Development of Anti-icing Coatings Applied to Insulators in China

Key words: icing, anti-icing coating, hydrophobic material, semiconducting silicone rubber, Joule effect, field operation

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Various anti-icing and de-icing methods for insulators currently being investigated in China are described in this article with particular reference to the application of semiconductive silicone rubber coatings to insulators.

Introduction

Icing of transmission lines due to extreme weather conditions has caused many failures in power networks worldwide [1]. As China has much of its land 2,000 m above sea level, intense snow and ice storms at this altitude have caused significant losses to the economy, and the harsh conditions have made life very difficult in these regions [2]. The winter of 2008/2009 was particularly harsh with freezing rain, which continued for more than three weeks in the central provinces, causing 218 ice flashovers. In particular, Hunan and Jiangxi Provinces experienced the severest storms resulting in damage to 37% of the 500-kV power transmission towers, collapsing many towers.

Considerable work has been done in China on understanding the reasons for, and preventing, the icing flashover of insulators [3]–[10], but in this article the various anti-icing and de-icing methods for insulators currently being investigated in China are discussed with particular reference to the application of semiconductive silicone rubber coatings on insulators.

Coating of Insulators With Hydrophobic Materials

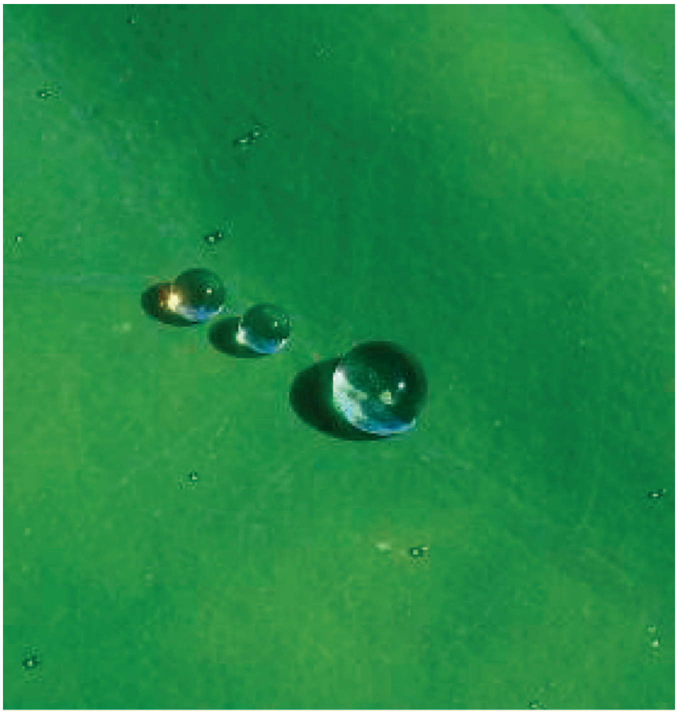
Ice accretion on insulators can drastically reduce the effectiveness of electrical insulation, leading to flashovers and outages. The irregular shape of insulators makes it difficult to develop devices for automatic de-icing. Consequently, most efforts to eliminate ice on insulator strings have focused on passive methods, such as modification of the insulator surface characteristics.

The use of hydrophobic materials on insulators cannot prevent the formation of ice, but it can reduce the adhesion of ice on insulators. As the adhesion is weak, ice will tend to slide off the surface by gravity.

An alternative approach is the use of "super-hydrophobic" coatings or surfaces in which the contact angle of water is greater than 150°. For such surfaces water droplets will easily roll or slide off the surface and are unlikely to stay in one place long enough to freeze or to adhere to the surface when they do freeze. To this end, considerable effort has been expended on improving the hydrophobicity of surfaces [11]–[15].

