Review of Research on Surface Contamination Characteristics of Composite Insulators

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Abstract: The accumulation of contamination on the surface of composite insulators is the key cause of its insulation performance degradation and pollution flashover accidents. A comprehensive understanding of pollution components and their electrical effects is the basis for accurate assessment of insulator status. In this paper, the contamination is divided into two categories: soluble and insoluble, and the analysis methods and research progress of the two are systematically reviewed. In terms of soluble substances, the measurement principle, engineering value and limitations of equivalent salt density (ESDD) are described. The application of ion chromatography (IC) and inductively coupled plasma emission spectroscopy (ICP) in the fine analysis of ion and cation components is emphatically introduced, and the quantitative relationship between soluble components and ESDD is discussed. In terms of insoluble, the physical significance of NSDD was summarized, and the progress of X-ray diffraction (XRD) in the identification of contaminated phases and X-ray fluorescence spectroscopy (XRF) and energy spectrum analysis in the study of elemental composition was reviewed. On this basis, the necessity of multi-means joint characterization is emphasized, and the existing problems and future development directions in current pollution assessment are pointed out.

Keywords: Outdoor Insulation; Composite Insulator; Surface Filth; Soluble; Insoluble

1. Introduction

As of 2025, the number of composite insulators in service in China 's power grid has exceeded 10 million, and its operational reliability is directly related to transmission safety. Although composite insulators have excellent anti-pollution flashover ability due to the hydrophobicity and hydrophobic migration characteristics of silicone rubber materials, the surface will inevitably accumulate pollution during long-term exposure to outdoor environments. When the pollution layer is wet under the conditions of fog, dew and rain, the soluble electrolyte dissolves to form a conductive liquid film, and the leakage current increases sharply, causing local arc, which may eventually lead to penetrating flashover. According to statistics, pollution flashover accidents account for a relatively high proportion of the total number of power system accidents, and their harm cannot be ignored [1-4].

Contamination can be divided into two major components according to solubility: soluble and insoluble. The soluble substance is mainly inorganic salt, which dissolves when it is wet and significantly reduces the surface resistance, directly determining the level of pollution flashover voltage. Insoluble substances include mineral dust, carbon black and other water-insoluble substances. Although they do not directly contribute to the electrolyte, they can adsorb and maintain water, thicken the water film, change the surface conductivity distribution of the fouling layer, and affect the development process of the local arc. Therefore, accurate characterization of the composition, content and physicochemical properties of soluble and insoluble substances is a prerequisite for in-depth understanding of the electrical hazards of pollution [5].

At present, ESDD and NSDD are widely used in engineering to measure the content of soluble salt and the amount of insoluble matter, respectively. However, a large number of studies have shown that it is difficult to fully reflect the complexity and harm of actual pollution by relying solely on these two parameters. It is necessary to use modern analytical techniques such as IC, ICP, XRD and XRF to conduct supplementary research at the micro level [6]. This paper systematically reviews the main research methods and results of soluble and insoluble contaminants on the surface of composite insulators at home and abroad, in order to provide a useful reference for the improvement of the contamination assessment system.

2. Study on Contamination Soluble

2.1 The Measurement Principle and Limitation of ESDD

ESDD is an internationally recognized general evaluation index of insulator contamination. It is defined as the mass density of water-soluble conductive substances in the contamination accumulated on the surface of insulators, which is equivalent to sodium chloride, and the unit is mg/cm^2. The standard measurement method is based on IEC 60815 and corresponding domestic standards. The procedure is as follows: scrub or soak the surface of the tested insulator with quantitative distilled water, transfer all the contamination to water, fully dissolve and measure the conductivity of the cleaning solution at a standard temperature (usually 20 °C), and then convert it to the equivalent NaCl mass according to the standard curve or empirical formula of conductivity-equivalent salt content. Finally, the ESDD is obtained by dividing the insulator surface area.

The reason why ESDD is widely used is that it is easy to operate and has good repeatability, and there is a relatively stable negative correlation between ESDD and insulator pollution flashover voltage. China 's relevant regulations directly use ESDD as the reference parameter for dividing the pollution area level and determining the creepage distance of the external insulation. However, the inherent limitations of the index also triggered a lot of discussion.

First, ESDD uses NaCl conductivity as the conversion scale, but the soluble salt composition in the actual natural contamination is extremely complex. Common ions include Ca^{2+}, Na^+, K^+, Mg^{2+}, NH_4^+, SO_4^{2-}, Cl^-, NO_3^-, etc. The molar conductivity of different salts is significantly different. For example, the conductivity of $CaSO_4$ solution is much lower than that of NaCl at the same mass concentration. When the proportion of low-conductivity salts such as $CaSO_4$ in the pollution is high, the ESDD value calculated based on the NaCl scale will seriously underestimate the total amount of actual soluble salts, resulting in the phenomenon of "low salt density." On the contrary, if the monovalent salt content of high conductivity is high, it may be overestimated [7,8]. Secondly, ESDD completely ignores the contribution of soluble organic matter and cannot reflect the water holding effect of insoluble matter. In addition, the operation details such as soaking temperature, stirring time and whether the sewage is filtered during the standard measurement process will have a significant impact on the results, resulting in reduced comparability between different source data. Therefore, ESDD alone has been difficult to meet the needs of accurate contamination assessment, and ion composition analysis has become a necessary supplement.

