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Negative Creeping Discharge along Aerial Insulated Wire in Wet Condition

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SUMMARY

Aerial insulated wires are supported by postinsulators and binding wires on reinforced concrete poles. When a lightning flash strikes near by the wires, an overvoltage due to the indirect lightning surge is induced in the conductive wire core. A creeping discharge can develop along the wire surface from the free end of the binding wire through the postinsulator and reinforced concrete pole if flashover occurs at the postinsulator, and this also leads to wire damage such as melting or snapping. This can occur under either rainy or thunderstorm conditions. In this case, it indicates that the wire surface is stressed by lightning impulses under wet condition. Consequently, it is important to prevent wire damage and to clarify the characteristics of creeping discharges along the wire surface under dry and wet conditions. In previous investigations, we observed the characteristics of creeping discharges along wire surfaces under dry conditions. In this investigation, we examined creeping discharges under both impulse voltages with various wave front durations and wet conditions on the wire surface. These voltages were applied to the conductive wire core as inductive lightning surges. The duration and phenomena of negative creeping discharges developing along the wire surface were measured using a still camera with an image intensifier. We report the characteristics of the development of negative creeping discharges along wire surfaces under wet condition. © 2015 Wiley Periodicals, Inc. Electr Eng Jpn, 194(4): 1–9, 2016; Published online in Wiley Online Library (wileyonlinelibrary.com). DOI 10.1002/eej.22789

Key words: aerial insulated wire; negative creeping discharge; inductive lightning surge; duration of wave front; wet condition.

1. Introduction

Lightning faults on aerial insulated wires in urban areas can be divided into direct strokes and indirect strokes. In particular, accidents caused by indirect lightning strokes have been reduced dramatically as a result of years-long research, including the development of zinc oxide elements and other devices [1]. Thus, at present, lightning protection focuses mainly on direct lighting strokes. However, even though fewer accidents are caused by indirect lightning strokes, invasion of the wire core by lightning-induced surge voltages remains a problem. Another unsolved problem is creeping discharges developing along the wire surface after breakdown of the postinsulator due to an indirect lightning stroke. Such creeping discharges cause wire faults due to piercing of the wire sheathing. It is therefore important to further improve lightning protection and to clarify the characteristics of creeping discharges induced by lightning. Wire support structures have a complex insulation system, including the wire core, insulation, binding wire, porcelain insulators, and other components. When an indirect lighting surge voltage invades a wire core and reaches its support point, flashover occurs on the surface of the porcelain insulator, and then develops via the binding wire into a creeping discharge. On the surface of the wire coating, there are weak points due to damage during installation, age deterioration, and the like. In addition, the development of a creeping discharge imposes electrical stress on the wire coating, thus promoting degradation. At such weak points of the wire coating, a single creeping discharge may or may not result in a puncture. However, the probability of a puncture increases with repeated creeping discharges, and pinholes eventually appear. Once a pinhole has appeared, there is no way to repair it, and the wire remains in service until replaced. If creeping discharges reach these pinholes, they can penetrate to the wire core and may cause severe faults on distribution lines.

Many puncture points on wire coatings exist near the binding wire. However, punctures are observed even several meters from the wire support due to the development of creeping discharges [2]. Even though weak points exist on the wire surface, points beyond the maximum length of creeping discharge development can be ignored in terms of disconnection faults. Weak points on the wire surface can cause line faults when they are located within the maximum length of creeping discharge development from the binding wire tip. As regards lightning protection of distribution lines, it is important to combine multiple aspects, such as interruption of short-time interphase ac follow currents and improvement of porcelain insulator performance. AC follow currents occur due to interphase short circuits caused by creeping discharges. Thus, ac follow currents are reduced when the risk of coating punctures is lowered. Therefore, strengthening conductor insulation is an important measure. One way of strengthening insulation is to make it thicker near the binding wires. In this case, the electric field is reduced at the binding wire tip and discharge tip, thus inhibiting creeping discharge development. If the maximum creeping discharge length is known, one can estimate how much the insulation performance of conductor coatings should be improved. For lightning protection of distribution lines, it is important to investigate the characteristics of creeping discharge development along the wire surface due to lightning-induced surges. However, the development of creeping discharges is affected by various factors, such as the wave front duration of the lightning surge, its peak value, the wire surface conditions, and so on. In particular, we have discussed the effects of the wave front duration and peak value elsewhere [3–12], but the influence of wire surface conditions remains unclear.