Conventionally, two approaches have been used to produce super-hydrophobic surfaces. The first is to create a nanostructured surface on a surface that is already hydrophobic (contact angle >90°), and the second is to modify the surface of materials already having low values of surface free energy [16]. Figure 1(a) shows water droplets on the surface of a lotus leaf, a naturally occurring super-hydrophobic surface, whereas Figure 1(b) shows water droplets on the surface of a biomimetic silicone rubber coating with a contact angle of more than 140°, fabricated in the Tsinghua University laboratory [17]. The white traces seen in Figure 1(b) are of the droplets sliding off the surface.

J. Yang et al. fabricated a super-hydrophobic surface that can be used on HV outdoor insulators [18]. The super-hydrophobic surface was obtained by combining $CaCO_3/SiO_2$ mulberry-like composite particles and self-assembly of polydimethylsiloxane (PDMS); the measured water contact angle and sliding angle



(a)

(b)

Figure 1. Super-hydrophobic surfaces: (a) lotus leaf, (b) silicone rubber with a surface mimicking the surface of the lotus leaf.

of the surface was about 164° and 5°, respectively [18]. The excellent hydrophobicity is attributed to the synergistic effect of the micron-scale roughness of the composite particles and the low surface energy of the PDMS.

Chongqing University developed a novel PDMS/nanosilica hybrid super-hydrophobic coating for anti-icing on insulators [19]. This super-hydrophobic coating has a surface with micron/nanometer dual-size structure having an average value of contact angle of 161°. In the icing experiment, icicles on the PDMS/nanosilica-coated insulator strings are short and sparse,

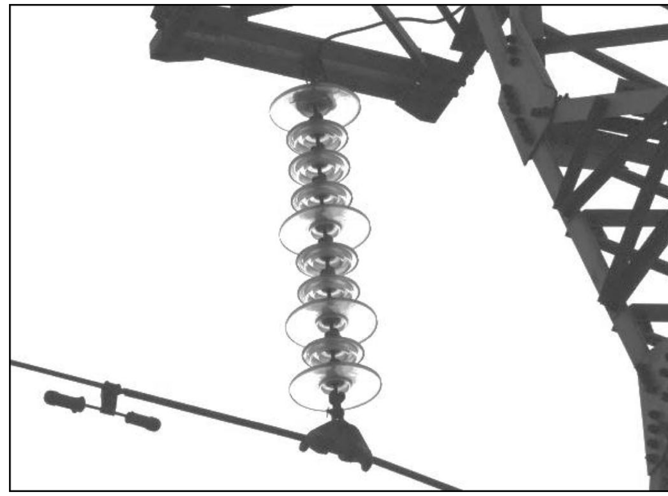


Figure 2. Increasing shed-to-shed distance at 110 kV (Yangdian Line in Guangdong).

in comparison with the ones on the untreated insulator string [20]. Furthermore, the flashover voltages of the insulators with the super-hydrophobic coating were found to be greater than for both the uncoated string and one where the insulators had a room-temperature vulcanizing (RTV) silicone rubber coating [11].

Xi'an Jiaotong University reported a simple method of producing a super-hydrophobic surface on silicone rubber by preparing moulds with surfaces of varying degrees of roughness [21]. A microstructure similar to that of a lotus leaf is formed on the silicone rubber surface and when the roughness of the surface was 6.33 μm, the static contact angle had a maximum value of 154°, and the sliding angle was 8°. However, testing of these surfaces applied to insulators, under icing conditions, has not yet been reported.

Dimensional and Orientation Approaches

Some mitigation methods used for improving the icing performance in the field are increasing the shed-to-shed distance (Figure 2) and changing the insulator orientation (Figure 3), which decreases ice bridging under icing conditions [22]. These two methods are not only used for porcelain or glass insulators,

Figure 3. Changing insulator orientation at 220 kV (Guanlang Line in Guangdong).

