Evaluation of Flashover Voltage Property of Snow Accreted Insulators for Overhead Transmission Lines, Part III - 154 kV Full-scale Flashover Voltage Test of Snow Accreted Insulators -

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ABSTRACT

In December 2005, Japan experienced a major outage in Niigata Kaetsu area due to a large amount of wet snow mixed with sea-salt accreted on several transmission line insulators. To clarify the causes of the snow-induced outage and increase reliability of the networks, a 154 kV class full-scale snow test procedure to evaluate various insulator designs was developed, and artificial flashover voltage tests of snow accreted insulators were carried out. High voltage flashover tests showed that the flashover voltage of both long-rod and cap & pin insulators was decreased with the increase of snow conductivity. Also, cap & pin insulators showed significantly higher flashover voltage than long-rod insulators. Thus substitution of long-rod insulators with cap & pin insulators appears to be reasonable as a countermeasure against snow induced flashovers.

Index Terms - **Insulator, wet snow, packed snow, sea-salt, flashover.**

1 INTRODUCTION

IN December 2005, Japan experienced a major outage in the Niigata Kaetsu area which lasted for up to 30 hours and was caused by snow accretion on insulators. During the event, porcelain long-rod insulators on several 154 kV and 66 kV lines were completely covered by wet, packed snow of relatively high conductivity. The observed conductivity was attributed to salt transported from the sea by strong wind. The large amounts of wet snow mixed with the sea-salt reduced insulation strength of the insulator strings and caused flashovers [1].

While extensive research has been performed on the effect of insulator ice and snow accretion on flashover characteristics [2-15], knowledge related to the effect of salt-containing wet snow is very limited, as these conditions are rare [16, 17]. In order to increase reliability of Japanese networks, CRIEPI initiated a comprehensive project related to the effect of ice and snow accretion on overhead lines [18]. Part of this project was to develop a 154 kV class full-scale snow test procedure to evaluate insulator designs.

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As the first step, flashover voltage tests of snow-accreted insulators with controlled snow conductivity, liquid water content, density, etc. were carried out using 33 kV class insulators. The target values for wet and packed snow with defined conductivity were verified on 33 kV insulators. High voltage flashover tests showed that the flashover voltage was comparable to the service voltage for conditions presented during the Niigata outage, and the results were repeatable [19]. Based on these tests, the procedure was considered feasible for testing of 33 kV insulators covered by wet and packed snow with defined conductivity. The test method was also verified on a preliminary basis for the full-scale 154 kV class insulators of various types and working positions.

This paper discusses the procedures for generation and accretion of wet and packed snow with well defined properties onto 154 kV class insulators in laboratory and the results of the flashover voltage tests.

2 BLACKOUT IN NIIGATA KAETSU AREA

The details of the wet snow storm in the Niigata case have been reported in [1]. Some important elements of this event are described briefly below.

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A strong low pressure system in Pacific Ocean moved from south to north along the east coast of Japan's main island, and another low pressure system in the Sea of Japan moved across the island on 22 Dec. 2005. The ambient temperature in the Niigata Kaetsu area, which is located in the northwest of the Japan's main island facing the Sea of Japan, stabilized in the range of 0 to +2 °C from 03:00 to 17:00 on 22 Dec. with heavy precipitation and wind. The total precipitation and the maximum 10 minutes average wind speed observed at Niigata Meteorological Local Agency was 26 mm from 03:00 to 17:00 and 14 m/s just before 09:00. The observation system of Tohoku Electric Power Co. recorded the maximum wind speed of more than 25 m/s at 11:00.

Cascading electrical failures on 154 kV and 66 kV transmission lines started just before 09:00 and resulted in numerous tripped lines. At about the same time, a couple of 275 kV transmission lines also tripped as a result of conductor galloping. A total of 30 transmission lines with 49 circuits tripped and induced a blackout over a large area.

Many porcelain long-rod insulator strings, which were used exclusively on 154 kV and 66 kV transmission lines, were packed with wet snow. Figure 1 shows an example of packed snow on insulator strings. The shape of packed snow on some insulators was cylindrical, while others were eccentric pennant into the wind direction. These shapes of snow on insulator strings are quite different from those which result from ice accretion or covered by snow without strong wind. The volume density of the packed snow ranged from 0.54 to 0.94 g/cm^3, and the maximum melted water conductivity was approximately 200 µS/cm at 25 °C.