Since aerial insulated wires are outdoors, they are exposed to rainfall and other weather phenomena. Lightning often occurs during rain, so that water drops adhere to the wire surface and create wet conditions. Such conditions have a strong influence on creeping discharges. Many investigations of creeping discharges have considered dry dielectric surfaces, but there have been few, if any, investigations discharge characteristics under wet conditions, such as the presence of water drops on the conductor surface. Thus, creeping discharge properties under wet conditions remain unclear not only for cylindrical dielectrics such as wires, but also for flat surfaces. In addition, there have been many investigations of lighting protection of distribution lines [13–18], but few dealing with creeping discharges on conductor surfaces.

We studied the development of creeping discharges along an aerial wire surface under dry conditions in a laboratory environment using impulse lightning voltages with different wave front durations (T_f) [3–12]. We also observed creeping discharges under wet conditions with water drops present on the conductor surface, representing an after-rain state, using a standard lightning impulse voltage to simulate a lightning-induced surge [3]. We found that positive creeping discharges do not depend on whether the wire surface is wet or dry in the case of standard lightning impulse voltages, but that negative creeping discharges develop very differently. However, these results pertain to standard lightning impulse voltages, and it was unclear how changes of T_f under wet conditions affect creeping discharge development. In addition, some details could not be studied because of limitations of equipment performance. In the case of insulated aerial wires, T_f of a lightning-induced surge is often as short as 10.0 µs or less [1]. It is therefore important to investigate the characteristics of creeping discharges for various T_f. In addition, since the polarity of lightning currents is almost always negative in summer lightning, the polarity of the lightning-induced surge is positive, while the polarity of creeping discharges that develop along the wire surface is negative. In the Hokuriku region, facing the Sea of Japan, the polarity of lightning currents in winter may be positive or negative. Thus, positive indirect lightning strokes occur throughout the year and cause negative creeping discharges along conductor surfaces. Therefore, investigation of the development of negative creeping discharges is significant. In this investigation, we considered wet conditions not considered in the previous study [3], and studied the properties of negative creeping discharges in cases of lightning-induced surges with T_f of 0.8 s or shorter.

2. Experimental Method

The support part of a utility pole and its experimental circuit are shown schematically in Fig. 1. In order to simulate lightning surges with different T_f, impulse voltages with T_f = 1.2µs, 2.0 µs, 4.0 µs, 6.0 µs, and 8.0 µs and

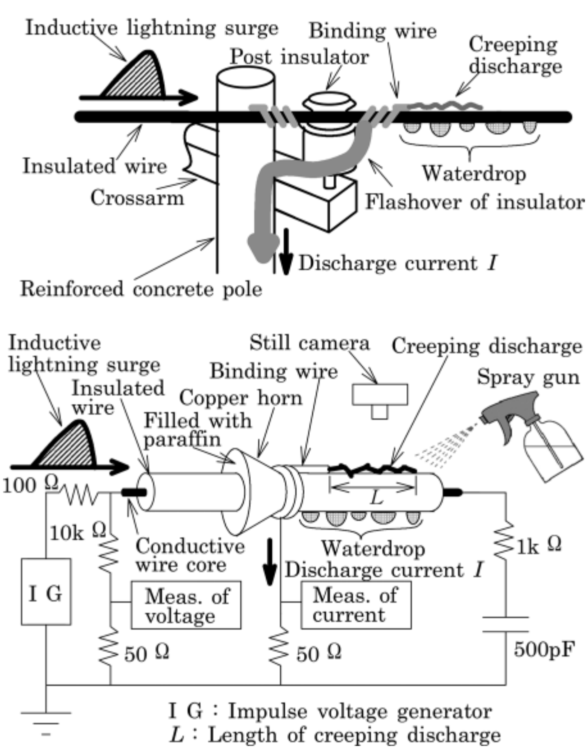

Fig. 1. Schematics of postinsulator on crossarm and experimental circuit.