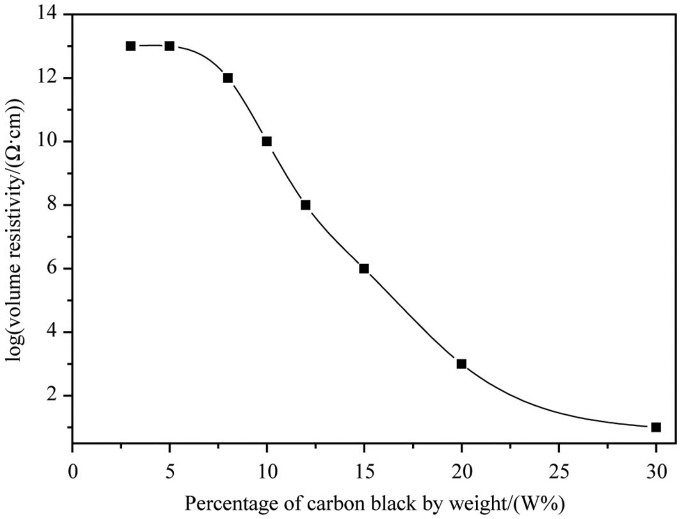
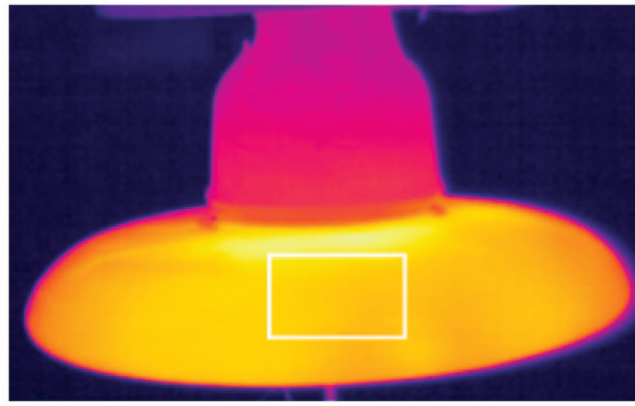
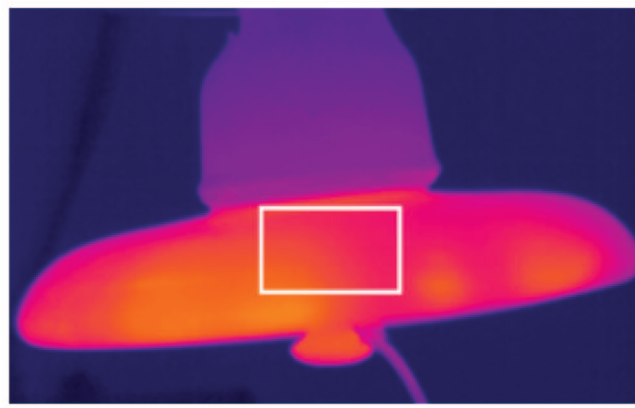


Figure 4. Volume conductivity of RTV coating with carbon black filler.



Ambient temperature (ºC)	18
Average temperature in the white rectangular box (ºC)	24



Ambient temperature (ºC)	−6
Average temperature in the white rectangular box (ºC)	19

Figure 5. Temperature of the insulator surface in two ambient conditions, −6 and 18°C [31].

but also for designing new composite insulators [23], [24], with some success.