Figure 1. Examples of packed snow on horizontally mounted long-rod insulator strings.

The worst of the weather ended before the night of the 22 Dec., and restoration work was started at midnight. More than 2,500 electrical workers climbed the towers and removed the packed snow from insulator surfaces by hand. The restoration work was very difficult, as the wet snow was nearly transformed into ice at that time. After 31 hours from the start of the interruption, the electrical system was entirely restored.

During restoration work, many traces of power arcs on insulator surfaces and hardware were observed on both horizontally and vertically mounted insulators, including V-strings. They were found over a wide area, and many traces were located inland, 30 to 40 km from the Sea of Japan. The measured conductivities of the packed snow were the highest in this area. Apparently, the sea-salt was carried by the wind to the inland area.

After the outage, Tohoku Electric Power Co. completed replacement of the long-rod insulators of one transmission line circuit by cap and pin insulators in the Niigata Kaetsu area, and they are conducting the same countermeasures in other areas where the similar events could occur.

3 FLASHOVER VOLTAGE TEST PROCEDURE FOR SNOW ACCRETED INSULATORS

To clarify the causes of the snow induced flashover and increase reliability of the networks, a 154 kV class full-scale snow test procedure to be used for evaluating various insulator designs was developed.

Various research has been carried out on the effect of insulator snow accretion on flashover characteristics, and representative snow test procedures and evaluation methods have been established in IEEE standard 1783-2009 [20]. In the test procedure, natural snow gathered from the ground is mixed with salt with a snow blower. Then the snow is dumped into the snow pile jig mounted on the insulators to simulate the accumulation of snow on horizontal oriented insulators. However, storing and handling natural snow still presents some difficulties.

The proposed test required generation of snow with well defined conductivity, density, etc.. The target values of the snow parameters, such as snowflake size, snow density, liquid water content and snow conductivity, are shown in Table 1. The target snow conductivity was the same as observed after the blackout at Niigata Kaetsu in 2005 and during continuous field observation in the same geographic region from 2007 to 2011 [21].

The test procedure consisted of four steps, 1) generation of artificial snow with defined conductivity, 2) accretion of packed snow on the insulator, 3) increase of liquid water content in the accreted snow, 4) voltage application. A 154 kV class porcelain long-rod insulator and cap & pin suspension insulator string were utilized for the tests. The number of insulator sheds, connection length, creepage distance and dry arc distance of both insulators is shown in Table 2. All the tests were performed using the test facilities of STRI in Ludvika, Sweden.

Table 1. Target values of snow parameters.

Parameter	Target value
Size of snowflakes	0.1-0.2 mm
Shape of snow	Cylindrical
Snow density	0.5 g/cm^3 and higher
Liquid water content	20-30%
Snow conductivity, σ_{25}	200 and 700 µS/cm

Table 2. Specification of test insulators.

Insulator type	Long-rod	Cap & pin
Shed number / profile	21	Anti-fog
Shed diameter [mm]	160	254
Connection length per unit [mm]	1,025	146
Creepage distance per unit [mm]	2,140	430
Number of units	2	13
Dry arc distance [mm]	1,774	1,960
Total creepage distance [mm]	4,280	5,590

3.1 ARTIFICIAL SNOW GENERATION

During snow generation, water with conductivity of 200 or 700 μS/cm was sprayed inside a large climatic chamber of 18 m diameter and 23 m height at -9 to -10 °C, which generated fine ice particles in the form of artificial snow (Figure 2). Snowflake size was about 0.1 to 0.2 mm, and the visual appearance was very similar to natural snow (Figure 3). The melted water conductivity of the artificial snow was 170 and 800 μS/cm as targeted, but the liquid water content was still zero. The collected artificial snow was kept in a storage freezer at -10 °C.

Figure 2. Wind tunnels placed in the large climatic chamber.

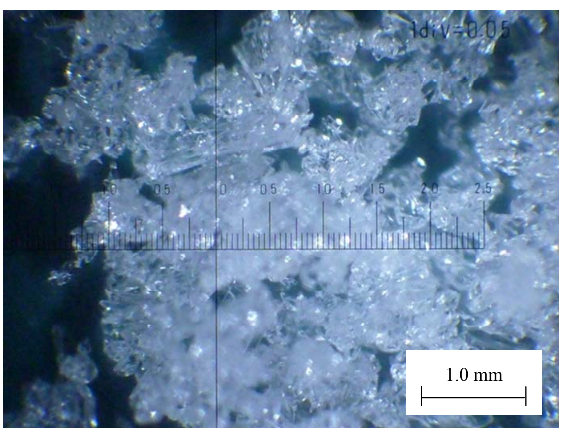


Figure 3. Appearance of the artificial snow.

