Research progress on uhv insulator functional coatings

ChaoFeng¹, Yungen Liu², Huisheng Ye¹, Yi Xie¹, Yi Long¹, Lian Hu¹ and Jun Wang¹

¹State Grid Hunan Electric Power Company Limited Research Institute, Changsha 410007, China
²State Grid Zhuzhou Power Supply Company, Zhuzhou, 412000, China
*Corresponding author’s e-mail:676459812@qq.com

Abstract. It is of great significance to develop functional coatings for uhv transmission lines which according to the working conditions and service environment to improve the safety, stability and economy of uhv transmission lines. This paper focuses on the latest research progress of uhv insulator functional coatings in recent years, including anti-fouling flashover coatings and anti-icing coatings. The preparation methods, main performance parameters, application conditions and existing problems of the two coatings were thoroughly discussed and the future development and research direction were also pointed out.

1. Introduction
With the wide application of uhv transmission lines, the operation and maintenance protection of hv insulators is essential for ensuring the safety of transmission lines and maintaining the stability of power system. Due to the imbalance of resource distribution and power load in China, only "west-to-east power transmission" can solve the growing energy gap in the central and eastern regions, that is, the secondary regulation of power supply and load can be effectively realized through ultra-high voltage transmission [1-2]. Two-thirds of China's national area is terrain with high altitude, and the average altitude of the large plateau area is more than 1000m. Therefore, uhv insulators inevitably have to deal with the challenges of the harsh external environment in the high altitude area during operation [3]. Compared with plain area, insulator pollution flashover and ice cover are more prominent in high-altitude area. Therefore, the development of insulator functional coating has become one of the key factors affecting the safe and stable operation of uhv transmission lines. Therefore, this paper summarizes the research progress in the development of uhv transmission line insulator functional coatings in recent years which emphasizing on the preparation of insulator functional coatings and their corresponding properties, in order to point out the direction for the development and research of uhv transmission line insulator functional coatings.

2. Anti-contamination flashover coatings
RTV is a new antifouling flashover coating synthesized from polysiloxane (or organosilicone). In the service process, due to the rapid aging of RTV coating, adding inorganic oxide can significantly improve the anti-aging performance, thus extending the service life of the coating. Therefore, inorganic oxides with high contact Angle for pollutants can be selected as antifouling flashover coatings. Guo Kai et al. enhanced the anti-flashover performance of k-rtv by adding nano silica particles and prepared a new anti-flashover coating [4]. Through a series of comparative experiments, the results show that when the content of nano SiO₂ is 30%, it has the best morphology characteristics
under atomic force microscope (AFM). At the same time, the obvious difference in morphological characteristics between k-rtv and RTV shows that k-rtv has more ordered microstructure than RTV, indicating that k-rtv has a higher ordered microstructure. As shown in figure 1, when k-rtv coating is applied on the glass surface, the water contact Angle on the solid surface reaches 147°. The increase of the contact Angle between water and glass surface makes it easier to clean the contaminants on its surface.

![Image](image_url)

**Figure 1. The contact angle test of K-RTV [4].**

Jing Hai et al. prepared a super-hydrophobic RTV coating with anti-pollution flashing property by filling CaCO\(_3\)/SiO\(_2\) composite particles into polydimethylsiloxane rubber. The prepared RTV coating has good hydrophobicity to the surface of the insulator, which can prevent the surface hydration of the insulator formed by continuous water film. The test results of pollution lightning voltage of insulators in different states showed that the average pollution lightning voltage of insulators coated with superhydrophobic RTV coating was 29.95kv, which was much higher than that of insulators coated with ordinary RTV coating (23.29kv) and those without RTV coating (11.34kv). The hydrophobicity test results show that the water contact Angle on the RTV coating is 165°, and the rolling Angle of water droplets is about 5°, which makes the water droplets move easily on the surface of the coating and has the function of self-cleaning [5].