Table 1. Data of insulated wire

	Conductor		
Finished outside diameter (mm)	Stated cross section (mm)^2	Structure (wires/mm)	Outside diameter (mm)
10.0	22.0	7/2.0	6.0
Insulation			
Thickness of insulated material	main material		Relative dielectric constant
2.0	Polyethylene		2.3

a wave-tail duration of 50.0 μs were applied to insulated wire with an impulse generator. In addition, to reproduce after-rain wet conditions, water drops (conductivity $\sigma = 215$ μS/cm, pH $= 5 - 6$) were sprayed onto the wire surface as uniformly as possible with an atomizer. Under these conditions, we observed the development of creeping discharges from the binding wire tip by means of a still camera provided with an image intensifier. When an impulse voltage is applied to the conductor, creeping discharges usually originate from both ends of the binding wire; however, our experiments were arranged so that a discharge originated only from one end, for simplicity of observation. Specifically, we attached a copper horn to one end of the binding wire as shown in the diagram, and filled the horn with paraffin to insulate the wire core. In addition, the binding wire was grounded through a resistance (20 Ω) in order to observe the discharge current, assuming flashover on the porcelain insulator surface. The binding wire was alloy wire (lead 97%, antimony 3%) with a diameter of 5.5. mm cut perpendicularly on both ends. Only the tip was modeled. The specifications of the insulated wire are given in Table 1. A 6.6-kV polyethylene-insulated wire with a length of 5 m was placed 75 cm above the laboratory floor. A grounded copper plate was placed on the floor to simulate the ground surface. After development of a creeping discharge, the wire surface was grounded and wiped with alcohol to remove residual charge. At the same time, water drops were applied with an atomizer to reproduce the wet conditions of the wire surface. The laboratory was air-conditioned to maintain a temperature of about 20 °C and a humidity of about 40%. In this experimental circuit, the polarity of the voltage applied to the wire core was opposite to that of the creeping discharge.

3. Experimental Results

3.1 Relation between peak value of applied voltage and length of negative creeping discharge

The relationship between the peak value of the applied voltage (below denoted by V_m) and the length of the creeping discharge for various T_f is illustrated in Fig. 2. The data are averages of 10 measurements. The spread of the discharge length was about ±10%. As can be seen from the diagram, the development length of negative creeping discharge under wet conditions increases monotonically with V_m, and remains almost unchanged when $T_f \leq 8.0$ μs. As reported previously [3, 6], there are regions with $T_f \leq 4.0$ μs in which the discharge length increases and decreases under dry conditions; however, under wet conditions, no regions of length decrease appeared at $T_f = 1.2$ μs. The observations made in this investigation indicate that negative creeping discharges under wet conditions did not show any length decrease regions at $T_f \leq 8.0$ μs.

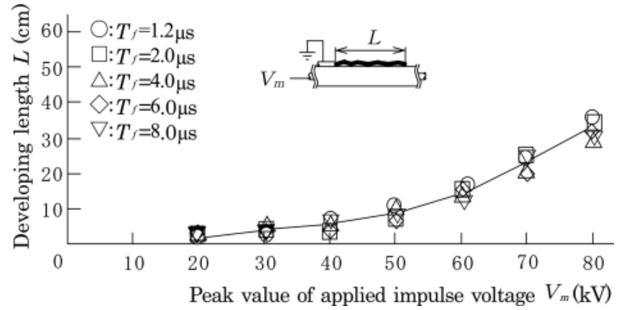

Fig. 2. Relationship between length of negative creeping discharge and applied impulse voltage in wet condition.

3.2 Discharge phenomena on wire surface

Our observations showed that when indirect lightning invades the wire core under wet conditions, two kinds of phenomena occur on the wire surface, namely, (1) development of a negative creeping discharge and (2) origination of a corona discharge from the surface of the water drops. Item (1), the development of a negative creeping discharge, can be further divided into (A) development along the surface of the water drops and (B) development during charging of water drops.

(1) Development of negative creeping discharge.
(A) Development along the surface of water drops.

Typical conditions of this phenomenon are illustrated in Fig. 3. This example involves discharge development near the tip of the binding wire at $V_m = 80$ kV, $T_f = 4.0$ μs, with a development length $L = 31.2$ cm. In the diagram, the creeping discharge develops from left to right. Here ① and ② are water drops adhering at the bottom of the wire. The creeping discharge developing on the wire surface reaches point A of water drop ① and then proceeds arcwise on the water drop. Thereafter, the discharge develops along the wire surface from point B, reaches point C of water drop ②, proceeds along the water drop, and returns to the wire surface at point D. Our observations showed that discharge