3.2 ACCRETION OF PACKED SNOW

For the snow accretion and voltage tests, the artificial snow was brought back to the large climatic chamber where the temperature was adjusted to about +1 °C. The snowflakes were blown onto the insulator by a small handheld vacuum cleaner operating in reversed mode until the snow accreted and filled the gaps between the sheds as observed in the Niigata case (Figure 4). The distance between the vacuum cleaner and the insulator was about 500 mm, and the wind velocity at the insulator was approximately 15 m/s.

Figure 4. Packed snow obtained by a small handheld vacuum cleaner.

Since the amount of snow accreted onto the insulators influences on their performance in flashover tests, weight of the snow was recorded before each test. This was accomplished by hanging the complete suspension set using a load cell from the overhead crane.

Figure 5 shows photographs of insulators with well packed, accreted snow at a density in the range of 0.5-0.6 g/cm^3. Cylindrical snow accretion, as observed in the Niigata case, was achieved by rotating the insulator on a turntable during accretion. Thickness of the accreted snow at the shed surface was about 20 mm for both the long-rod and cap & pin insulators.

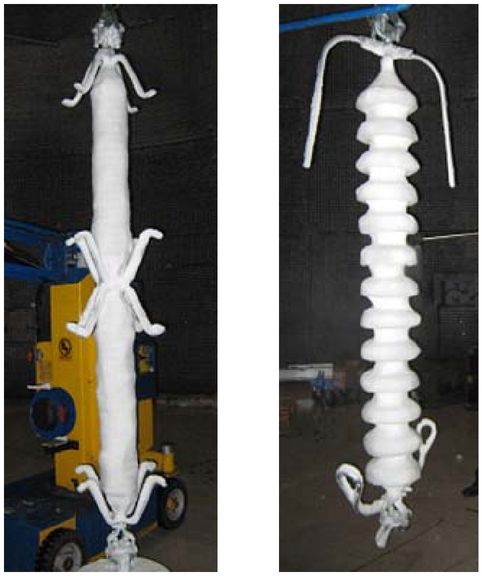
For the long-rod insulator, all the shed-to-shed spaces were filled with high density packed snow, resulting in cylindrical shape (Figure 5a). The cap and pin insulator strings maintained visible disk spacing after snow accretion (Figure 5b).

3.3 INCREASE OF LIQUID WATER CONTENT OF ACCRETED SNOW

Water with defined conductivity (the same as used for snow creation) was sprayed onto the accreted snow to increase the liquid water content to the range of 20-30%, which resulted in a snow density of 0.7-0.8 g/cm^3 (Figure 6). As the result, the target values for wet and packed snow with defined conductivity, density, etc. (Table 1) were attained and verified for the 154 kV insulators.

Average weight of accreted snow on the long-rod and the cap and pin insulators was 21.2 kg and 23.8 kg, and the standard deviation was 1.6 and 2.1, respectively. Snow weight per dry arc distance of the tested insulators was derived as 120 g/cm and 121 g/cm for the long-rod and the cap & pin insulators.

Upon completion of spraying, leakage resistance of the snow accreted insulator strings was measured using a mega-ohmmeter with results as shown in Table 3. The leakage resistance was very reproducible with repeated snow accretion for a given insulator type and snow conductivity.



a. Long-rod insulator. b. Cap & pin insulator string.

Figure 5. Snow accreted insulators.

Figure 6. Spraying water onto snow accreted insulator.

Table 3. Leakage resistance of snow accreted insulators measured before flashover voltage tests.

	Leakage resistance [MΩ]	
Snow conductivity, σ_{25} [μS/cm]	Long-rod	Cap & pin
170	0.21	0.73
800	0.04	0.27

3.4 FLASHOVER VOLTAGE TEST

After spraying the conductivity-adjusted water onto the accreted snow surface, high voltage flashover tests were performed in the same test chamber used to create the samples, but at a temperature in the range of +1 to +2 °C, using a 250 kVac, 500 kVA test transformer. Figure 7 shows the test setup in the climatic chamber. Figure 8 shows the test circuit. During the flashover voltage tests, leakage current was monitored through a shunt resistance of 150 Ω.

