

Challenges in Insulation of Transmission Equipment with Climate Change

The power grid is a critical infrastructure for reliable energy transmission. It underpins economic development, supports daily life, and plays a pivotal role in achieving carbon peaking and carbon neutrality goals. However, in recent years, global climate change and the increasing frequency of extreme weather events have posed unprecedented challenges to energy infrastructure.

Insulators, positioned between the high-voltage components of the grid and ground potential, serve a dual purpose: providing both mechanical support and electrical insulation. As key components directly exposed to outdoor environments for extended periods, insulators form the “first line of defense” for the power grid against climate-induced stress. They are also among the most widely used devices in power systems. By the end of 2023, China had over 7.37 million strings of porcelain insulators, 11.11 million strings of glass insulators, and 14.72 million strings of composite insulators in operation. These insulators collectively form the critical interface between high-voltage transmission lines and the ground. A single pollution flashover event in any one string can cause an unplanned outage of the entire transmission line and may even trigger cascading failures across the grid.

External insulation has long been a key factor influencing the reliability of transmission and transformation equipment. Over the past several decades, researchers worldwide have conducted extensive laboratory and field studies on pollution flashovers. Based on experimental data and operational experience, they have developed design methods to improve the external insulation. However, traditional pollution models and anti-flashover techniques generally treat the site pollution severity (SPS) as a static variable, relying heavily on controlled lab tests and historical field data.

In reality, the contamination and moisture conditions on insulator surfaces are highly dynamic, responding rapidly to environmental changes. In regions with unique environmental conditions or microclimates, surface states of insulators can vary significantly over short periods. This has led to frequent pollution flashover incidents in areas where environmental conditions change abruptly.

In recent years, China has experienced hundreds of such incidents due to a range of factors:

- Sudden transitions during contamination accumulation of insulators (e.g., long dry without rainfall)
- Rapid moisture changes (e.g., persistent “returning dampness” or high humidity)
- Sudden emission of special pollutants (e.g., new chemical plants or firework)
- Simultaneous fast accumulation and wetting (e.g., sea fog)
- Extreme high pollution levels near industrial hubs

These events have resulted in frequent unplanned AC transmission line outages and derated operation of DC lines, causing direct economic losses totaling hundreds of billions of yuan in China and several other countries.

The challenges stem largely from an incomplete understanding of the dynamic mechanisms behind insulator contamination and wetting under complex environmental conditions. There is also a lack of a robust theoretical foundation tailored to natural, variable environments and an absence of truly effective online monitoring and pollution forecasting technologies. As a result, the maintenance of external insulation remains inefficient and imprecise.

According to estimates from relevant authorities, the current global cost of external insulation operation and maintenance is approximately USD 28–34 billion annually. Developing scientific and efficient methods for external insulation operation and maintenance has therefore become one of the most pressing challenges facing the modern power industry (Figure 1.1).

In response to the urgent need for rational design and scientific operation and maintenance of external insulation for transmission and transformation equipment under increasingly complex climatic conditions, this book systematically presents the latest research progress on the dynamic evolution characteristics of surface wetting and pollution-induced discharge of high-voltage transmission and transformation equipment. It explores key technologies for pollution flashover prevention and control under complex operating environments and extreme weather conditions. The aim is to provide valuable references for the

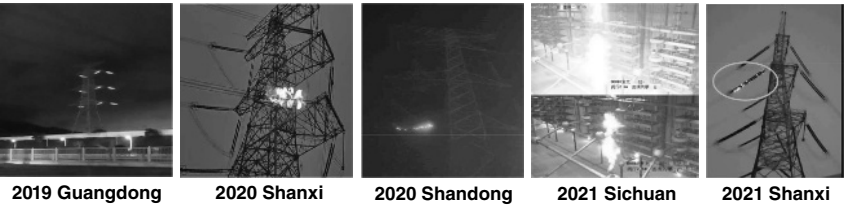


Figure 1.1 Flashover incidents in recent years.

design, selection, monitoring, and maintenance of external insulation systems for high-voltage transmission and transformation equipment in extreme environments, thereby contributing to the safe and stable operation of China's power transmission and transformation infrastructure.

1.1 Classical Theories of Pollution Discharge on Insulators

1.1.1 Pollution Flashover Models

Although pollution flashover incidents were reported as early as the beginning of the 20th century in the United Kingdom, over four decades of research failed to clearly establish the specific physical mechanism behind discharges on wet polluted surfaces. It was not until 1958 that Obenaus first proposed a quantitative analytical model to describe pollution flashover, as illustrated in Figure 1.2. This model suggests that the gradual development of localized arcs along the surface of the pollution layer ultimately leads to the occurrence of a flashover.

After the appearance of a localized arc, the arc forms a series circuit with the remaining polluted layer, which constitutes the classical pollution flashover model. Once discharge occurs, the voltage–current relationship across the insulator can be described by the following equation:

$$U = AxI^{-n} + R(x)I \quad (1.1)$$

where:

U is the applied voltage across the insulator,

A and n are arc characteristic parameters,

x is the arc length (i.e., the length of the local arc),

$R(x)$ is the resistance of the remaining pollution layer,

I is the leakage current.