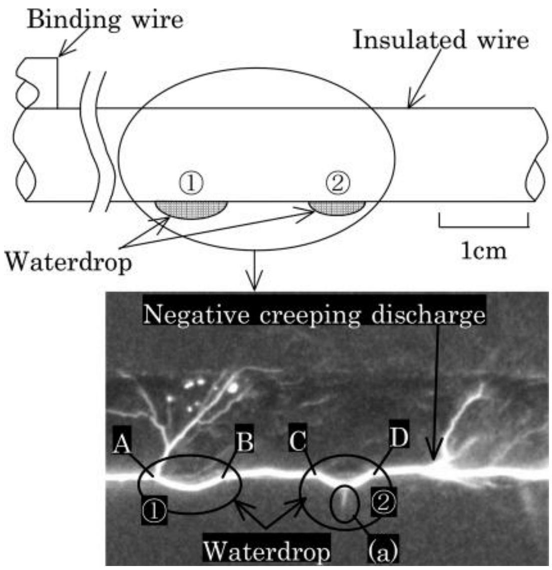

Fig. 3. Typical phenomena along surface of water drop in negative creeping discharge at V_m = 80 kV (T_f = 4.0 μs, L = 31.2 cm).

development along the surface of water drops occurs mostly at $V_m \geq 70$ kV and $T_f \leq 4.0$ μs. In addition, discharge development along the surface of water drops was often observed immediately after discharge inception, when the leader emitted strong light. But immediately before discharge extinction, a discharge tip with weak light emission did not develop along the surface of the water drops, but instead tended to develop with charging of the water drop (this case (B) is considered below). Thus, we may conclude that the development of a negative creeping discharge along the surface of water drops occurs when the electric field at the discharge tip is strong enough to ionize the air near the surface of the water drops. In addition, light emission as described in (a) was confirmed from the edge of water drop ②. This was a corona discharge originating from the surface of the water drop, as will be explained later

(B) Development with charging of water drop.

Typical conditions of this phenomenon are illustrated in Fig. 4 . This example pertains to discharge development near the discharge tip at V_m = 60 kV, T_f = 8.0 μs, and development length L = 13.5 cm. In the diagram, ①–⑧ are water drops adhering to the wire. After developing along the wire surface, the creeping discharge reaches water drop ① at point A and branches inside the water drop, exiting from points B and C. The discharge exiting at point B develops along the wire surface and reaches water drop ②, while the discharge exiting from point C develops along the wire surface and reaches point D via water drops ④ and ⑤. It then reaches water drop ⑥ at point E, exits at point F toward water drop ⑦, and reaches the latter at point G. After that, the discharge emerges at point H, reaches water

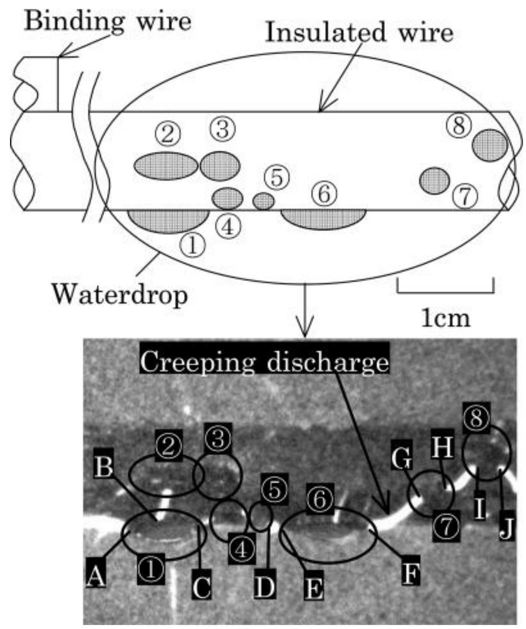

Fig. 4. Typical phenomena around water drop in negative creeping discharge at V_m = 60 kV (T_f = 8.0 μs, L = 13.5 cm).

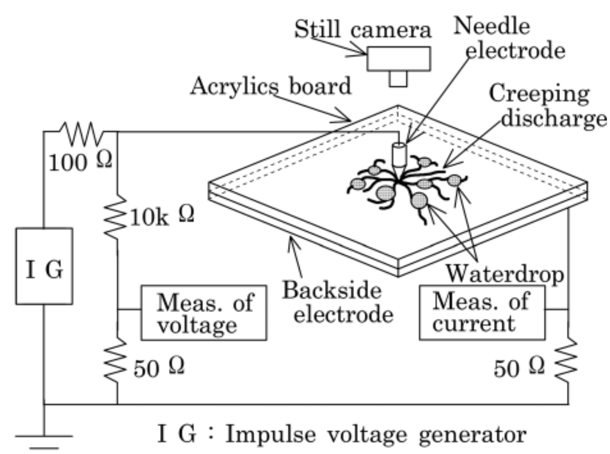

Fig. 5. Experimental circuit using dielectric plate in wet condition.

drop ⑧ at point I, and exits at point J. In contrast to Fig. 3, a creeping discharge does not develop along the surface of the water drops in Fig. 4. When the leader arrives at the edge of a water drop, light emission ceases, and then reappears strongly when it emerges at the other edge.