The applied voltage was increased to the desired value at a rate of 3-7 kV/s and thereafter kept constant until the insulator either flashed over or withstood, i.e., when the risk of flashover was considered negligible based on monitoring of leakage current levels. If flashover occurred at the applied test voltage, the test voltage was decreased about 7% for the next test.

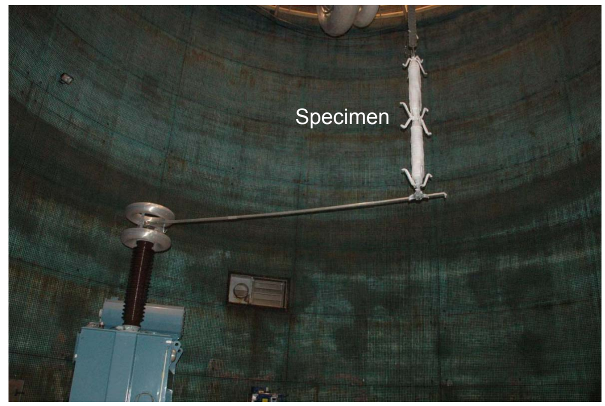


Figure 7. Setup for flashover voltage tests in the climatic chamber.

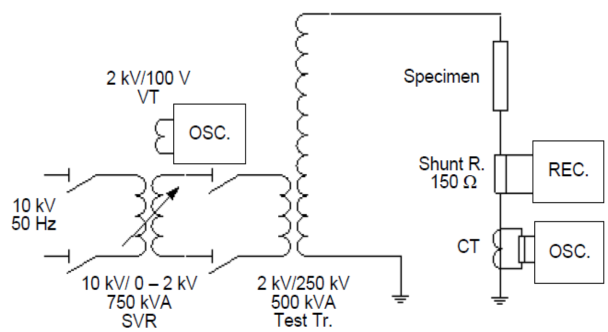


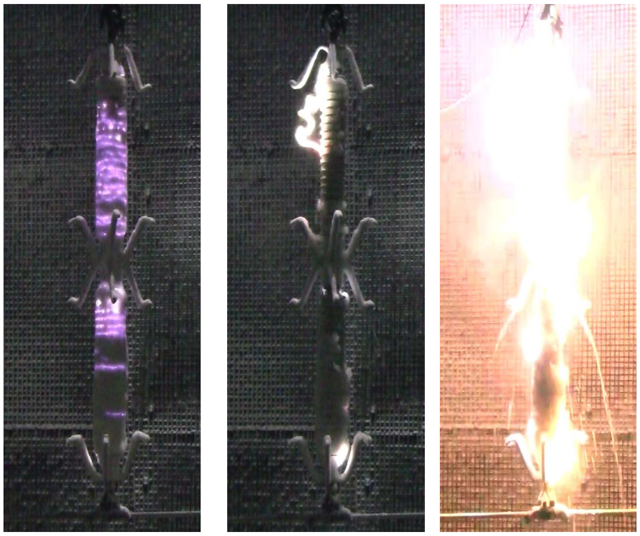
Figure 8. Test circuit of flashover voltage tests.

Figure 9 shows photographs of discharge activity at 134 kV during the voltage tests with the long-rod insulator. Figure 10 shows the time variation of applied voltage and leakage current observed during the same test. Typically, three phases of flashover process were identified during the voltage test.

a. During the initial period of voltage application, small visible discharges appeared inside the accreted snow, and the leakage current increased with increased applied voltage.

b. A few tens of seconds after voltage application, intensive discharges developed and distributed along the insulator. A number of air gaps were created in the snow as a result of melting, and maximum currents in the range of 100-600 mA were observed.

c. Thereafter, an arc grew along the surface and finally developed into a complete flashover after a few minutes.



a. Initial period of voltage application. b. Before flashover. c. Flashover

Figure 9. Photographs of discharge activity during a voltage test with the long-rod insulator.

Figure 11 shows the typical sinusoidal waveform of the leakage currents observed during the initial period, which changes into a distorted waveform due to intense discharge activity.