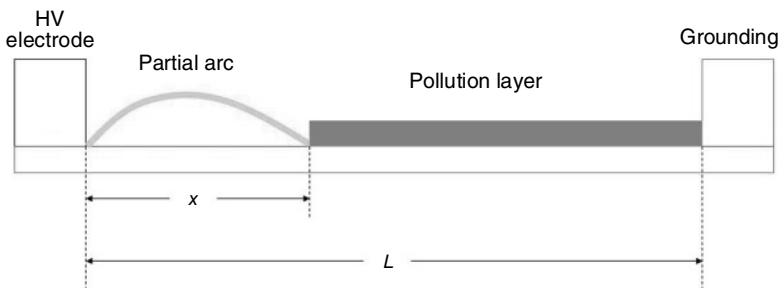


Figure 1.2 Obenaus pollution flashover models.

The first term on the right-hand side of Eq. (1.1), AxI^{-n} , reflects the negative volt-ampere characteristic of the arc. For a given arc length x , the relationship between voltage U and current I forms a “U-shaped” curve, with a minimum voltage needed to sustain the arc, known as the arc sustaining voltage, U_{ext} . If the supply voltage is lower than U_{ext} , the arc cannot be maintained and will extinguish—hence the name extinguishing voltage. Studies have shown that this extinguishing voltage varies with the arc length and reaches a maximum value, known as the critical flashover voltage U_c . This concept forms the basis for much of the experimental and theoretical research into pollution flashover phenomena.

Neumarker was the first to use it to calculate the pollution flashover characteristics of rod-type insulators. However, due to reliance on graphical methods, its application was cumbersome. Alston and Zoledaiowski later developed a more generalized analytical approach through mathematical derivation. Based on the Obenaus model, Alston and colleagues derived expressions for the critical flashover voltage U_c , critical arc length x_c , and critical leakage current I_c , providing a more rigorous theoretical foundation for flashover analysis.

$$U_c = A^{\frac{1}{n+1}} L r_c^{\frac{n}{n+1}} \quad (1.2)$$

$$X_c = \frac{L}{n+1} \quad (1.3)$$

$$I_c = \left(\frac{A}{r_c} \right)^{\frac{1}{n+1}} \quad (1.4)$$

All the above model derivations assume that the conductivity of the residual pollution layer resistance remains constant. However, Wilkins pointed out the variability of the residual pollution layer resistance based on the fundamental model and obtained an analytical expression for the residual pollution layer resistance on the surface of complex-shaped insulators:

$$R(x) = \frac{1}{\pi K} \ln \frac{L-x}{r_0} \quad (1.5)$$

where K is the surface conductivity, and r_0 is the arc root radius.

Furthermore, the critical flashover condition under DC voltage can be derived. Assuming the arc length x is a given fixed value, according to the minimum value theory of the $U-I$ curve, the minimum voltage U_n required to sustain a specific arc length x can be obtained.

$$U_n = \left(1 + \frac{1}{n} \right) (nxA)^{\frac{1}{n+1}} R(x)^{\frac{n}{n+1}} \quad (1.6)$$

U_n is also a function of the arc length x . When the arc length reaches the critical arc length x_c , the voltage required to sustain the arc reaches its maximum value, meaning flashover becomes inevitable. Furthermore, the expression for the critical current can be derived as:

$$I_c = \left[\frac{nx_c A}{R(x_c)} \right]^{\frac{1}{n+1}} \quad (1.7)$$

In the analysis of AC pollution flashover, Claverie and Rizk extended the Obenaus model by proposing that AC flashover not only requires the applied voltage to exceed the minimum extinction voltage but also must satisfy the arc reignition condition. Claverie experimentally summarized the reignition conditions of AC arcs, while Rizk derived the reignition conditions from a mathematical perspective using an energy balance equation.

However, the pollution flashover models developed based on the Obenaus model, whether for DC or AC flashover conditions, have not addressed the development mechanism of surface arcs on the pollution layer. Jolly pointed out that the extinction criterion in Obenaus's model is only a necessary condition for pollution flashover, not a sufficient one. This criterion only indicates that flashover will not occur below the critical voltage U_c , but does not provide the exact flashover voltage. Most studies based on the Obenaus model assume that arc development conditions are automatically satisfied, thus describing only the static process of pollution flashover.

Sundararajan proposed the first dynamic model to describe the evolution of surface arcs on flat plates. However, this model does not consider the unevenness of pollution and moisture on insulator surfaces and assumes the existence of only a single local arc. The dynamic model has the following shortcomings: first, the arc development criterion is not entirely reliable; second, the treatment of the residual pollution layer is overly simplified, assuming uniform and constant conductivity without considering its time-varying nature. Moreover, the residual pollution layer size is assumed to have a linear relationship only with arc length. Rizk also proposed a dynamic model describing arc development. Although this model considered the effects of current, evaporation, and boiling on pollution layer resistance, it did not fully address the arc development conditions and derived the relationship between arc velocity and current mainly based on experimental observations. Experimental results show that surface arc development modes on the pollution layer are diverse, including growth, stagnation, and even retreat.