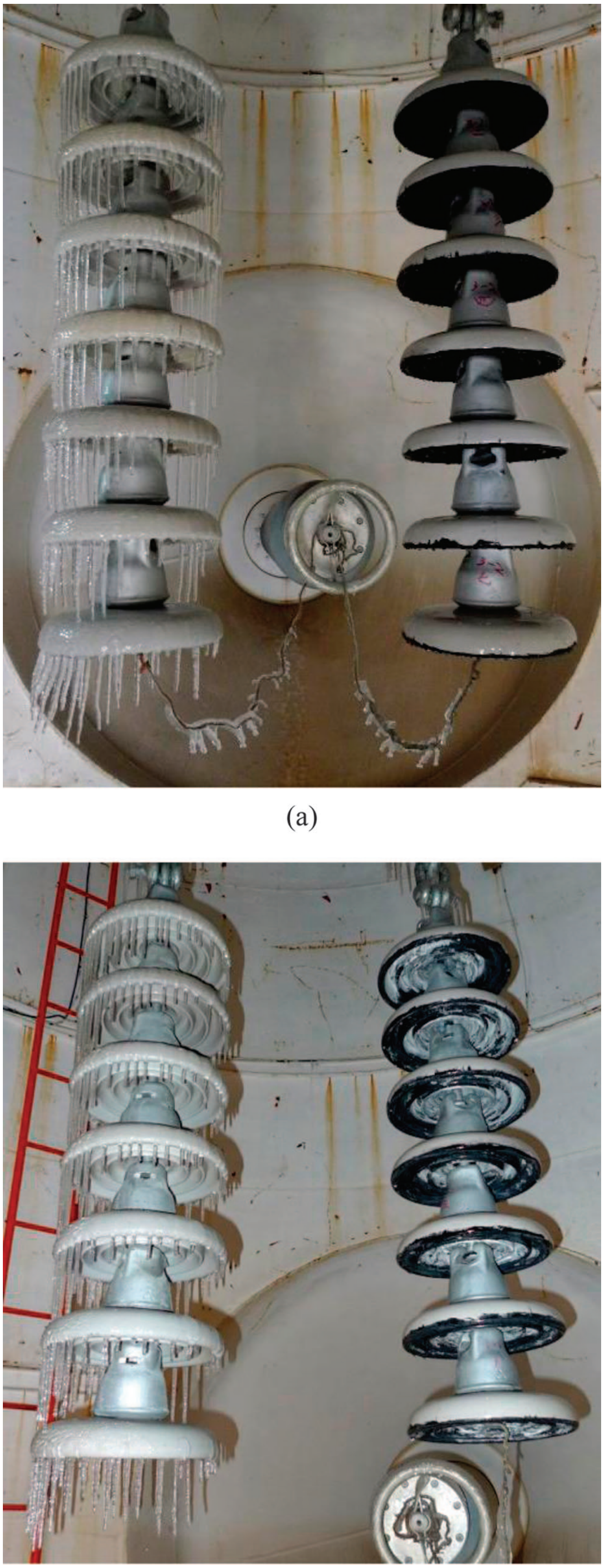
Semiconductive Silicone Rubber Coatings

Because of their long-lasting pollution-flashover resistance and good hydrophobicity, RTV coatings are widely used to improve the electrical performance of insulators under polluted conditions [25]. However, regarding anti-icing performance, mixed results have been reported; one study showed reduced ice accretion on insulators [26], yet another has shown a lower icing flashover performance [2].

It is well known that semiconducting porcelain insulators show higher flashover voltages than conventional porcelain insulators due to drying of the surface by Joule heating, and by a more uniform voltage distribution along the insulator, and

Configuration						
Coating types	No coating	Normal RTV coating	A	B	C	D
Leakage current mA	0.37	0.23	0.43	0.97	1.36	4.78

Figure 6. Comparative views of icicle formation on three-unit strings energized at 15 kV for various surfaces including no coating, normal room-temperature vulcanizing (RTV) coating, and semiconductive coatings A, B, C, and D having increasing values of leakage current [32].



(a)

(b)

Figure 7. Icing of insulator strings: (a) clean and (b) contaminated strings, with and without semiconducting silicone rubber coating applied to the bottom surface of the insulators.

considerable work was done on this in the 1970s [27]–[29]. However there have been problems with thermal runaway and damage to the glaze by surface discharges, which greatly reduced their effectiveness.

Silicone rubber (SiR) coatings are made partially conductive by adding conductive fillers, such as carbon black and carbon fibers, into normal RTV silicone rubber [30]. Such materials are widely referred to, although inaccurately, as "semiconducting" coatings as their electrical conductivity is dependent on the type and the volume concentration of the conductive particles. At low concentrations the conductive particles are mostly separated by the insulating polymer, but as the concentration increases to percolation, conductive networks form within the polymer matrix. Consequently, the resistivity decreases quickly for concentrations of 10 to 20% as shown in Figure 4 [30].