Zhuang et al. proposed a new nano titanium dioxide photocatalyst for improving the anti-pollution flashover performance of ceramic insulators in uhv dc lines under pollution conditions [6]. TiO\(_2\) coated insulator was prepared by spraying a certain amount of TiO\(_2\) sol on ceramic insulator and calcining. The physical and chemical properties of titanium dioxide films were studied. The effects of titanium dioxide films on the self-cleaning and electrical properties of ceramic insulators were evaluated. Compared with the uncoated insulator, the prepared titania coated insulator has stronger self-cleaning ability in heavy pollution environment due to its excellent photocatalytic performance. In addition, TiO\(_2\) coating, as a semiconductor, can also improve the field strength distribution of insulator strings. The TiO\(_2\) coating prepared in the experiment can not only promote the self-cleaning function of the insulator, but also maintain or even improve the high-voltage electrical performance of the insulator string. Moreover, due to the reduction of pollutants on the surface of the insulator coated with TiO\(_2\) coating, the occurrence of pollution flashover can be effectively inhibited.

Jia et al. developed a silica-based antifouling flashable hard coating with self-cleaning function in order to solve the problem of large amount of fouling on the surface of ordinary RTV coating. A series of comparative tests were carried out to analyze the improvement of self-cleaning performance of silicone hard coating compared with ordinary RTV coating [7]. Test results show that the tiny impurity particles adsorption ability of silicone carbide coating improved enormously. Although the hydrophobic mobility of prepared sample exhibite no obvious improvement than normal RTV coating, the hydrophobic enhanced to some degree even in high humidity environment medium and long-term service.
In order to solve this problem, Huang et al. added coupling agent to improve the dispersion of color filler, and prepared a new type of antifouling flaring fluorocarbon coating by mixing fluorocarbon resin, self-made mixed solvent, color filler, auxiliary agent and curing agent [8]. Fluorocarbon resin with excellent weatherability was selected as the film forming material, and rutile nano TiO$_2$ with anti-uv aging was added, which greatly improved the aging resistance of the coating. How to improve the performance of the anti-pollution flashover fluorocarbon coating was emphatically studied from three aspects, such as the optimization of coupling agent, the way of adding modified nano filler and the choice of defoaming agent. The nano-inorganic particles were modified by using titanate coupling agent. Further comprehensive electrical properties of the test results show that the new anti-pollution flashover dope the volume resistivity of $2.48 \times 10^{10} \, \Omega \cdot \text{m}$, breakdown voltage is 21.1 kV/mm, the relative dielectric constant and dielectric loss tangent value were 6.08 and 0.106, dielectric strength is 18.1 kV/mm, at the same time, the coating of light rate can reach 98%.

Uhv transmission lines were often located to cross high-altitude and heavily polluted areas. In this case, the pollution flashover problem of insulators is the first to be solved, because the pollution flashover voltage will decrease as the altitude increases. Huang et al. applied the photocatalytic technology to coat the surface of porcelain/glass insulator with a layer of TiO$_2$ coating by utilizing the characteristics of TiO$_2$ being non-toxic, with stable catalytic activity and preparation of containers [9]. When exposed to sunlight, TiO$_2$ photocatalytic coating automatically absorbs ultraviolet light and dissolves organic/inorganic pollutants adsorbed on its surface, so as to reduce the oil-wet performance of external insulation, maintain self-cleaning state for a long time and improve anti-pollution flashover performance. Insulator covered a photocatalytic coating exhibit an average mechanical and electrical damage load of 104 kN, load abrasi on and test the amount of 0.002 g, puncture resistance power frequency voltage larger than 120 kV. At the same time, the net wet flashover test results prior to its service show that the average wet power frequency flashover voltage is 294 kV which increased by 15.7% than ordinary insulator.