In summary, existing pollution flashover models are mainly static and neglect arc development conditions. Although some dynamic models have been proposed, they still exhibit significant deficiencies. The fundamental reason is

Table 1.1 Arc characteristic parameter measurement results.

Researcher	<i>A</i>	<i>n</i>	Pressure <i>p</i> (kPa)	Measurement method
Alston	63	0.76	101.3	AC arc between two metal electrodes in air
B.F. Hampton	530	0.24	101.3	In water vapor conditions
Bergman	84	0.7	70.3	AC arc on flat plate surface
Zhicheng Guan	138	0.69	101.3	DC arc on polluted insulator
Kawamura	63	0.5	101.3	DC arc on triangular glass
Kawamura	35	1.0	13	DC arc on triangular glass

that the arc development mechanism remains unclear. Future research should focus on deeply investigating the arc development mechanism and establishing more comprehensive time-varying models to more accurately describe the arc evolution characteristics. This represents a key research direction in the theory of insulator pollution discharge.

1.1.2 Local Arc Volt-Ampere Characteristics

The study of the volt-ampere (*U*–*I*) characteristics of local arcs typically follows the relation: $U = AI^{-n}$. The fundamental problem is to determine the values of the two arc characteristic parameters *A* and *n*. However, different researchers have obtained widely varying values for these parameters. A summary of previous research results on arc characteristic parameters is shown in Table 1.1.

The results in the Table 1.1 indicate that the arc characteristic parameters obtained by different experimenters under varying test conditions differ significantly. Therefore, there can be considerable errors when using these arc characteristic parameters for analyzing the local arc volt-ampere characteristics. If one uses local arc characteristic parameters directly for volt-ampere analysis, the results may differ substantially from the actual values.

1.2 Insulator Contamination

The insulator contamination is influenced by a variety of factors. Many researchers have conducted extensive studies on the causes of contamination accumulation. Overall, these influencing factors can be categorized into three main groups: meteorological conditions, atmospheric pollution, and insulator-related parameters.

Meteorological conditions such as wind, precipitation, temperature, and humidity play a significant role. Wind affects the dispersion of pollutants from

their sources, the resuspension of dust from the ground, and the airflow characteristics around the insulator surface. Higher wind speeds can transport more contaminant particles toward the insulator in a given time but may also remove some already deposited particles. The direction of the wind may cause uneven contamination distribution on the insulator surface. Rainfall has a strong cleaning effect, significantly reducing surface pollution. Humidity influences not only moisture absorption and flashover risk but also the adhesion of contaminant particles to the insulator surface.

Atmospheric pollution is the primary source of contaminants accumulating on insulator surfaces. Its impact is mainly related to pollutant concentration, composition, and particle size. Soluble salts present in airborne solid or liquid particles can settle on insulators, increasing the surface pollution degree. Particle size affects their behavior in the air and their deposition on the insulator, as different-sized particles are influenced differently by electric fields, wind, and gravity.

Insulator-specific parameters include shape, mounting method, material, and operating voltage. Different insulator shapes create different airflow patterns around them, influencing the probability of particle collisions with the surface. Shape also determines the shading and self-cleaning effects. Different materials exhibit varying adhesion characteristics and responses to rainfall cleaning. Voltage levels affect the strength of the electric field around the insulator, which in turn impacts the behavior of charged particles—especially fine particles that may be influenced more by electrostatic forces. AC and DC voltages also influence contamination differently: under similar conditions, contamination under AC is slightly higher than when de-energized, while DC contamination is significantly higher.

Long-term studies have shown that insulator contamination exhibits strong seasonal patterns. The contamination rate is significantly affected by the time of year. From October to March in North China, reduced rainfall and cold weather, and increased air pollution due to heating by coal lead to a rapid buildup of surface contaminants. This buildup typically peaks in the two to three months before the first significant rainfall in spring. During the rainy season from April to September, heavy rain cleanses the insulator surfaces effectively. In some cases, insulators experience a net reduction in contamination during this period. This seasonal cycle of dry-season accumulation followed by rainy season cleaning results in a long-term saturation effect on insulator contamination.

The contamination characteristics of DC cap-and-pin insulators were investigated over a pollution season. The relationship between equivalent salt deposit density (ESDD) and exposure time followed the equation:

$$\text{ESDD} = Ae^{BM} \quad (1.8)$$

where M is the number of exposure months, and B and A are constants dependent on environmental conditions and insulator structure.

Due to the complexity of contamination mechanisms, it is difficult to isolate the dominant contributing factor. Atmospheric conditions, insulator geometry, electric fields, wind fields, and gravity all interact, making experimental results highly variable and often case-specific. While significant progress has been made in understanding contamination patterns, the fundamental mechanisms remain unclear, posing challenges for improving antipollution flashover strategies.

Currently, there are three main approaches to studying contamination on insulators:

1.2.1 Natural Contamination Stations or Field Measurements

These involve long-term monitoring of insulators under real operating conditions and remain the most widely used method for both AC and DC systems. They provide accurate, practical data but require extended periods to gather sufficient information. Differences in regional climate and geography can also lead to varied conclusions. Since the 1970s and 1980s, numerous natural contamination stations have been established worldwide, offering valuable data for pollution resistance design and maintenance strategies.