The carbon-filled SiR hydrophobicity and hydrophobicity transfer are not affected by the small percentage of carbon which tests to decrease the adhesion force between the ice layer and the material surface [30]. Additionally, Joule heating generated by the partially conducting coating delays the formation of ice.

Fully Coated Insulators

As current flows through the partially conductive coating, Joule heating increases the surface temperature until an equilibrium temperature is reached, and the warm surface discourages the accretion of ice on the insulator surface. Figure 5 shows the surface temperature at two ambient temperatures and for dry conditions where it can be seen that surface temperature of the insulator in an ambient temperature of −6°C is 19°C.

Figure 6 [32] shows the results of artificial icing experiments on three-unit porcelain insulator strings with no coating, normal RTV coating, and four semiconducting coatings, A, B, C, and D, having increasing values of leakage current. In these experiments the insulator strings were energized at 15 kV in an ambient temperature of −4°C for four hours prior to water being sprayed into the chamber for three hours while the leakage current was

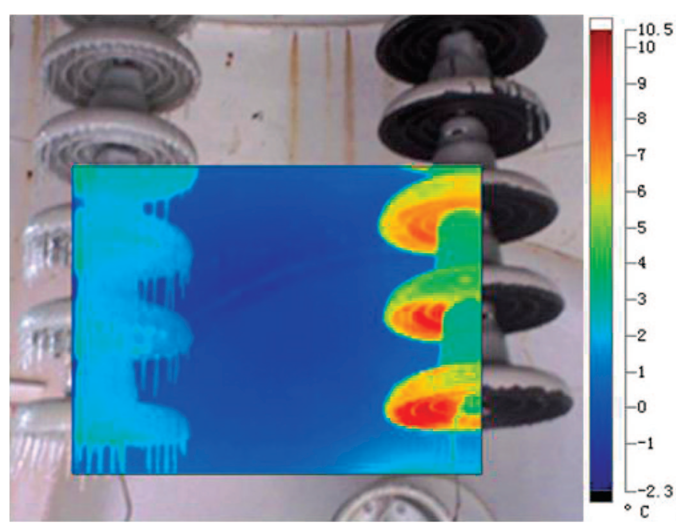


Figure 8. Thermal image superimposed on visual image of insulators in the icing test; left, uncoated insulators; right, insulators coated only on bottom surface.

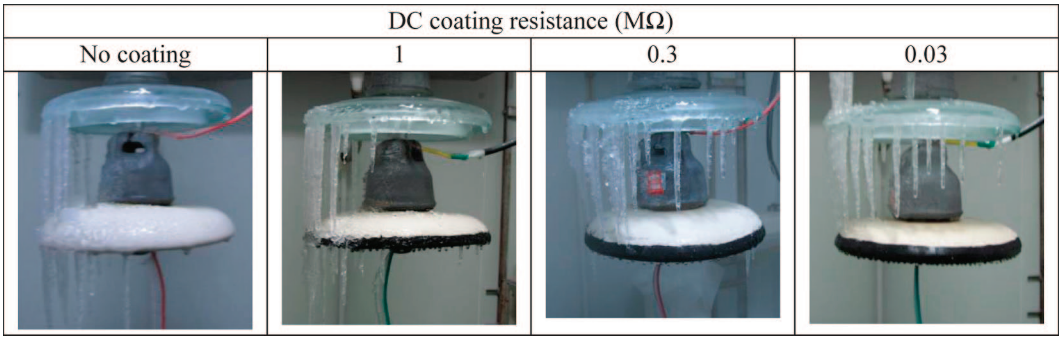


Figure 9. Anti-icing performance after two hours at −6°C of bottom-coated insulators (bottom unit) energized at 5 kV as a function of coating DC resistance.

recorded. The photographs in Figure 6 were taken 30 minutes after the water spraying had stopped, allowing for stabilization.