4 FLASHOVER VOLTAGE PROPERTY OF SNOW ACCRETED INSULATORS

4.1 FLASHOVER VOLTAGE TESTS OF 154 KV CLASS INSULATORS

Several flashover voltage tests of the snow accreted 154 kV class long-rod and cap & pin insulators were carried out with the snow conductivity of 170 and 800 μS/cm. To understand the process of snow outage at Niigata Kaetsu and clarify usefulness of the countermeasure against snow induced flashover, long-rod insulator and cap & pin insulators were compared. Table 4 shows conditions of the flashover voltage tests.

In this study, withstand to the flashover test was defined as no flashover within one hour of voltage application with

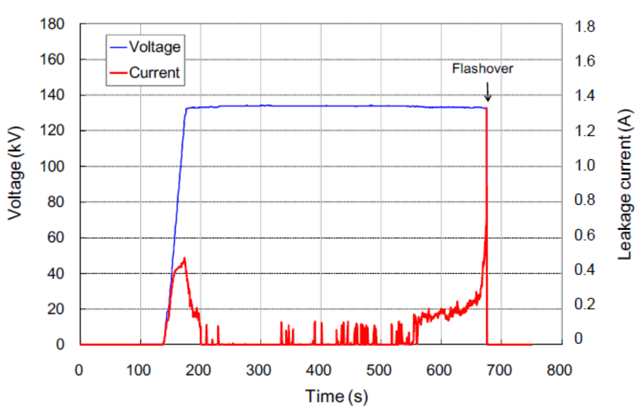
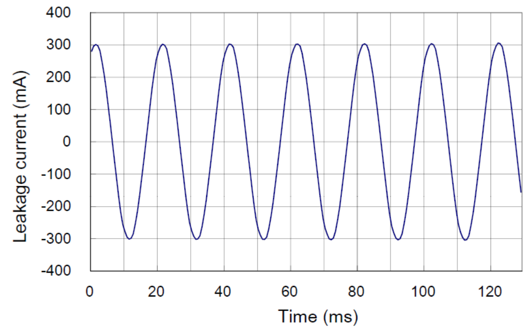
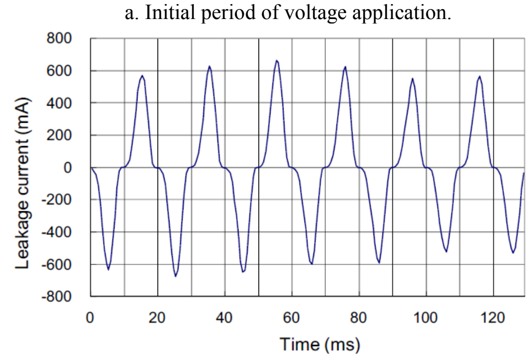


Figure 10. Time variation of voltage and leakage current during the test.



a. Initial period of voltage application.



b. After intensive discharge developed.

Figure 11. Waveforms of leakage current during the test.

sufficiently low leakage current that future flashover seemed unlikely. For the cap and pin insulators, voltage tests were normally finished within ten minutes, because significant parts of snow often fell down rapidly. The minimum flashover voltage of an insulator was defined as being equal one voltage step higher than the maximum withstand voltage which the insulator withstood twice.

Table 4. Conditions of flashover voltage test.

Temperature	0 to +2 °C
Snow conductivity, σ_{25}	170 and 800 μS/cm
Liquid water content	About 20% （water 4 L / snow 20 kg）
Insulator type	Long-rod and Cap & pin (anti-fog)
Sample setup	Vertical position
Voltage application	Constant: Voltage step: 7% (Ramp speed: 3 – 7 kV/s)

4.2 RELATION BETWEEN SNOW CONDUCTIVITY AND FLASHOVER VOLTAGE

Table 5 presents the results of the flashover voltage tests. Figure 12 shows the minimum flashover voltage of the snow accreted long-rod and cap and pin insulators at the two snow conductivities. The test results showed that the flashover voltage of both long-rod and cap and pin insulators decreased with the increase of snow conductivity. The lowest flashover voltage of the long-rod insulator at the higher snow conductivity was comparable to the maximum operating voltage 93 kV (normal operating voltage is 89 kV) of 154 kV transmission lines in the Niigata Kaetsu area. However, the difference between the lowest flashover voltage in the artificial snow tests and the operating voltage is presumably caused by some uncertainties of snow parameters measured at the sites during the Niigata case.

Table 5. Results of 154 kV full-scale flashover voltage tests of snow accreted insulators.