We observed water drops closely to examine what phenomena occur around a water drop when a discharge arrives. The experimental circuit is shown in Fig. 5. For easier observation, we conducted these experiments on a flat dielectric (acrylic board) to which water drops adhered more readily than to cylindrical dielectrics such as insulated wires. Specifically, a grounded copper plate was used as

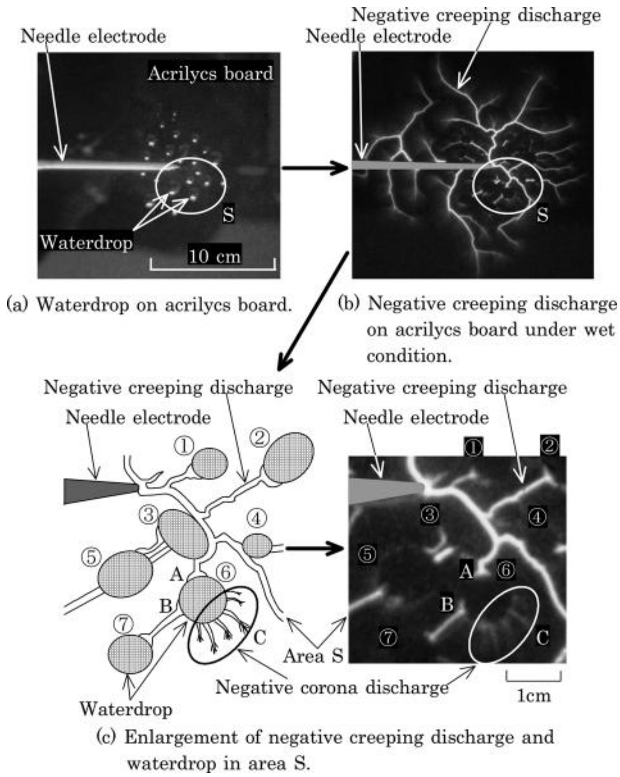

Fig. 6. Typical phenomena of negative corona discharge around surface of water drops on dielectric plate at $V_m = -40$ kV in $T_f = 1.2$ μs.

the back electrode, on which an acrylic plate (thickness 2.5 mm, size 600 mm × 600 mm, and relative permittivity 2.0) was placed; a stainless steel needle electrode (length 140 mm, diameter 5 mm, point angle 20°) was installed in the middle of the plate. When a negative impulse voltage $V_m = -40$ kV, $T_f = 1.2$ μs was applied to the needle electrode, a negative creeping discharge developed radially on the acrylic board from the electrode. In addition, water drops of the same kind as in the experiment illustrated in Fig. 1 were applied to the acrylic board. Discharge development was observed by means of a still camera provided with an image intensifier.

The conditions of negative creeping discharge development on the surface of the acrylic board with water drops are shown in Figs. 6(a) to (c). Diagram (a) shows the water drops on the acrylic board prior to voltage application. Multiple drops were concentrated around the needle electrode. Diagram (b) illustrates the general appearance of the negative creeping discharge. The leaders spread radially from the needle electrode, and some reach the water drops. Diagram (c) is a close-up view of area S. As can be seen from the diagram, negative creeping leaders branch from the needle electrode tip and arrive at water drops ①–⑦. The leader in area S originates from the needle electrode, develops in the neighborhood of water drop ③, and reaches

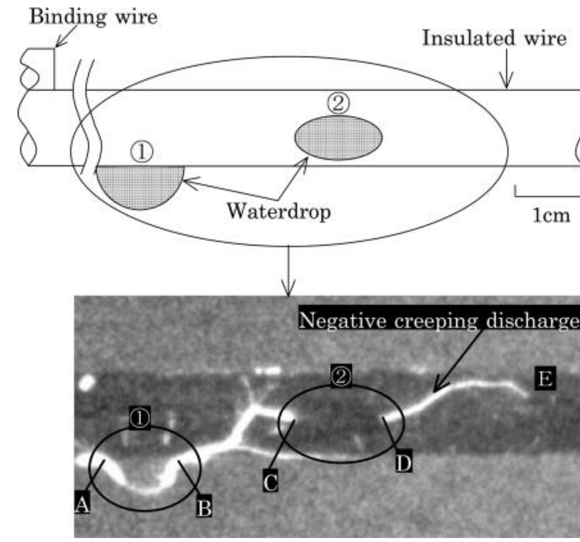

Fig. 7. Typical phenomena near tip of negative creeping discharge at $V_m = 80$ kV ($T_f = 1.2$ μs, $L = 32.3$ cm).