2.2 Application of IC in the Analysis of Contaminated Ions

IC is the mainstream technology for qualitative and quantitative analysis of soluble anionic and cationic components in insulator pollution. The working principle is as follows: the filtered sewage sample is injected into the ion chromatography system, and the sample is carried by the mobile phase through the ion exchange chromatographic column, and the separation is realized based on the difference in affinity between different ions and the stationary phase. The separated ions enter the suppressor in turn to reduce the background conductivity, and then are detected by a conductivity detector or an optical detector. IC can be used to determine a variety of anions such as F^-, Cl^-, NO_2^-, Br^-, NO_3^-, SO_4^{2-}, PO_4^{3-} and cations such as Na^+, NH_4^+, K^+, Mg^{2+}, Ca^{2+} at one time. The detection limit can reach the level of μg/L, and the sensitivity and accuracy are high.

Huang [9] used ion chromatography to systematically test the natural contamination components on the surface of porcelain, glass and composite insulators in Chongqing area. Aiming at the randomness of the traditional ion pairing method, the ion pairing method based on fuzzy clustering was proposed. It was found that the main contamination component on the surface of insulators in this area was $CaSO_4$, and the contamination components of insulators with different materials were different due to the different capture ability of the surface to particles. Wang [10] carried out IC analysis on soluble ions of natural contaminants at 17 monitoring points in Sichuan Province. Combined with atomic absorption spectroscopy (AAS) verification, it was also found that Ca^{2+} and SO_4^{2-} were absolutely dominant, and the contents of Na^+ and Cl^- were relatively low, indicating that the evaluation results of ESDD had a certain degree of distortion. There are significant differences in the composition of pollution ions between coastal and inland areas. Xie [11] found that the measured value of soluble salt content on the surface was 0.688 % by IC analysis for 110 kV composite insulator flashover accident in coastal area, which was mainly composed of hydrochloride and sulfate, and the chloride ion content was prominent. This high salt content is a key factor leading to rapid pollution flashover. Chen [12] quantitatively studied the correlation between soluble ions and ESDD in insulator contamination in Wuhan through a six-month natural contamination test and IC analysis. The results showed that the correlation coefficient between Ca^{2+} and ESDD was as high as 0.96, while the correlation coefficients between Cl^- and Na^+ and ESDD were only 0.2 and 0.1, respectively, which strongly confirmed that $CaSO_4$ was the dominant component in the actual control of ESDD level in the inland industrial-domestic mixed pollution environment, and the influence of NaCl was limited. Guo [13] used IC and ICP to analyze the anionic and cationic components in the soluble salts of insulator contamination in different typical environments in Ningxia: industry, agriculture, urban residential areas, and desert areas. It was found that the soluble components were mainly divalent salts represented by $CaSO_4$.

2.3 ICP Application

In addition to ion chromatography, inductively coupled plasma optical emission spectrometry (ICP-OES) is also an important method for the determination of various metal elements and some non-metal elements in pollution. The principle is as follows: the sample solution is introduced into the high temperature plasma torch in the form of aerosol, and the elements to be measured are atomized and excited. When the excited atoms or ions return to the ground state, the characteristic emission spectrum is generated, and the quantification is realized by detecting the spectral line intensity. ICP-OES has a very low detection limit and a wide linear range for Ca, Na, Mg, Al, Fe, K and other elements, and can simultaneously determine dozens of elements, forming a good complementarity with ion chromatography [14]. Cao [15] combined IC and ICP to determine the composition of the contamination, and supplemented by scanning electron microscopy to observe the micro-area morphology. It was confirmed that the soluble component of the contamination was mainly $CaSO_4$, and the insoluble component was mainly SiO_2, and the proportion of insoluble components reached more than 78%.

Based on the above research, there are obvious differences in the ion composition of the filthy soluble substances on the insulator surface under different pollution sources in different regions. Cl^- and Na^+ are relatively enriched in coastal areas, and ESDD is closely related to NaCl content. The value of ESDD is mainly determined by the contribution of Ca^{2+} and SO_4^{2-} Since the conductivity of NaCl and $CaSO_4$ is several times different at the same mass concentration, if the unified conductivity-salt density conversion relationship is still used, the ESDD values between different regions will inevitably be unequal in chemical nature.