1.2.2 Wind Tunnel Testing

Wind tunnel experiments allow researchers to study contamination accumulation under controlled conditions. This method offers a faster way to generate large datasets for systematic analysis. As early as 1979, researchers Mark N. Horenstein and James R. Melcher explored the impact of electric fields on particle deposition in DC high-voltage environments. Their findings revealed that particles smaller than 10 μm are significantly influenced by electrostatic forces, whereas larger particles are dominated by aerodynamic drag. Wind tunnel results show that the contamination rate is closely related to wind speed and is typically higher on the top surface of the insulator. The structural design also matters: initially clean insulators accumulate contaminants slowly, but the rate increases after a thin pollution layer forms. Composite insulators typically perform better than ceramic ones in these tests. Additionally, larger umbrella sheds accumulate less contamination than smaller ones, while dust-laden airflow speed and exposure duration are key factors.

1.2.3 Computational Fluid Dynamics

Advances in computer technology have made computational fluid dynamics (CFD) a valuable tool for simulating airflow and particle movement around insulators. Using numerical models like random trajectory or random walk

models, researchers can track particles in turbulent flow and predict how they interact with the insulator surface. By calculating collision rates, SPS of insulator can be estimated under various conditions. CFD offers high repeatability and control, enabling analysis of the effect of individual variables. However, its accuracy depends heavily on the precision of the mathematical models and parameter settings, making experimental validation essential.

1.3 Insulator Wetting

The wetting, along with the insulator pollution accumulation, is both critical stages in the process of pollution flashover. Flashover will not occur in the absence of either condition, making both equally important from the perspectives of flashover mechanisms and antipollution strategies. Factors influencing the moistening characteristics of insulators fall into three main categories: environmental conditions (fog, rain, dew, icing, etc. and their related parameters), pollution-related factors (types and contents of soluble salts and inert substances), and the insulator's own characteristics (type, suspension method, and surface temperature). The amount of water that saturates the insulator surface is significantly affected by the mechanism of pollution layer moistening. Numerous studies have explored the moisture characteristics of insulators through parameters such as leakage current and pollution flashover voltage, achieving substantial progress. In the early 1980s, Canadian researcher M. Leclerc conducted foundational studies on surface moistening mechanisms, classifying the modes into droplet impact, condensation, adsorption, and molecular diffusion. Building on this framework, subsequent studies further examined how insulator pollution degree, ambient temperature, and other factors influence surface wetting.

1.3.1 Droplet Impact

Under conditions of heavy fog or light rain, when relative humidity approaches 100%, small droplets collide with the insulator surface due to gravity, wind, and electric fields, leading to rapid wetting of the surface pollution layer. The rate of this process is mainly determined by droplet density, velocity, and trajectory. Different types of fog, therefore, significantly influence impact moistening behavior. Artificial fogs used in pollution tests include steam fog, cold fog, and hybrid fog. Cold fog is typically produced via ultrasonic atomization or aspiration, while steam fog is generated by heating deionized or tap water in boilers. Hybrid fog combines both. Large-scale artificial pollution test chambers in China and abroad generally use steam or hybrid fog.

1.3.2 Molecular Diffusion

Moistening by molecular diffusion involves the transformation of airborne water vapor into liquid phase on the pollution layer. This process is often analyzed using the two-film theory to quantify mass transfer flux and rate. Since the vapor pressure of deionized water is higher than that of the pollutant solution, water molecules in the atmosphere continuously diffuse into the pollution layer. The mass transfer flux J_A of water molecules through the gas and liquid films is given by:

$$J_A = k_L \alpha (C_A^* - C_A) \quad (1.9)$$

where α is the surface area per unit mass, k_L is the film mass transfer coefficient, C_A^* is the equilibrium concentration of component A, and C_A is the actual concentration.

1.3.3 Adsorption Moistening

Naturally accumulated pollutants on insulator surfaces typically consist of a mix of soluble and insoluble substances. Some materials—particularly soluble salts, sugars, and compounds like caprolactam—exhibit strong hygroscopicity. As a result, even at relatively low humidity, the pollution layer can absorb water molecules from the air. Several surface flashover events in China have been linked to adsorption moistening. For instance, shortly after the commissioning of the 500 kV Gangcheng Substation in Zhanjiang in 2006, severe surface discharges occurred despite humidity being below 80%. Subsequent analysis revealed high concentrations of strongly hygroscopic substances like sugars and aluminum phosphate in the surface contaminants.

1.3.4 Condensation

When the surface temperature of an insulator drops below the dew point for the current temperature and humidity conditions, rapid condensation of water vapor can occur, leading to fast moistening of the pollution layer. The dew point temperature D_p is calculated as:

$$H = [\lg(RH) - 2]/0.4343 + 17.62T/(243.12 + T) \quad (1.10)$$

$$D_p = 243.12H/(17.62 - H) \quad (1.11)$$

where RH is the relative humidity and T is the ambient temperature.