It can be seen that the lengths of the icicles on insulators with coatings A through D are significantly shorter than those on insulators without coating or normal RTV coating, and clearly the anti-icing performance improves with increasing leakage current through the semiconductive coatings.

Coating Only on the Lower Surface of the Insulators

A disadvantage of having a semiconducting coating on insulators is the high power loss under normal conditions when heating is not required. One solution to this is to apply the semiconducting coating to the underside of the insulator, thereby preventing power loss under normal conditions but allowing for heating when there is sufficient conductivity from the pollution and water on the upper side of the insulator [33].

Seven-unit insulator strings, with and without the underside coated with semiconductive silicone, were tested for icing in a climate chamber at −7°C for two hours and with 63.5 kV applied to the strings. The solid layer method, using a mixture of common salt (NaCl) and Kaolin, was used for applying the artificial pollution. The values of soluble deposit density and nonsoluble deposit density were 0.1 and 0.6 mg/cm^2, respectively. As can be seen in Figure 7, ice bridging on the uncoated strings is evident, whereas the bottom surface semiconductive strings show little or no icicles. This was found for both the clean and polluted insulator strings.

Figure 8 shows the uncoated insulator string was at about −6°C ambient temperature, but the coated string reached 10°C.

Additionally, the anti-icing performance was greatly affected by the DC resistance of the bottom coating. In a further experiment, insulators energized at 5 kV were subjected to the simulated freezing rain test at −6°C. The results after two hours showed good anti-icing performance for coating resistance below about 0.3MΩ (Figure 9). However, this was only found to be effective for glaze ice but not for rime ice, but coating both upper and lower surfaces was found to be effective for rime ice (Figure 10).

When there is no water runoff from the top- of bottom-coated insulators; the high resistance of the water layer makes the bottom-coated insulators ineffective for anti-icing. This is apparent in Figure 10 in which the water conductivity is 50 μS/cm and higher, showing that the bottom-coated insulators are effective for rain water with conductivity above 50 μS/cm.

Flashover Test and Voltage Distribution

The flashover of single insulators with semiconducting coating on the underside was tested using the solid layer method and the constant voltage up-and-down test method. The soluble

