic control type circuit breaker (FKB series) that was developed by NTT Facilities.

Table 1 Circuit Breakers used in the test

Supplier	AF	I_n	I_{cs}	Breaking method: Over-current	Breaking method: Short circuit-current
A	225A	225A	27kA	Heat actibated	Electro-magnetic
		125A			
	100A	100A	15kA		
	50A	50A	7.5kA		
		30A			
B	225A	225A	5kA		Electro-magnetic
	100A	100A	5kA	Electro-magnetic	
	50A	50A	2.5kA		
		30A			
NTT-Facilities (FKB series)	225A	70A	10kA	Electronic control	
		30A			

AF: Ampere flame, I_n: Rated current,

I_{cs}: Rated breaking capacity

In Japan, a circuit breaker that has a frame size of 225 AF and a rated current of 225 A is used as an SPD disconnector for class I SPD. The circuit breaker samples used in the test are listed in Table 1.

B. *FKB series*

The FKB is an electronic control type circuit breaker from NTT Facilities. The main electrical specifications are listed in Table 3.

Table 2 Main electrical specifications of the FKB

Type	FKB series	
AF	225AF	
Voltage and power system	200VAC 3 ϕ 3W	
I_n	15,20,30,40,50, 60,70,80,90,100	110,120,130,140
I_{cs}	10kA	25kA
Breaking method	Electronic control + electromagnetic	

FKB has the same size as conventional 225 AF breakers, so it features high compatibility for conversions. The outer appearance and dimensions are shown in Fig. 3.

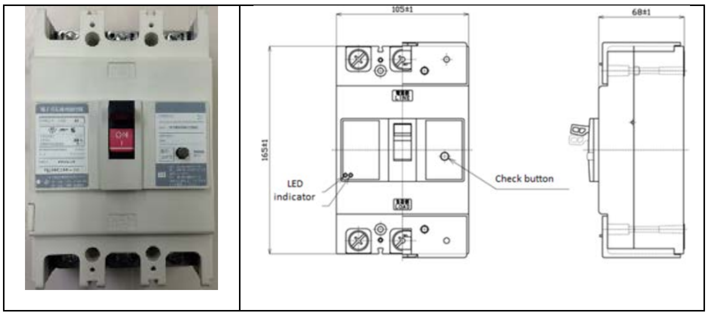

Fig.4 FKB appearance and dimensions

C. *Testing setup*

The tests involve a flow of impulse current from the primary side to the secondary side of a circuit breaker that is in the ON state and observation for the phenomena listed below.

1) Impulse current that fuses the contacts of the circuit breaker
2) Impulse current that trips the circuit breaker
3) Impulse current that damages the outside appearance or causes loss of circuit breaker function

The impulse current is applied for each phase. A class I impulse generator with a 10/350 μs current waveform was used. The impulse current value was increased from 5 kA to 35 kA in steps.

The impulse test setup and the test circuit are shown in Fig. 5 and Fig.6, and an example of the impulse current waveform is shown in Fig. 7.

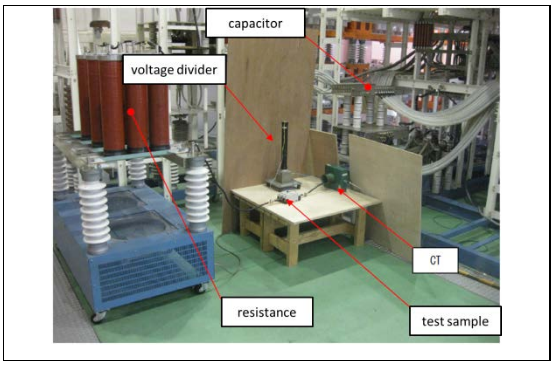

Fig.5 Impulse generator (test setup)

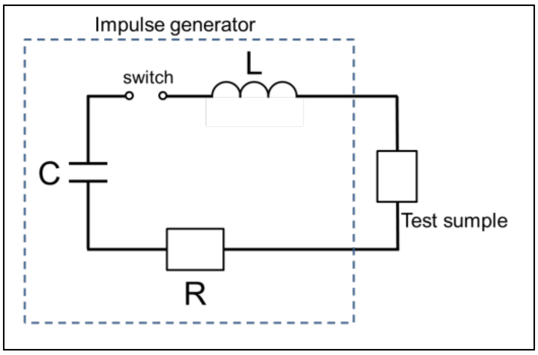

Fig.6 Impulse generator (test circuit)

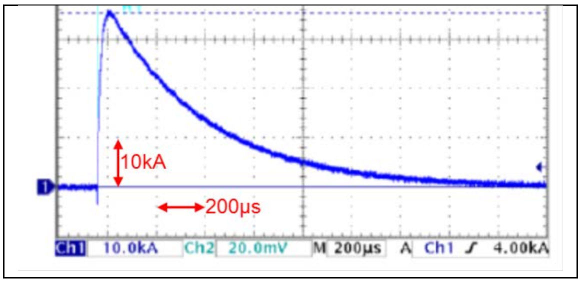

Fig.7 The example of impulse current waveform

D. *Test results*

The test results are presented in Table 3. We confirmed that light is emitted near the circuit breaker contacts when the impulse current is applied, that is inferred to be a result of arcing between contacts that occurs due to contact floating caused by the impulse current.