In desert regions, early-morning flashovers may be attributed to thermal gradient moistening. Although the air humidity is usually low, the insulator surface temperature can drop below the ambient temperature at night, triggering

condensation. Experimental studies have explored the relationship between temperature gradients and peak leakage current, but data on actual moisture accumulation during this process remains scarce.

1.4 Characterization Parameters for External Insulation

Selecting appropriate parameters to characterize the external insulation condition of transmission lines is essential for accurately assessing their operating status and preventing pollution flashover accidents. The external insulation performance of an insulator is primarily determined by the degree of surface contamination and moisture absorption. At present, the main methods for characterizing insulator surface contamination include ESDD, surface conductivity, leakage current, pollution flashover voltage, and flashover voltage gradient. These parameters can generally be divided into two categories: measurements of contamination directly on the insulator surface, and assessments based on environmental pollution monitoring.

Environmental monitoring focuses on tracking meteorological and atmospheric parameters in the insulator's surroundings to indirectly infer surface pollution levels. Common techniques include the use of directional dust deposit collectors and analysis of airborne pollution samples. However, because this approach only provides indirect information about the actual condition of the insulator surface, it has seen limited application in domestic power systems.

Parameters used to characterize the insulator contamination include ESDD, pollution layer conductivity, localized surface conductivity, leakage current, dust deposit density, and flashover voltage gradient. In addition to these, some research has introduced further indicators such as the volume conductivity of collected pollution samples, the characteristics of leakage current pulses, and the frequency of flashover events. These extended parameters offer a more comprehensive understanding of external insulation behavior under both artificial and natural contamination conditions.

1.4.1 ESDD

ESDD is a key parameter for evaluating the contamination level of insulators. It represents the amount of NaCl-equivalent conductive salt deposited per unit surface area of the insulator. The non-soluble portion of the contamination can be measured and calculated as the Non-Soluble Salt Density (NSDD).

Under artificial pollution test conditions, the flashover voltage of an insulator typically has a negative power-law relationship with its surface ESDD. However,

factors such as the magnitude of the NSDD, the type of salt, and the distribution of the contamination layer can all influence the relationship between ESDD and flashover voltage. To account for the influence of different salt types and dust components on the insulator's flashover voltage, a multiparameter correction is introduced based on Eq. (1.12), resulting in the following form:

$$U = U_0 \times \prod_i K_i$$

$$U_0 = A \times \text{ESDD}^{-\beta} \quad (1.12)$$

where:

U is the flashover voltage of the contaminated insulator;

U_0 is the 50% flashover voltage under ideal conditions (uniform pollution on both upper and lower surfaces, with NaCl as the sole conductive material in the contamination);

k_i are correction factors for various influencing parameters;

A is a discharge constant determined by the insulator's material and structure;

β is a weighted average exponent related to the surface conductivity.

Through experimental studies, domestic and international research institutions have obtained empirical correction factors (k_i) under various conditions, including different levels of soluble salt density, dust content, pollution composition, and pollution distribution. In practice, insulators with the same ESDD under natural and artificial pollution often exhibit different flashover voltages. Even after applying corrections, a completely equivalent relationship between the two is not achieved. Furthermore, when using ESDD to evaluate contamination levels, if the composition of natural pollution or the distribution of pollutants on the insulator surface is unknown, it remains difficult to accurately estimate the flashover voltage. This highlights a limitation of ESDD: while useful, it is not an ideal or comprehensive parameter for characterizing insulator contamination.

1.4.2 Insulator Flashover Voltage and Flashover Voltage Gradient

Flashover voltage is the most direct physical quantity used to characterize the external insulation performance of an insulator. One of the main objectives of contamination level assessment is to estimate the insulator's flashover voltage, thereby providing a basis for operational decision-making. Research has shown that under typical conditions, there exists a correlation between the flashover voltage gradient E (kV/m) and a pollution severity index H , as expressed in the following relationship:

$$E \propto H^{-p} \quad (1.13)$$

From a mathematical perspective, the parameter p is regarded as a weighted average representing the electrolyte surface characteristics. Researchers have provided values for these parameters under different types of insulators and test conditions. Experimental results demonstrate that this relationship generally holds for various types of artificial pollution tests. However, it has also been observed that the regression coefficients obtained from natural pollution tests often differ from those derived from artificial pollution tests. Thus, the mathematical equivalence between natural and artificial contamination conditions remains unresolved, presenting an ongoing challenge in pollution flashover research.

1.4.3 Leakage Current

Extensive research has been conducted both domestically and internationally on the relationship between leakage current and the external insulation condition of insulators. Studies indicate that leakage current is influenced by both environmental factors (such as relative humidity and temperature) and surface contamination characteristics (such as contaminant composition, degree of pollution, and uniformity). Due to its strong correlation with external insulation performance and its capability for continuous online monitoring, leakage current has become widely applied in insulation diagnostics.

Parameters such as the leakage current value immediately prior to flashover, the number of leakage current pulses, and the maximum leakage current under operating voltage can be used to characterize the insulation condition. Among these, the maximum leakage current under operating conditions is currently the most commonly used indicator. This is because:

- The number of leakage current pulses has limited correlation with flashover voltage.
- The pre-flashover leakage current is difficult to measure in real time.