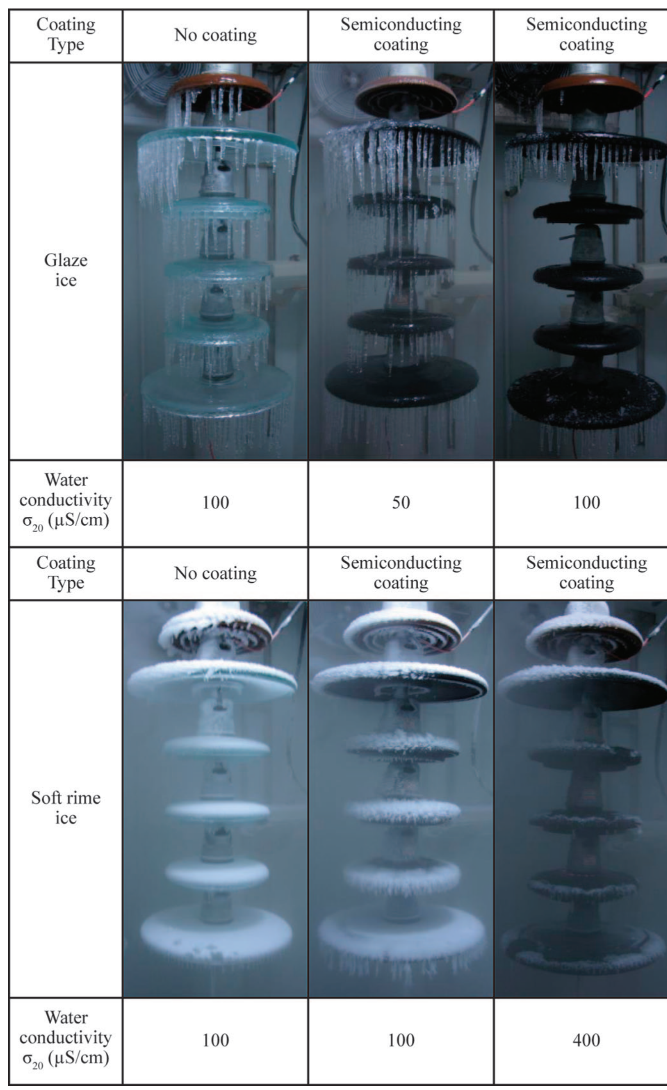


Figure 10. Glaze and soft rime anti-icing performance for bottom-coated insulators with DC resistance of 0.03 MΩ in an ambient temperature of −6°C.

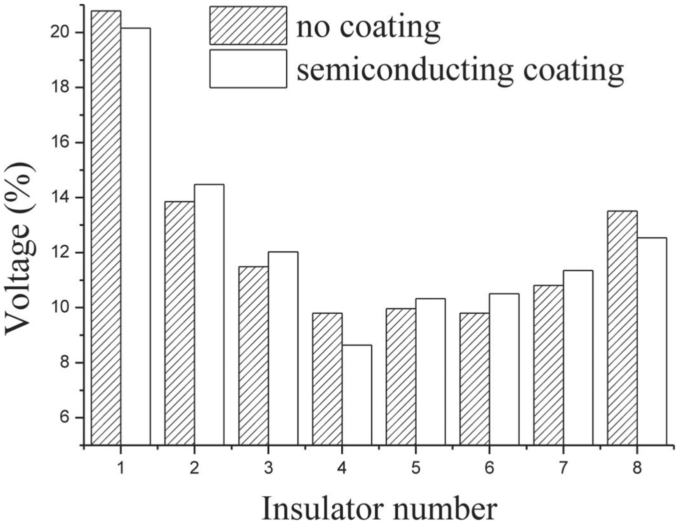


Figure 11. Potential distribution along coated and uncoated insulator strings as a percentage of the applied voltage. Unit 1 is the grounded end.

(a)

(b)

Figure 12. Site work: (a) spray-painting insulator strings in situ and (b) spray-painting insulator strings for replacement.

deposit density and nonsoluble deposit density were selected as 0.05 and 0.5 mg/cm^2, respectively, simulating a moderate pollution area. The tests revealed U_{50} of insulators was 59% higher, rising to about 22 kV/unit, compared with 14 kV for the insulators without a semiconducting coating [34].

The potential distribution was also determined under service voltage by measuring the voltage across each insulator along eight-unit strings. The applied voltage was 63.5 kV. Comparative results for coated and uncoated strings are shown in Figure 11. As expected, the potential distribution along the coated string was somewhat more uniform than along the uncoated string.

Table 1. The Guandong and Yunnan Grid Transmission Lines for Anti-icing Insulator Coating Trials.

Grid	Voltage level (kV)	Transmission line	Towers
Guangdong	220	Pingtong	5
		Guanlang	5
	110	Shuiji	5
		Damei	5
		Huangshui	5
		Tanshui	5
		Mingnan	5
		Yangdian	2
	35	Huixijia	2
		Lianhe	2
	10	Gaoshangan	1
Yunnan	110	Taoli	1

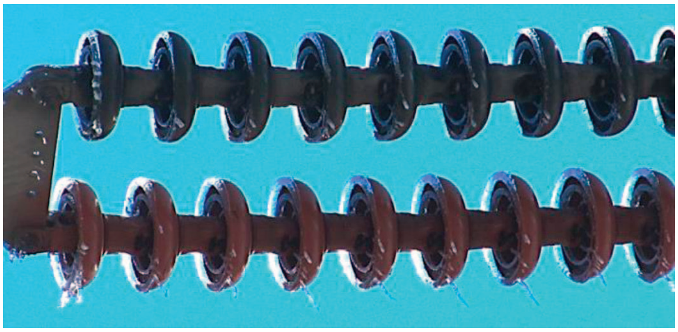


Figure 13. Comparison of the anti-icing performance of semi-conducting SiR coating on the bottom surface of insulators (upper string) and a normal SiR coating on insulators (lower string).