Yan et al. prepared a new type of super hydrophobic anti-flashover coating with good wear-resistance by taking advantage of the characteristics of low surface energy and micro-rough surface of polymer and using methyl silicone resin as the film forming material [10]. As the Si-O bond in methyl silicone has a bond energy of up to 450kJ/mol, and there is no unsaturated bond in the main chain structure with low carbon content, it has the characteristics of good thermoplasticity and excellent mechanical properties. The preparation of super hydrophobic antifouling flash for the binary structure of micro/nano composite coating surface, randomly scattered distribution of 1~5 microns micron grade bumps in nanoscale processes studded with 50~100 nm. The surface of the water droplets in the super hydrophobic antifouling coating appearance was as shown in figure 2 during hydrophobic test. The water volume is 10 μL with an average static contact Angle of 157.2° and contact Angle hysteresis average of 2.3° which implying that super hydrophobic antifouling flash has more excellent super hydrophobic coating performance. With 200g weight as wear load and 1500 mesh sandpaper as wear contact, the mechanical wear resistance of the coating was evaluated, as shown in figure 3. Further pollution flashover performance test showed that under severe pollution condition, the decrease range
of power frequency pollution lightning pressure was only 17.0%, far lower than the 30.9% decrease range of ordinary RTV under the same condition. At the same time, the test results show that the critical leakage current of the superhydrophobic coating is only 84.7mA, far lower than 104mA of RTV insulator string and 1187.1mA of exposed glass insulator string. According to the results of pollution flashover test and flow passage test, the new coating of methylsilicone resin has excellent anti-pollution flashover performance, which can be widely used in uhv transmission channel crossing the seriously polluted area.

3. Anti-contamination flashover coatings

One of the major problems for power systems in cold climates is line icing caused by extreme weather such as freezing rain, freezing in clouds, frost and wet snow. Ice covering of transmission lines and insulators may cause line tripping, line fracture, tower and pole fault, conductor dancing, insulator flashover and communication interruption, which may lead to huge economic losses. Because the icing of transmission lines and insulators will bring great risks, in recent years, a lot of research has been carried out on anti-icing of lines and insulators [11-12].

Fang et al. declared the design of anti-icing coating from the theoretical level, and proposed to combine hydrophobicity and semiconductor characteristics to achieve the best anti-icing effect of coating [13]. The higher the hydrophobicity of the semiconductor silicone rubber, the lower the adhesion between the ice cover and the coating surface in extreme weather, so the initial ice cover is difficult to tightly adsorb on the insulator coating. At the same time, water exist as random spread of small water droplets on the hydrophobic surface rather than the form of a continuous water film due to the surface hydrophobic structure of polymer coating. With the increase in volume, most of the coating surface water droplets will slide leading to water volume that can be converted into film greatly reduced. On this basis, the semi-conductive property of the coating itself is used to increase the heat output of the insulator and make the surface temperature rise to prevent the surface from icing. When the power is on, the leakage current flows over the coating surface and generates joule heat, which causes the surface temperature of the insulator to rise. The porcelain insulator itself also generates medium loss and heat in the strong electric field, which further causes the temperature of the insulator to stay away from the freezing point. A large number of tests have proved that, on the premise of fully guaranteeing the electrical characteristics of insulators, increasing the heat on the surface of insulators is conducive to preventing the formation of ice on the surface.

Zuo et al. prepared the organic resin /SiO2 superhydrophobic coating on the glass substrate by using the nano-particle filling method [14]. The static contact angle reached 161.1±1.3°, and the rolling angle was less than 1° which possessed good hydrophobic properties. The microscopic characterization results of the coating showed that with the addition of SiO2, a cross-linked three-dimensional network structure was formed on the surface of the composite coating, and nanoscale protrusions were scattered on the micron protrusions. The existence of these "hover-like" structures directly reduces the effective contact area between the droplets and the coating, thus achieving superhydrophobic effect. In order to simulate in close to the actual service conditions of the parameters, the use of multi-function artificial climate laboratory simulation of the snow conditions under the ice performance test were applied. The experimental environment temperature control is 5°C, water temperature is set as 4±1°C. After 80 minutes of the experiment, the comparative analysis showed that although 90% of the surface of the insulator coated with anti-icing coating was covered with ice, the weight of the icing was only 51% of that of the ordinary insulator which indicating that the coating had excellent anti-icing performance and could effectively reduce the icing area and weight.