When the current is increased further, there is a tendency for the circuit breaker to trip. Further increase of the current results in expulsion of carbide from the gas outlet near the contacts and degradation of the insulation by soot near the bolt clamp. Ultimately, the circuit breaker case is cracked open, exposing conductors.

Contact fusion occurred at a lower current than is needed to trip the circuit breaker. Contact fusion does not easily occur in circuit breakers that have a small rated current and ampere frame (breaker size). The reason that contact fusion occurs more easily in circuit breakers that have a large rated current is considered to be that, even if contact floating occurs, the spring pressure that forces the contacts together is high, so the contacts tend to return to the original state without proceeding to the tripped state after continuing in the floating state. In that case, the contacts that have been heated to a high temperature by the arc will fuse when they come back into contact. The tendency for contacts to fuse is also considered to depend on how easily the contacts float, the type of contact material, and other structural characteristics.

The simplified relation of the impulse current value and breaker failure mode is shown in Fig. 8.

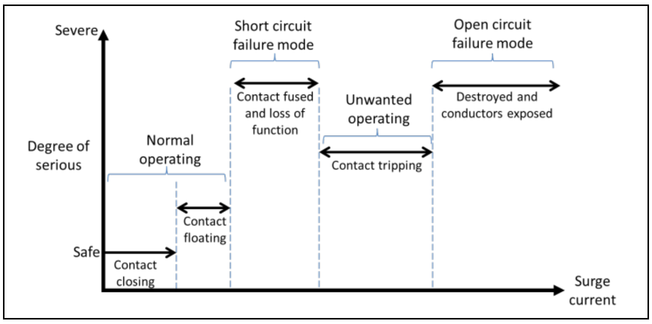

Fig.8 Relationship between impulse current value and circuit breaker failure mode

Damage to appearance that exposes conductors tends to occur in breakers that have small breaking capacity and ampere frames. Because the current that flows through the contacts when the breaker is tripped by the impulse current greatly exceeds the breaker capacity, the destruction is considered to result from the pressure of metal gases produced by arc heating exceeding the strength of the breaker case. To prevent circuit breaker failures that expose conductors, circuit breakers that have more space inside the case, stronger cases, and higher ampere frames should be selected.

Table 3 Test results

Supplier	I_n	Light emission	Contact point fusion	tripping	Damage to appearance
A	225A	15.1kA	None	25kA	None
	125A	10kA	10kA	Not tested	Not tested
	100A	10.1kA	None	15.1kA	None
	50A	7.5kA		10.1kA	29.6k
	30A				30kA
B	225A	20.2kA		31.8kA	None
	100A	15.1kA		15.1kA	29.8kA
	50A	Not confirmed		7.6kA	30kA
	30A			5.28kA	29.6kA
NTT Facilities	70A	10kA		20kA	None
	30A			15kA	None

The results show that the FKB developed by NTT Facilities features a higher ability to withstand impulse current than the conventional mechanical circuit breakers for the same rated current. Furthermore, there was no damage to the appearance or function of the FKB from the 30 kA impulse current that destroyed the conventional circuit breaker and exposed conductors. Additionally, the tripping impulse current was higher by a factor of 1.5 compared to the conventional circuit breakers and no contact fusion occurred.

E. Conclusion

When a large surge current flows through a circuit breaker, such as the direct lightning to the antenna tower, an open mode or short circuit mode failure may occur. Currently, circuit breaker standards do not include requirements or testing methods for the ability to withstand lightning current, and there had previously been no investigation of measures for preventing recurrence.

We performed tests to evaluate circuit breaker tolerance of lightning current, confirm actual performance, and investigate the failure mode of circuit breaker. The results are listed below.

- We classify circuit breaker failure mode due to lightning impulse current into short circuit mode and open circuit mode. Short circuit mode makes contact fusing. Open circuit mode includes trip and damage to appearance.
- Generally, circuit breakers that have a large rated current tend to have a high impulse current tolerance for tipping and damage to appearance. The tripping current is about 15 kA for a 100 AF breaker and about 5 to 10 kA for a 50 AF breaker.
- For a 225 AF class circuit breaker, the tripping impulse current is large, but the contact structure allows contact fusing to occur after contact floating. Contact fusing disables the interrupt function and so presents a serious danger.
- The FKB series with breaking function combined electronic control and electromagnetic developed by NTT Facilities is less easily tripped by impulse current than any other conventional circuit breakers, and so is less susceptible to damage that can expose conductors. The FKB is thus effective for use as a measure against lightning damage to facilities.
- The FKB series can be applied to an SPD disconnector for class I SPD. And we continue to develop FKB series of rated current equal to or less than 60A that prevents tripping by an impulse current of a 20 kA.

REFERENCE

[1] IEC60947-1 Low-voltage switchgear and controlgear Part 1: General rules

[2] IEC60947-2 Low-voltage switchgear and controlgear Part 2-1: Circuit-breakers