Current leakage current prediction methods can be broadly classified into heuristic (technical) methods and quantitative modeling methods:

- *Heuristic methods*, such as expert judgment, rely heavily on the experience and technical skill of the evaluator.
- *Quantitative methods* build predictive models, such as multiple regression or artificial neural networks, to forecast surface leakage current.

Among these, neural network models are the most widely used. However, most of these models are based on laboratory data, and their input variables are relatively limited. As a result, they often fail to account for the complexity of real-world operational environments, which limits their practical application in the field.

1.4.4 Surface Conductivity

The surface conductance of an insulator is defined as the ratio of the power-frequency current flowing along the surface of the insulator to the voltage applied across its terminals. Surface conductance reflects the overall insulation condition of the insulator surface, accounting not only for the contribution of conductive components within the contamination but also for the moisture absorption effects of the non-soluble components.

Since the conductance of the pollution layer is influenced by the shape and dimensions of the insulator, a normalized parameter called surface conductivity (K) is introduced to facilitate comparisons between different types of insulators. It is defined as:

$$K = f \times G = f \frac{I}{U} \quad (1.14)$$

where:

U is the voltage applied across the insulator string,

I is the leakage current flowing along the surface,

f is a shape factor that reflects the geometric configuration of the insulator.

The shape factor f is given by:

$$f = \int_0^L \frac{dx}{\pi D(x)} \quad (1.15)$$

where:

L is the creepage distance of the insulator,

$D(x)$ is the diameter at a point x along the creepage path.

To accurately measure the overall surface conductivity, an appropriate voltage must be applied across the insulator string. This voltage should be high enough to reflect the insulation condition under operating conditions, yet the duration of the voltage application must be short to minimize the effects of heating and partial discharge. Currently, there is no internationally standardized procedure regarding the voltage magnitude or duration for surface conductivity measurements. Table 1.2 summarizes the voltage application parameters used by different research institutions for measuring overall surface conductivity.

Due to the complexity of instruments and methods required to measure the overall surface conductivity of an insulator string, as well as the associated costs, such measurements are not economically viable for large-scale deployment.

To address this limitation, the concept of local surface conductivity was introduced. From a physical standpoint, overall and local surface conductivity

Table 1.2 Voltage requirements for surface conductivity measurement by different research institutions.

Standard/institution	Requirements
German standard	24 kV per meter of discharge distance
IEC 60507	At least 700 V per meter of creepage distance (as specified for artificial pollution tests)
CIGRE	30 kV per meter of insulator length
Standards from former Soviet Union	Measurement conducted at 80% of the flashover voltage

represent the same underlying parameter—surface conductivity—but differ primarily in measurement approach. Measuring overall surface conductivity typically requires applying voltage across the entire insulator string, which involves full-string wetting and high-voltage equipment. In contrast, local surface conductivity measurements involve wetting only a localized area of the insulator surface, then measuring the conductivity in that region to estimate the local surface conductivity.

This localized method offers several advantages:

- It reflects the degree of local contamination,
- It enables analysis of pollution distribution patterns,
- It allows researchers to observe contamination accumulation and loss trends without damaging or altering the pollution layer.

Because of these benefits, local surface conductivity has been widely adopted under laboratory conditions. To estimate the overall insulation performance using partial measurements, researchers commonly use direct averaging or weighted averaging. However, under conditions of uneven pollution distribution or unclear distribution patterns, these averaging methods can introduce errors when evaluating the overall performance of the insulator string. Currently, there is no well-developed or standardized equipment for surface conductivity measurement.

1.5 Pollution Monitoring Technology

The current selection process for external insulation on transmission lines begins with plotting pollution maps based on ESDD measurements. Insulator configurations are then determined based on specific creepage distance and insulator design parameters. However, with the development of industry and

agriculture, the environmental conditions surrounding transmission lines have changed significantly, while pollution maps are not updated in real time. Moreover, the accumulation of surface pollution on insulators requires a certain contamination period, meaning that ESDD measurements cannot reflect the insulation status of insulators in real time. As a result, flashover incidents caused by insufficient creepage distance still occur. Implementing online monitoring and assessment of insulator pollution conditions can guide daily maintenance of transmission lines, reduce the randomness in the application of antipollution measures, improve productivity, and lower labor intensity. Therefore, online monitoring of pollution status is an inevitable trend in the development of modern power grids.

Multiple technologies are available for online monitoring of external insulation, including leakage current monitoring, partial discharge detection, infrared thermography, ultraviolet imaging, and comprehensive assessments based on meteorological and environmental parameters. Among these, leakage current monitoring is the most commonly used method. Leakage current monitoring offers the advantage of continuous online observation. The real-time measurements correlate with the amount of surface contamination and moisture content on the insulator, allowing for a degree of assessment of the pollution status. However, the development of pollution assessment systems based on leakage current faces challenges. One major issue is the short lifespan of sensors, which cannot operate reliably over long periods. Another is that leakage current is influenced by multiple variables—including line voltage, pollution levels, and moisture content of the pollution layer. Existing evaluation models—such as neural networks, wavelet transform models, time-domain and frequency-domain analysis models, phase angle models, and fundamental wave models—mainly analyze the trend of leakage current without establishing a direct correlation with the flashover voltage of insulators.