water drop ⑥ at point A. After that, it emerges from point B toward water drop ⑦. Multiple corona discharges occur near water drop ⑥. In addition, a slight emission is observed around water drop ⑤, which indicates a weak corona discharge. Thus, we may conclude that when a negative creeping discharge arrives at a water drop, the electric charge concentrates around the water drop and the electric field intensifies there, causing negative corona discharges on the acrylic board. If electron injection into a water drop due to a negative creeping discharge is small, and the electric field around the water drop does not rise sufficiently, then discharge development is limited to corona discharge near the water drop. However, if the electron injection is large and a local rise of the electric field occurs around the water drop, electron emission occurs and the discharge resumes on the flat surface. Similar phenomena are likely to occur when water drops adhere to an insulated wire surface. Therefore, regarding the conditions of the negative creeping discharge in Fig. 4, we may assume that the discharge develops with charging of the water drops. Our observations showed that this phenomenon occurred frequently at $V_m < 70$ kV or $T_f > 4.0$ μs.

Figure 7 shows a typical case of a negative creeping discharge when a leader proceeds along the surface of a water drop, reaches another water drop, and charges it. This example pertains to the neighborhood of the discharge tip at $V_m = 80$ kV, $T_f = 1.2$ μs, and $L = 32.3$ cm. In the diagram, ① and ② are water drops adhering to the wire. A leader developing along the wire surface reaches water drop ① at point A, proceeds arcwise on the water drop, and returns to the wire surface at point B. After that, it arrives at water drop ② at point C. Here, light emission ceases, later resuming at point D. This means that the discharge

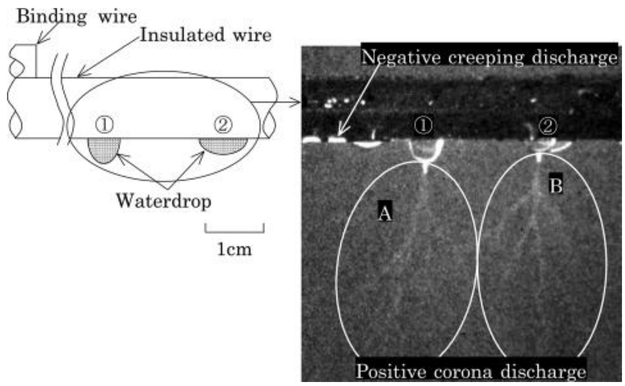

Fig. 8. Typical phenomena of positive corona discharge from tip of water drop at $V_m = 80$ kV ($T_f = 8.0$ μs, $L = 31.7$ cm).

injects an electric charge into the water drop instead of developing along its surface. After that, the development of the discharge ends at point E. Water drop ② is closer to the discharge tip than water drop ①. Our observations showed that when a water drop is close to the discharge tip, the discharge develops while charging the water drop. As a creeping discharge develops, its internal voltage drops, and the electric field at the leader tip decreases sharply immediately before discharge extinction. We may conclude that the ability to ionize the ambient air declines so that the leader cannot develop along the surface of the water drop; instead, it injects an electric charge into the water drop. Thus, the discharge develops along the surface of water drops or charges the water drops, depending on the distance from the water drop to the binding wire tip and on the combination of V_m and T_f.

(2) Origination of corona discharge from surface of water drops.

Figure 8 illustrates a corona discharge developing from the surface of water drops. In this example, $V_m = 80$ kV, $T_f = 8.0$ μs, and $L = 31.7$ cm. In the diagram, ① and ② are water drops adhering to the wire. As can be seen from the diagram, dendritic coronas A and B from water drops ① and ② occur in air. Such corona discharges occurred regardless of T_f, but were not observed at $V_m \leq 70$ kV. In addition, a corona discharge from the surface of the water drops was observed beyond the development length of the creeping discharge. These results indicate that the corona discharge from the surface of the water drops is not caused by a negative creeping discharge developing along the wire surface; this is a positive corona discharge caused by the positive impulse voltage applied to the conductor. That is, when a positive impulse voltage is applied to the conductor, the electric field on the surface of water drops increases along with the potential of conductor, the ambient air is ionized, and a corona discharge develops in the air around the wire. Thus, at $V_m \geq 80$ kV, as the negative creeping discharge develops along the wire surface, a corona discharge of the opposite (positive) polarity extends into the air from the surface of water drops.