Wei et al. developed a new ice-proof model for insulator coating based on the electrothermal ice-proof method by forming an instantaneous through-flow loop between the over-cooled water droplets on the surface of the insulator and the coating during operation [15]. During the coating process, suitable conductive fillers such as carbon fiber or zinc oxide are added to the substrate to form a semiconductor coating. Considering the presence of pollutants in the atmospheric environment,
raindrops falling on the surface of the insulator generally have a certain conductivity which can act as a pass-through medium, and then form a complete instantaneous pass-through loop with the gold tool and conductive coating. In the process of operation, if there is a certain amount of water on the surface of the insulator, the circuit will be switched on instantaneously, and if there is no water, the circuit will be disconnected, that is, the so-called "breaking effect" is realized. Artificial climate chamber simulation parameters are set as follows, the temperature is 6°C, the diameter of the water droplet is 25 ~ 35 microns, water flow is 0.129L/min, water content is 3.58g/L, injection angle is 80°, the sample distance from the nozzle 0.7 ~ 0.9m. The test results show that there is basically no leakage current on the surface of the clean insulator string in the whole test process, and the average leakage current of the coated insulator designed as "breaking effect" is 8mA, which shows a good ice-proof effect.

In addition to the use of hydrophobic functional groups or micro-nano structure of polymer to design anti-icing coating, and the use of physical and chemical methods to enhance the thermal effect of coating to achieve the effect of melting ice by modification to reduce the freezing point is also an effective method. Based on this idea, Zhang et al. conducted a large number of screening of organometallic compounds in order to find an additive that can reduce the freezing point of water [16]. When the target additive reacts with water, it releases small organic molecules that lower the melting temperature and forms metal oxides. On the one hand, the released small organic molecules have a greater polarity difference from the main components of organic coatings, so they will self-agglomerate and penetrate through the ice-coating interface into the ice under the guidance of intermolecular force, lowering the freezing point of water to melt the ice. On the other hand, the presence of liquid water promotes the development of the dynamic reversible reaction towards the direction of accelerating the hydrolysis of organometallic compounds, which further releases the small organic molecules and promotes the melting of ice.

Although the coating of semiconductor on the insulator can effectively prevent the icing, there is a disadvantage, that is, when operating in normal conditions that do not need heat, there will be a large loss of energy. To solve this problem, Wei et al. coated the insulator below with a semiconductor coating, which could avoid energy loss under normal working conditions [17]. However, when enough current passed through the pollution and water above the insulator, the leakage current would generate heat to melt the ice. Under the environment of -7°C, 63.5kv voltage was applied to the lower coated semiconductor silicone and the 7 unit insulator string without coating, respectively. NaCl and kaolin were selected as the common mixture for artificial synthesis of pollutants, and the soluble and insoluble deposition density values were 0.1mg /cm² and 0.6mg /cm², respectively. The results show that there is an obvious ice bridge on the uncoated insulator, while there is only a small amount of ice on the insulator coated with semiconductor anti-ice coating. In addition, the lower coating of the DC resistance on the ice resistance performance is also greater. In ice prevention trials, when under 5 kv voltage insulator in freezing rain - 6 °C, the lower the DC resistance of coating was 0.3 MΩ, two hours later, the ice on the insulator is less. However, experiments have proved that this coating method is only effective for rime, but not significant for frost and ice. However, it is also effective to prevent frost and ice by coating the whole surface above and below the insulator.

4. Conclusions
1) By coating or plating anti-pollution flashover coating on the surface of the insulator, the surface hydrophobicity can be improved, and the surface oil-wet performance of the insulator can be reduced, the adsorption of tiny particles can be significantly reduced, and the anti-pollution flashover ability of the insulator can be effectively improved.