In order to overcome this defect, some scholars have proposed that the composition of ESDD should be corrected according to the results of ion chromatography or ICP, or an empirical model based on the main ion content and pollution flashover voltage should be directly established. In his review, Li [16] systematically expounded the classification of soluble pollutants into soluble salts and insoluble salts, considered the influence of total ion species, and advocated the establishment of a multi-level pollution assessment system including organic and inorganic components, soluble and insoluble components. This requires the accumulation of long-term data in each power grid area to obtain the unit mass conductivity of different proportions of salts, so as to construct a more scientific pollution correction factor. It can be predicted that with the development of online contamination monitoring technology and miniaturized ion chromatography, it will be possible to obtain the composition information of contaminated ions in real time, and the macroscopic parameter ESDD will be supplemented by the key component dimension.

3. Study on Filthy Insoluble

3.1 Equivalent Grey Density

NSDD, referred to as ash density, refers to the mass of water-insoluble pollutants on the unit surface area of insulators. The standard measurement method is usually to filter the dirty liquid with pre-dried weighing filter paper after cleaning the insulator, and then dry the filter residue to constant weight, which is obtained by dividing the mass increment by the surface area of the insulator. Gray density and salt density are listed as the two parameters of the current pollution degree characterization in China. A large number of artificial pollution tests and natural pollution tests at home and abroad show that under the same ESDD conditions, with the increase of ash density, the pollution flashover voltage of insulators decreases significantly [17].

The influence mechanism of ash density has the following aspects: insoluble particles can adsorb a large amount of water, so that the actual water content of the fouling layer increases and the conductive water film thickens when it is moistened; the capillary effect between fine particles prolongs the surface drying time. Some insoluble substances (such as carbon black, metal dust) have certain electronic conductivity, which can reduce the surface resistance locally. The spatial distribution of insoluble causes uneven thickness of the fouling layer, causing electric field distortion and local arc. Based on these reasons, the gray density value can be used as a simple and practical quantitative parameter of insoluble content, which has guiding significance for pollution measurement and insulation coordination design in production and operation. However, the ash density is only a reflection of the total mass, without distinguishing the composition, particle size and morphology, and the information provided by it has great limitations [18].

3.2 XRD Phase Identification Study

XRD is a key technology to explore the mineral composition and crystal structure of insulator insoluble by using the diffraction phenomenon of crystal to X-ray to identify the phase composition of the material. The contaminated powder sample was placed in an X-ray diffractometer to produce diffraction at different angles. The obtained diffraction pattern was compared with the standard card database to determine the crystal phase.

The limitation of XRD is that it can only identify crystalline materials, and it is difficult to give effective information on amorphous components in natural and industrial emissions, which need to be complemented by means of electron microscopy and energy dispersive spectroscopy.

3.3 XRF and Energy Spectrum Analysis

XRF and energy dispersive X-ray spectroscopy (EDS) are commonly used semi-quantitative and quantitative analysis tools to obtain the elemental composition of the whole pollution. XRF uses a primary X-ray to excite the sample to produce a secondary characteristic X-ray, and determines the type and content of the element according to the fluorescence energy and intensity. EDS is usually carried out on a scanning electron microscope (SEM), which can perform point, line, and surface elemental analysis on the micro-area.

EDS analysis also revealed the diversity of particle size and morphology of insoluble. The pollution particles on the surface of composite insulators are mainly irregular angular, with a particle size range of 0.2~100 μm. There are a large number of submicron particles in some environments, with large specific surface area and strong water holding capacity, so the effect of reducing pollution flashover voltage is more obvious. Through the combined analysis of XRF/EDS and XRD, it is possible to know both the elements and the phases, and the evaluation of the insoluble rises from the simple quality index to the level of physical and chemical interaction.

3.4 The Comprehensive Effect of Insoluble on the Electrical Characteristics of Pollution

The composition and properties of insoluble matter directly affect the conductivity, dielectric constant and wetting characteristics of the pollution layer, which is one of the key factors to determine the actual pollution withstand voltage of insulators. The results show that in the artificial pollution test with high conductivity insoluble particles, the leakage current increases significantly, and the flashover voltage is 10 %~20 % lower than that with only inert SiO_2. The insoluble substances with hydration activity such as cement and gypsum undergo a dissolution-recrystallization process after being wetted, which changes the microstructure of the fouling layer and the surface hydrophobicity migration process, and indirectly affects the pollution flashover characteristics. In addition, the organic components in insoluble such as oil and dust not only reduce the overall hydrophilicity of the fouling layer, but also may delay the migration of small silicone rubber molecules to the surface through the coverage effect and weaken the hydrophobicity recovery ability [19,20].