4. Development of Negative Creeping Discharge under Wet Conditions

As shown in Fig. 2, the development length of the negative creeping discharge under wet conditions increases monotonically with V_m regardless of the value of T_f. On the other hand, under dry conditions, the development length of the negative creeping discharge is reported to have regions of both increase and decrease as V_m rises [3]. Such regions of decrease were explained by the fact that positive ions produced by collisional ionization at the discharge tip are repulsed by the positive potential of the conductor and diffuse into the ambient air. Thus, the discharge changes from the "clinging type" to the "jumping type" [9, 11]. In this investigation, we found that under wet conditions, a negative creeping discharge tends to develop along water drops on the wire surface. The relative permittivity of the wire coating material (polyethylene) used in our experiments was 2.3, while that of water drops is about 81: the relative permittivity of the water drops is about 35 times that of the wire coating. Therefore, when a discharge develops along the surface of the water drops, positive ions produced by collisional ionization at the discharge tip are adsorbed onto the surface of the water drops, which prevents their diffusion in the ambient air even though they are repelled by the potential of the conductor. In addition, the discharge does not change to the jumping type when water drops are charged during discharge development. This means that under wet conditions, the discharge develops without jumping from the wire surface, in contrast to dry conditions. This can explain the absence of decrease regions in the development length characteristics.

In the experiments conducted in this investigation, water drops were applied to the wire surface, simulating the after-rain state, and the creeping discharge was measured with the water drops stationary. In real rain, the water drops are not stationary but constantly strike the wire surface, move toward the bottom, and fall to the ground. If the speed of development of the negative creeping discharge is comparable to the speed of travel of water drops on the wire surface, then the movement of water drops may affect discharge development. If water drops move on the wire surface and fall when a negative creeping discharge develops on their surface, the discharge must migrate to the wire surface immediately before the water drops fall. In this case, the negative creeping discharge behaves as under dry conditions. Therefore, we may expect a jumping-type discharge with a shorter development length. However, the average development speed of negative creeping discharges under dry conditions at V_m = 80 kV and $T_f \leq 8.0$ μs is reported to be 5×10^4 m/s to 8×10^4 m/s [6]. In addition, considering air resistance and other factors, the falling speed of water drops is below 10 m/s [19], and therefore the development length of the negative creeping discharge is unlikely to be affected by the behavior of water drops on the wire surface, so that the water drops may be assumed to be stationary even during rain. That is, the results of this study are applicable even when water drops strike the wire surface during rain.

5. Conclusions

Both direct and indirect lightning may cause a creeping discharge on the surface of aerial insulated wires. In addition. lightning often strikes during rain, when water drops adhere to the wire surface (wet conditions). In this case, the development of creeping discharges on the wire surface is different from dry conditions. In this investigation, we created wet conditions by applying water drops to a wire surface to reproduce the after-rain state and observed negative creeping discharges by using artificial lightning surges with different T_f. Thus, we obtained new results regarding the development length of negative creeping discharge and their behavior on the wire surface under wet conditions in the case of short impulses with $T_f \leq 0.8$ μs. These results are summarized below.

(1) Development length of negative creeping discharges. At wave front durations $T_f \leq 8.0$ μs, the development length of negative creeping discharges increases monotonically with the peak value of the applied voltage regardless of the wave front duration.

(2) Discharge phenomena on wire surface. Discharge phenomena on the wire surface due to positive indirect lightning include two types, ① and ②, which are described below. In addition, type ① has two aspects, (A) and (B).

① Development of negative creeping discharge

(A) Development along surface of water drops. At peak applied voltages $V_m \geq 70$ kV and wave front durations $T_f \leq 4.0$ μs, creeping discharges near the binding wire tip tend to develop along the surface of water drops. The electric field at the discharge tip is strong and the ambient air is easily ionized.

(b) Development with charging water drops. At peak applied voltages $V_m < 70$ kV or wave front durations $T_f > 4.0$ μs, the discharge tip immediately before extinction is more likely to inject an electric charge into a water drop than to develop along the surface of the water drop. This occurs when the ionization capability declines because of weakening of the electric field at the discharge tip.

② Positive corona discharge from surface of water drops. When the peak applied voltage is $V_m \geq 80$ kV, regardless of the wave front duration T_f, a dendritic positive corona discharge develops in the air from the surface of the water drops adhering to the wire. This is because the electric field on the surface of the water drops increases with the conductor potential due to the positive impulse voltage, and the ambient air is ionized.