Therefore, it can be concluded that previous monitoring systems primarily served the purpose of observing data, without linking surface pollution levels to predefined safety thresholds. They could not evaluate pollution status and flashover risk warnings. More accurate monitoring systems and more intelligent expert evaluation platforms are urgently needed. A key step in improving online pollution monitoring systems is resolving the relationship between real-time measurements and the worst-case scenario values, as flashover typically occurs only when the insulator surface is fully saturated with moisture, not under normal operational (non-saturated) conditions.

Beyond leakage current monitoring, other pollution detection techniques have also been explored. For example, infrared thermography is based on the fact that leakage current on wet, polluted insulators generates Joule heating, which increases surface temperature. The more severe the contamination, the more

significant the temperature rise. However, this heating phenomenon is heavily influenced by ambient temperature, humidity, and operating voltage. Studies have shown that clean insulators and dry, polluted insulators do not exhibit noticeable temperature changes during operation, while wet, polluted insulators show significant variations.

To enhance infrared-based detection, researchers have combined image processing techniques with infrared imaging to extract relevant features. For instance, a wavelet-based generalized Gaussian distribution and maximum a posteriori estimation method has been proposed for infrared image denoising, which outperforms traditional methods. For infrared images where insulator-background contrast is weak, some researchers have divided the image into background and insulator regions, used grayscale histogram metrics to compute intra-class absolute differences, and applied pulse-coupled neural networks with iterative processing to achieve optimal image segmentation. Additionally, combining hyperspectral imaging and infrared thermography has proven effective. Hyperspectral data provide information on surface contamination composition and concentration, while infrared imaging reveals thermal characteristics. Together, these parameters can be used to establish models that classify pollution levels, expanding the scope of pollution state detection.

Apart from online monitoring, offline computational methods also play a critical role in pollution assessment. These methods correlate environmental monitoring data, such as the concentrations of fine particulate matter with aerodynamic diameters of $2.5\text{ }\mu\text{m}$ or less (PM_{2.5}) with measured ESDD to build pollution prediction models. It helps devise anti-flashover strategies for regional grids, thereby improving system reliability.

In summary, both domestic and international efforts have made significant progress in insulator contamination monitoring, resulting in the development of a variety of technical solutions. However, each method has its limitations. Future research should focus on enhancing the accuracy, reliability, and adaptability of monitoring technologies to better ensure the safe operation of power systems.

1.6 Main Content of the Book

As climate conditions grow increasingly complex, there is a pressing need for the rational design, scientific operation, and effective maintenance of external insulation in high-voltage transmission and transformation equipment. In response, this book systematically presents the latest research on the dynamic evolution of surface wetting and pollution-induced discharge phenomena affecting external insulation systems. We hope it could offer a comprehensive analysis of the challenges that climate change poses to insulation performance. It explores the

intricate relationships between environmental factors, material properties, and surface contamination, all of which have a direct impact on insulation reliability and service life.

The content is divided into four major thematic sections, as shown in Figure 1.3.

1. This section (Chapters 2–6) delves into how various environmental factors—such as saturated and unsaturated humidity, temperature variations, fog, and salt dissolution—impact the wetting behavior of contaminated insulation surfaces. These mechanisms are crucial to understanding the formation and persistence of conductive paths that lead to insulation failure.
2. Covered in Chapters 7–10, this section focuses on the hydrophobic properties of insulation materials and their effects on contamination wetting. It investigates how different levels of surface hydrophobicity and material characteristics influence flashover behavior and how these effects are modulated by other factors.
3. Chapters 11–12 introduce modern techniques for monitoring contamination on insulation surfaces. Special attention is given to real-time monitoring systems that operate under various humidity conditions, offering practical insights into predictive maintenance and reliability improvements.
4. The final technical section (Chapters 13–14) presents advanced analysis and correction strategies for soluble salt contamination on insulation surfaces. It includes spatial and temporal analysis methods and solutions to improve contamination assessments under changing environmental conditions.

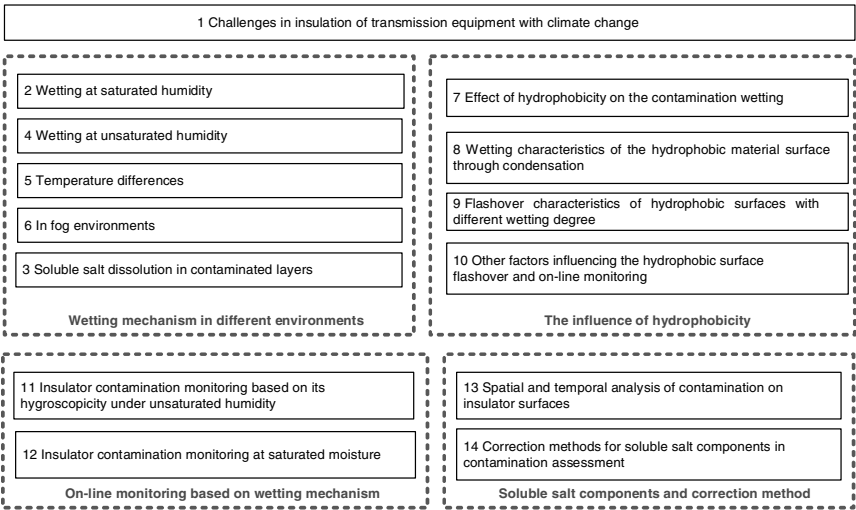


Figure 1.3 The book's graphical summary.