Insulator type		Long-rod		Cap and pin	
Snow conductivity, σ_{25} [μS/cm]		170	800	170	800
Applied voltage [kV]	222			X	
	207			O O	
	157				X
	146				O O
	136				O
	132	X O			
	124	O O	X O		
	116		X O		
	108		X O		
	100		O O		
Minimum FOV [kV]		132	108	222	157

X: Flashover O: Withstand

To bring the test results into the context of previous testing on snow-covered insulators [11-15], the Snow Stress Product (SSP) model can be used. The SSP is defined as snow weight (grams per cm of dry arc distance) multiplied by snow conductivity (μS/cm) at 20 °C and is related to the empirical expression of the maximum flashover stress (kV per meter of dry arc distance), $E_{ws} = 600\ (SSP)^{-0.19}$ [15]. As the result of rough calculation, the measured flashover voltage data in this study seem to be consistent with the previous test results on snow-covered insulators [11-15]. However, because the shed spaces were remained in the case of the cap & pin insulators, modification of the dry arc distance may be required.

In this research, snow accretion was performed without voltage, prior to the high voltage tests. However, if the insulators were energized during snow accretion as for the operating transmission lines, the process leading to flashover might differ from that during the laboratory tests. Leakage current through the accreted snow and partial discharge appearing on the snow surface may prevent snow accretion and increase the liquid water content of snow. The effect of voltage application during snow accretion and changes in volume and conductivity of the melted water in the accreted snow remain to be evaluated.

4.3 COMPARISON BETWEEN LONG-ROD AND CAP AND PIN INSULATORS

The cap & pin insulators showed significantly higher flashover voltage than the long-rod insulators for the same snow conductivity. The reason may relate to the configuration of the insulators, especially the difference in the shed spacing appears to be important. The small shed spacing of the long-rod insulator is easily bridged with packed snow, which results in a shorter creepage distance. Also, accreted snow tends to fall off the cap & pin insulator more easily during the voltage tests. Thus substitution of the long-rod insulators with the cap and pin insulators seems to be reasonable as a countermeasure against snow induced flashovers.

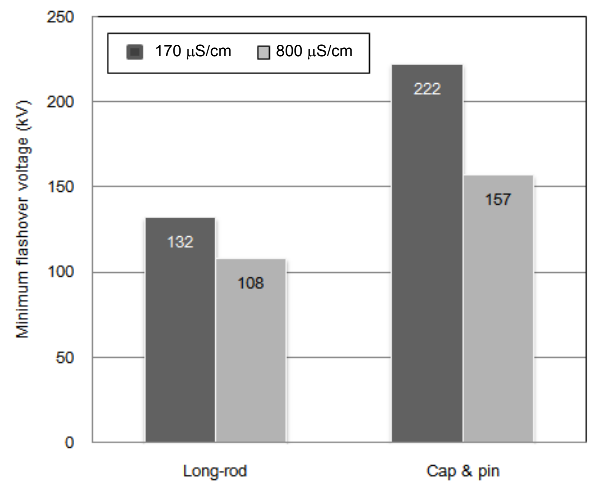


Figure 12. Results of flashover voltage tests of snow accreted insulators.

5 CONCLUSIONS

Flashover voltage tests of snow-accreted insulators with controlled snow conductivity, liquid water content, density, etc. were carried out using the full-size 154 kV class insulators to develop a test method for transmission class insulators of various designs. The test procedure consisted of four steps, 1) generation of artificial snow with defined properties, 2) accretion and packing of snow on the insulator, 3) increasing the liquid water content of accreted snow in a controlled manner, and 4) AC voltage tests of the snow-accreted insulators. The target values for wet and packed snow with defined conductivity were reached and verified on 154 kV insulators.

The tests data indicate that the flashover voltage of both long-rod and cap & pin insulators decreased with increasing snow conductivity. The flashover voltage of the long-rod insulators with accreted snow of 800 μS/cm conductivity was comparable to the service voltage in the Niigata Kaetsu area. Therefore the test procedure appears suitable for evaluation of the flashover properties of insulators with wet snow accretion packed with sea-salt and is more practical than the existing snow test method, because it does not call for storing and handling natural snow.

Also, the cap and pin insulators had significantly higher flashover voltage than the long-rod insulators due to the larger shed spacing. Thus substitution of the long-rod insulators with the cap and pin insulators appears to be a reasonable countermeasure against snow induced flashovers.

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