Field Application of Anti-icing Coatings

The semiconducting SiR coating has been used in a few short sections of Guangdong and Yunnan Grid transmission lines (Table 1). These lines are mostly at high altitude and in areas that tend to have smog and high humidity.

Two methods were adopted for spray-painting insulators in the field for a trial. Only the bottom surfaces of the insulators were painted with semiconductive SiR coating. Tableure 12(a) shows coating by spraying the insulator strings in situ, whereas Figure 12(b) shows coating the insulator strings on the ground for direct replacement. The coating uniformity and quality is much better using the latter method, but the installation costs are much higher.

Figure 13 shows icicles on the semiconductive SiR–coated (upper) and normal SiR–coated (lower) strings in freezing-rain conditions. It can be seen that the number and lengths of the icicles on the insulators in the upper insulator string are considerably smaller and shorter than on the insulators in the lower string, showing that the SiR coating is heating the insulators.

In the field trials, leakage current and meteorological acquisition devices were installed on one tower of the Yangdian Line of the Guangdong Grid. Figure 14 shows the leakage current from two phases over the period January to March 2011. The leakage current is seen to increase between 5 and 20 mA during the supercooled water rain but drop between 1 and 2 mA during fair weather so the power loss is quite low.

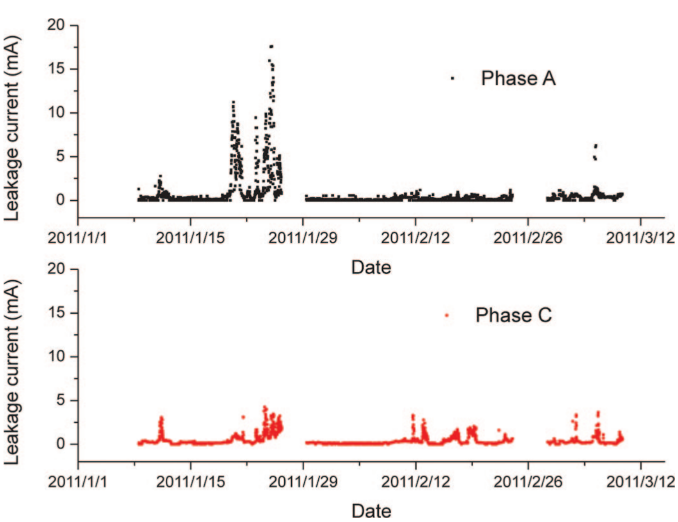


Figure 14. Leakage current on phase A during freezing rain and on phase C during fair weather.

Conclusions

This article summarizes some of the recent work on anti-icing coatings done on insulators in China, and the following can be concluded.

- Considerable progress has been made in developing super-hydrophobic surfaces for insulators, although little field testing has been done to date.
- The application of semiconducting SiR to insulators in both laboratory and field tests has been shown to improve in the electrical performance of insulators under icing conditions.
- Joule heating generated by semiconducting SiR coatings increases the surface temperature and reduces or eliminates the formation of glaze ice on insulators.
- The application of semiconducting SiR coating to the underside of insulators reduces ice accretion while controlling power loss, but the method is only effective for glaze ice and is sensitive to both the conductivity of the SiR coating and the water.

Acknowledgments

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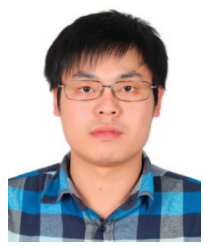

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