Bibliography

- Bojovschi, A., Rowe, W., and Wong, K. The influence of hanging water droplets on discharge activity, application to high voltage insulators, *Appl. Phys. Lett.*, 2011, 98 (9), 091504.
- Bruggeman, P., Guns, P., Degroote, J. et al. Influence of the water surface on the glow-to-spark transition in a metal-pin-to-water electrode system, *Plasma Sources Sci. Technol.*, 2008, 17 (4), 045014.
- Fujii, O., Honsali, K., Mizuno, Y. et al. A basic study on the effect of voltage stress on a water droplet on a silicone rubber surface, *IEEE Trans. Dielectr. Electr. Insul.*, 2009, 16 (1), 116–122.
- Fujii, O., Honsali, K., Mizuno, Y. et al. Vibration of a water droplet on a polymeric insulating material subjected to AC voltage stress, *IEEE Trans. Dielectr. Electr. Insul.*, 2010, 17 (2), 566–571.
- Guan, Z., Yu, S., and Jia, Z. The pollution and hydrophobicity properties of RTV coating, *High Volt.*, 1993, 19 (4), 28–32.
- He, L. and Gorur, R.S. Source strength impact analysis on polymer insulator flashover under contaminated conditions and a comparison with porcelain, *IEEE Trans. Dielectr. Electr. Insul.*, 2016, 23 (4), 2189–2195.
- Jiang, X.L., Zhao, S.H., Xie, Y.B. et al. Study on fog flashover performance and fog-water conductivity correction coefficient for polluted insulators, *IET Gener. Transm. Dis.*, 2013, 7 (2), 145–153.
- Liang, X. and Li, S. Looking to the future of composite insulators, 2015 INMR World Congress, Munich, Germany, 2015, pp. 18–21.
- Liang, X., Gao, Y., Wang, J. et al. Rapid development of silicone rubber composite insulator in China, *High Volt.*, 2016, 42 (9), 2888–2896.
- Liu, Y. and Du, B.X. Energy eigenvector analysis of surface discharges for evaluating the performance of polymer insulator in presence of water droplets, *IEEE Trans. Dielectr. Electr. Insul.*, 2014, 21 (6), 2438–2447.
- Liu, Y., Du, B., and Farzaneh, M. Self-normalizing multivariate analysis of polymer insulator leakage current under severe fog conditions, *IEEE Trans. Power Deliv.*, 2017, 32 (3), 1279–1286.
- Liu, Y., Wu, Y., and Du, B.X., Dynamic formation mechanism of water droplet and induced surface discharges on SiR composites, *High Volt.*, 2019, 4 (1), 59–64.
- Nazemi, M.H. and Hinrichsen, V. Experimental investigations on water droplet oscillation and partial discharge inception voltage on polymeric insulating surfaces under the influence of AC electric field stress, *IEEE Trans. Dielectr. Electr. Insul.*, 2013, 20 (2), 443–453.
- Obenaus, F. Contamination flashover and creepage path length, *Deutsche Elektrotechnik*, 1958, 12, 135–136.

- Salem, A.A., Rahman, R.A., Kamarudin, M.S. et al. Factors and models of pollution flashover on high voltage outdoor insulators: review, IEEE Conference on Energy Conversion (CENCON), 2017, pp. 241–246.
- Soares, D., Mendonça, S., Neto, E. et al. Electrical field on non-ceramic insulators and its relation to contact angles for constant volume droplets, J. Electrostat., 2016, 84, 97–105.
- Wilkins, R. and Al-Baghdadi, A.A.J. Arc propagation along an electrolyte surface, Proc. Inst. Electr. Eng., 1971, 118 (12), 1886–1892.
- Wilkins, R. Flashover voltage of high-voltage insulators with uniform surface-pollution films, Proc. Inst. Electr. Eng., 1969, 116 (3), 457–465.
- Yang, L. Evaluation of wetting condition and its effects on pollution flashover voltage of aerodynamic insulators, IEEE Trans. Dielectr. Electr. Insul., 2016, 23 (5), 2875–2882.
- Zhang, C.Y., Hu, J.Y., Li, J.C. et al. Experimental study on the contamination deposition characteristics of insulators in a fog–haze environment, IET Gener. Transm. Dis., 2018, 12 (2), 406–413.
- Zhang, C.Y., Wang, L.M., Guan, Z.C. et al. Pollution flashover performance of full-scale ± 800 kV converter station post insulators at high altitude area, IEEE Trans. Dielectr. Electr. Insul., 2013, 20 (3), 717–726.