Therefore, the harm of insoluble substances cannot be completely characterized by gray density alone. It is necessary to carry out a comprehensive characterization of the phase, element, particle size and microstructure of insoluble substances in typical polluted areas. This can not only optimize the local pollution degree evaluation model, but also provide a scientific basis for formulating targeted anti-fouling and cleaning strategies. Some researchers have begun to explore the establishment of a modified flashover voltage prediction model based on XRD semi-quantitative mineral composition and gray density, but the related research is still in its infancy [21].

4. Multi-Means Comprehensive Analysis of Filth

In summary, the detection method of insulator surface contamination is shown in Figure 1.

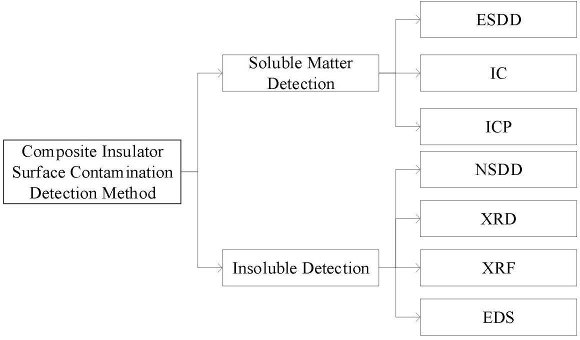

Figure 1. Composite Insulator Surface Contamination Detection Method

Table 1 summarizes the main analytical methods discussed above, highlighting their respective functions and limitations.

Table 1. Summary of Analytical Methods for Soluble and Insoluble Contaminants on Composite Insulator Surfaces

Analytical Method	Category	Information Provided	Advantages	Limitations
ESDD	Soluble	Total mass density of soluble salts	Simple operation, standardized	Cannot distinguish ion species
IC	Soluble	Qualitative and quantitative analysis of anions and cations	High sensitivity, simultaneous multi-ion detection	Requires laboratory equipment
ICP	Soluble/Elemental	Multi-element quantification of metals and some non-metals	Wide linear range, simultaneous multi-element analysis	Cannot distinguish ion valence states
NSDD	Insoluble	Total mass density of water-insoluble substances	Simple, standardized, directly reflects bulk insoluble content	No information on composition, particle size
XRD	Insoluble	Mineral phase composition and crystal structure identification	Identifies specific crystalline phases	Cannot detect amorphous components
XRF	Insoluble/Elemental	Elemental composition of bulk sample	Semi-quantitative to quantitative; covers wide elemental range	Limited sensitivity for light elements; no phase information
EDS	Insoluble/Micro-area	Micro-area morphology, particle size distribution, and elemental composition	Visualizes particle shape and size; point/line/area analysis; high spatial resolution	Semi-quantitative; small sampling area may not represent bulk sample

The above analysis shows that the surface contamination of composite insulators is a complex mixed system composed of a variety of soluble salts, insoluble minerals, amorphous carbon and trace organic matter. A single method cannot give a comprehensive picture: ESDD and gray density reflect the total amount of soluble and insoluble substances respectively; IC and ICP revealed the ion spectra of soluble substances; XRD identification of insoluble crystalline phase; XRF/EDS provides a complete picture of the elements; SEM shows the microstructure and particle size distribution. Only by organically integrating these analytical methods and carrying out multi-level and multi-dimensional characterization can the nature of pollution chemistry be truly related to its dielectric and conductive effects.

At present, one of the biggest challenges in pollution research is that the equivalence between natural contamination and artificial contamination test is not fully established. Although the artificial pollution flashover test can control the salt density and ash density, it cannot reproduce the complex phase composition, particle size gradation and heterogeneous distribution in natural pollution, resulting in greater uncertainty of the test results. For this reason, some studies have proposed 'simulated filth' or 'standard filth formula' based on local typical natural filth to narrow the gap between laboratory conditions and on-site operation.

5. Conclusion

The research on surface contamination of composite insulators is divided into two directions: soluble and insoluble. ESDD is the core of engineering quantification of soluble substances, but its evaluation effect is significantly affected by ion composition. IC and ICP techniques can effectively analyze the types and contents of soluble salts, revealing that $CaSO_4$ is the main soluble component in most areas of China, and NaCl accounts for a relatively high proportion in coastal areas. In terms of insoluble matter, ash density is an important auxiliary parameter. XRD and XRF/EDS provide pollution source information from the perspective of phase and element, respectively. Quartz and aluminosilicate are common insoluble matter matrices in various places, and industrial pollution sources give them diversified mineral and element characteristics.

To achieve accurate pollution status assessment, we cannot rely on a single macro indicator.

We must build a multi-system evaluation framework based on the multi-means comprehensive characterization results of the actual pollution in the region. With the development of on-site rapid detection technology and artificial intelligence methods, it is expected to achieve a leap from regular offline detection to real-time online diagnosis in the future, providing stronger technical support for the differentiated operation and maintenance of composite insulators and the formulation of anti-fouling strategies.

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