Negative creeping discharges may develop under wet conditions close to the surface of water drops, or may inject electric charge into water drops. For this reason, the jumping observed at the discharge tip under dry conditions is unlikely to occur. Consequently, the discharge development length increases monotonically with the peak-applied voltage. Assuming the after-rain state, we observed discharges with water drops at rest on the wire surface. However, these results also apply to rain conditions, because the speed of descent of the water drops is very slow compared to the discharge development speed. The results of this study can provide useful guidelines for insulation improvement in the wire support part and the safety of aerial distribution lines.

REFERENCES

1. Prediction of lightning sparkover rate in distribution lines. Current state and future issues. IEEJ Tech Rep No. 937, 2003 (in Japanese).
2. Lightning protection measures for distribution lines. ETRA 1985;40(6).
3. Nishi T, Hanaoka R, Ishibashi R. Impulse creeping discharge phenomena on aerial insulated wires under dry and wet conditions. Trans IEEJ 1996;116-B(4):482–488. (in Japanese)
4. Nishi T, Hanaoka R, Miyamoto T. Influence of applied impulse voltage on creeping discharges along aerial insulated wire. Trans IEEJ 1997;117-B(1):130–136. (in Japanese)
5. Nishi T, Hanaoka R, Miyamoto T. Influence of electric field strength of wire surface on creeping discharges along aerial insulated wire. Trans IEEJ 1998;118-B(1):85–91. (in Japanese)
6. Nishi T, Hanaoka R, Takata S, Miyamoto T. Influence of wave front duration of impulse voltage on creeping discharges along aerial insulated wire. IEEJ Trans PE 2003;123(1):83–89. (in Japanese)
7. Nishi T, Hanaoka R, Takata S, Miyamoto T. Characteristics of creeping discharge along aerial insulated wire under impulse voltage with various wave front durations. IEEJ Trans PE 2005;125(11):1091–1097. (in Japanese)
8. Nishi T, Hanaoka R, Takata S. Development process of positive creeping discharge along aerial insulated wire. IEEJ Trans PE 2008;128(9):1111–1118. (in Japanese)

9. Nishi T, Hanaoka R, Takata S. Development process of negative creeping discharge along aerial insulated wire. IEEJ Trans PE 2010;130(4):443–450. (in Japanese)
10. Mizuno T, Hanaoka R, Nishi T, Takata S, Kanamaru Y. Distinctive discharge generated under impulse voltage and negative creeping discharge along aerial insulated cable. IEEJ Trans FM 2010;130(11):993–998.
11. Nishi T, Hanaoka R, Takata S. Transition of progressing aspect of negative creeping discharge along aerial insulated cable. IEEJ Trans PE 2011;131(9):786–792. (in Japanese)
12. Nishi T, Hanaoka R, Takata S. Relationship between creeping discharge along aerial insulated wire and duration of wave front of inductive lightning surge. IEEJ Trans PE 2013;133(3):277–285. (in Japanese)
13. Sekioka S, Hayashi T, Miyazaki T, Sakamoto Y, Okabe S. Experimental study of influence of distribution line support system on flashover characteristics. IEEJ Trans PE 2010;130(6):566–574. (in Japanese)
14. Hirai T, Okabe S, Takinami T, Chindo T. Observation of lightning phenomena on distribution lines using composite techniques. IEEJ Trans PE 2004;124(7):956–964. (in Japanese)
15. Asano K, Miyazato K, Hara K, Shimomura T, Horinouchi Y. Study of flashover model on overhead distribution lines. IEEJ Trans PE 2003;123(11):1373–1379. (in Japanese)
16. Hongo Y, Michishita K. Estimation of sparkover rate of medium-voltage line due to indirect lightning hit taking account of correlation between peak value and front duration of return-stroke current waveform. IEEJ Trans PE 2007;127(1):292–298. (in Japanese)
17. Yokoyama S. Lightning protection of power distribution lines against direct lightning hits. Trans IEEJ 1994;114-B(6):564–568. (in Japanese)
18. Sugimoto H. Effect of overhead ground wire installation under distribution lines on surge arrester failures. IEEJ Trans PE 2010;130(5):529–535. (in Japanese)
19. Takano Y, Takehara K, Etoh T. Measurement of terminal velocity and deformation of falling raindrops using an ultra-high-speed video camera. JSCEJB 2009;65(4):332–340. (in Japanese)

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