2) The ice coating plays a role on the basis of the principle of interface super hydrophobic on the insulator surface forming a layer of super hydrophobic coating, or by the electrothermal effect of semiconductor coating, or adding additives to reduce the freezing point of water to achieve the effect
of ice prevention. These above method can reduce the ice area, the weight of ice to a certain extent, improving insulator ice pressure and to reducing lightning ice adhesive strength.

Acknowledgment
The research was supported by State Grid Hunan Electric Power Company Limited Research Institute (Project No. 5216A019000H, Project No. 52153219000F).

References
[1] Zeng Q.Y. (2012) Study on power transmission capability of 1000 kV ultra high voltage transmission system. Power. Sys. Techno., 36: 1–6.
[2] Ma Q.Y., Zheng B., Ban L.G., Xiang Z.T. (2015) Secondary arc current analysis of an untransposed EHV/UHV transmission line with controllable unbalanced shunt reactor. IEEE T. Power Deliver., 30:1458-1466.
[3] Li B., Guo F.R., Li X.B., Bo Z.Q. (2014) Circulating unbalanced currents of EHV/UHV untransposed double-circuit lines and their influence on pilot protection. IEEE T. Power Deliver., 29:281-304.
[4] Guo K., Du Y.S., Wu Y.P., Mi X.C., Li X.G., Chen S.H. (2017) Morphology and FT-IR analysis of anti-pollution flashover coatings with adding nano SiO₂ particles. Mater.Sci. Eng.,274: 012031.
[5] Jing H., Jin X.Y., Jang C., Zhuo R.Y. (2011) Preparation and performance of RTV coating for anti-pollution flashover with superhydrophobicity by filling CaCO₃/SiO₂ composite particles into silicone rubber. Adv. Mater. Research, 328- 330:1263-1267.
[6] Zhuang J.D., Liu P., Dai W.X., Fu X.Z. (2010) A novel application of nano anticontamination technology for outdoor high-voltage ceramic insulators. Inter. J. Appl. Ceram. Tec., 7: E46-E53.
[7] Jia Z.D., Wang W., Zhang Q.L., (2012) Self-cleaning hard coating of insulator for the usage of anti-pollution flashover. High Voltage Eng., 38: 2044-2050.
[8] Huang J., Zhou Y.Y., Zhu Z.P., (2014) Study on preparation and application of anti-pollution flashover fluorocarbon coatings. Paint & Coating Industry, 44:25-30.
[9] Huang H., Cai X.B., Hu J.T. (2014) Application of photocatalytic induced self-cleaning insulator in high altitude heavy pollution areas. Yunnan Electric Power, 42:78-81.
[10] Yan X.Z., Li L.Y., Li J. (2018) Anti-pollution flashover performance of methyl silicone resin superhydrophobic coating. High Voltage Eng., 44:2835-2843.
[11] Wang Y.Y., Xue J., Wang Q.J., (2013) Verification of icephobic/anti-icing properties of a superhydrophobic surface. ACS Appl. Mater. Inter., 5: 3370-3381.
[12] Yang S.Q., Xia Q., Zhu L., (2011) Research on the icephobic properties of fluoropolymer-based materials. Appl. Surf. Sci., 257: 4956-4962.
[13] Fang Z.Y., Chen F., Meng X.D., (2015) Study on the design for RTV coatings of semiconducting anti icing. Northeast Electric Power Techno.,11:31-33.
[14] Zuo Z.P., Liao R.J., Guo C., (2015) Fabrication of superhydrophobic surface on insulator and its anti-icing properties. J. Electr. Eng., 10:99-105.
[15] Wei X.X., Jia Z.D., Sun Z.T., (2012) An anti-icing method with switch-off effect for glazed ice on insulators. Proceedings of the CSEE,32:186-192.
[16] Zhang R., Yi H., Wan X.D., (2012) Icemelting type of anti-icing coating for transmission line insulators. Insulating Mater., 45: 22-26.
[17] Wei X.M., Jia Z.D., Sun Z.T., (2012) Study of anti-icing performance of insulator strings bottom-coated with semiconductive silicone rubber coating. IEEE T. Dielect. El. In.,19:2063-2072.