Abstract: The electric field distributions along gas-solid interfaces determine the reliability, lifetimes and sizes of gaseous insulated switchgears/pipelines (GIS/GIL), which also affect the reliability of power systems. In this study, the characteristics of steady and transient electric field distributions were first introduced, followed by the concept of functionally graded materials (FGMs). The development histories of FGM applied in electrical engineering and the related optimisation methods were described in detail. The field regulation effect and fabrication technology of different FGM insulators were also compared. To overcome the limitations of traditional FGM insulators, the design of surface FGM (SFGM) was proposed, together with their preparation methods and electrical performance. Furthermore, the future development prospects of FGM and SFGM insulators for compact GIS/GIL were summarised.

1 Introduction

Nowadays, large-scale wind farms inland and offshore, as well as solar generation stations, are under planning or construction, which requires reliable and economical power transmissions and conversions. The technology of gaseous insulated switchgears and pipelines (GIS/GIL) invented in the 1960s has been proven feasible since the installation of the first high voltage GIS in 1968 and the first 420 kV GIL in 1974 [1]. GIS and GIL are indispensable for power generation, transmission and distribution, based on their various advantages compared with the traditional methods [2].

Spacers are the most critical components in GIS/GIL, playing the role of electric insulation, mechanical support and chamber isolation [3, 4]. However, the mismatch of dielectric parameters at gas-solid interfaces causes electric field (E-field) concentration around the spacers, leading to partial discharges and even flashovers over spacers. For the AC case, the E-field distribution mainly depends on the permittivity of involved dielectrics [5]. For the DC case, the steady-state E-field distribution depends on the conductivity distribution. Since the conductivity of the epoxy insulator is strongly temperature dependent, it is very difficult to design the DC gas–solid insulation system [6].

The E-field optimisation of the gas–solid system can help increase the flashover voltage and downsize the devices, thereby saving costs and reducing greenhouse gas emissions [7]. To improve the insulation performance of GIS/GIL, various techniques have been applied to reduce the E-field concentration such as modifying the spacer shape and installing shielding/embedded electrodes [8]. However, these methods have high cost and low efficiency; thus, efficient and simple techniques are highly desired.

With the continuously increasing demand for electrical power, the status of large-capacity and long-distance power transmissions is particularly prominent. The critical issues in the development of high voltage GIS/GIL are the reliability of the insulation system and the greenhouse effect of SF6 gas. All the above problems can be effectively solved or relieved by E-field optimisations.

2 E-field distribution in GIS/GIL

2.1 E-field under AC voltage

In an AC GIS/GIL, for a specific geometry, the E-field distribution is capacitive and mainly depends on the insulating materials' permittivity. Equations for the field calculation are shown below:

\[ V \cdot J = 0 \]  
\[ J = \sigma E + j\omega D \]  
\[ E = -\nabla V \]

where \( E \) is the E-field strength, \( V/m \); \( V \) is the electric potential, \( V \); \( J \) is the current density, \( A/m^2 \); \( \sigma \) is the volume conductivity of the involved dielectrics, \( S/m \); \( \omega \) is the angular frequency of the power grid, rad/s and \( D \) is the electric flux density, \( C/m^2 \).

As the relative permittivity of a material is almost independent of the E-field and temperature, the field distribution in an AC GIS/GIL can be obtained by a steady state calculation, which can then be extrapolated to almost all voltage stresses.

2.2 E-field under DC voltage

Under DC voltage, the E-field distribution is initially capacitive (similar to AC) and then progressively becomes resistive. The E-field distribution in DC GIS/GIL depends on the electrical conductivities of the insulating materials, which are affected by many factors such as temperature, running time and gas convection, and have a very large uncertainty [15, 16]. When the E-field strength at the gas–solid interface exceeds a certain threshold, processes such as field-electron emission, gas ionisation or carrier injection triggers flashovers along insulator surfaces [17].
closely related to the dielectric and conductance characteristics of thereby reducing the service life of the equipment. Considering the distribution undergoes a process from steady-state to transient-induced by local E-field distortions in actual GIS equipment will which of the three field distribution states (capacitive, resistive or flashovers on the insulator surface. In addition, when a DC generated by the reclosing will be combined with it. The E-field lifetime curve, i.e. the voltage–time (V–t) curve, is used. Fig. 1 shows a schematic representation of the life time curve of solid dielectrics. The relationship between the breakdown strength and the life time is typically expressed as follows [21]:

\[ t = t_0 \left( \frac{E}{E_0} \right)^n \]  

(4)

where \( E \) is the breakdown strength; \( t \) is the operation time; \( t_0 \) and \( E_0 \) are values on the life time curve as reference; and \( n \) is a voltage endurance coefficient of epoxy insulators. For a typical epoxy spacer, \( n \) is obtained in the range from 10 to 20.

Therefore, the E-field distortion at the gas–solid interface is considered the basic cause of flashovers or breakdown of insulators. It is also the development bottleneck of ultra-high voltage gas-insulated equipment, which needs to be solved urgently.

3 Bulk FGM insulator for compact GIS/GIL

The current common solutions in response to the above issues can be divided into two categories: The first one is based on structural optimisation. The second one is mainly based on the modification of insulating materials, e.g. nanocomposite, surface treatment, non-linear conductivity materials, etc. [22, 23].

In recent years, researchers have tried to find new technologies to solve the above problems. Some of them have constructed insulating structures with non-uniform distributions of dielectric parameters (dielectric constant/conductivity) to release local E-field [24]. Due to the distinct advantages of FGMs in homogenising E-field distributions and simplifying insulation structures, their great application potential is attracting the attention of scholars worldwide.

3.1 Origins of FGM Insulators

FGMs are advanced engineering materials designed for a specific property or function in which spatial gradations in the structure and/or composition endow them with tailor-made characteristics. Bever and Duwez first researched the theoretical significance of graded structure composite materials in 1970 [25]. A decade later, Brealey et al. [26] from the General Electric Company first fabricated a capacitance-graded 23 kV post insulator using the lamination method, i.e. laminating and adhering materials with different dielectric properties to compose a graded insulation structure. Compared with ungraded insulators, the withstand voltages of the graded insulators showed an increment of \( \sim \)10%. Later, Hayashi and Watanabe prepared coaxial disk-type and post-type FGM spacers using the lamination process. For the disk-type FGM spacers, the permittivity distributions decreased from the HV electrode to the GND electrode in the radial direction in different manners, as shown in Fig. 2. The results showed that the E-field strength at the HV triple junction was greatly weakened by \( \sim \)44% in a superior manner and the surface breakdown voltage was obviously improved by using FGM spacers compared with the ungraded spacer [27, 28].

Although the effects of lamination method on improving the insulation properties of epoxy insulators have been confirmed by many researchers, there are some limitations on its application. For instance, the lamination method has difficulty achieving a continuous change in dielectric properties, which results in E-field distortions between gradients. Future studies should focus on relieving variations in dielectric properties, reducing defects between different layers and increasing the long-term efficacy to further improve the E-field distribution and the withstand voltage.

3.2 Fabrication of bulk FGM Insulators

3.2.1 Centrifugation method: The centrifugation method is one of the classical methods for FGM preparation. Kurimoto et al. [29] first succeeded in fabricating \( \epsilon \)-FGM spacers by applying centrifugal force to epoxy/SiO\(_2\)/TiO\(_2\) composites. Particles move in the liquid epoxy resin under the centrifugal force, forming gradient distributions of filler contents, i.e. permittivity gradients. The permittivity distribution of an \( \epsilon \)-FGM spacer can be controlled by
controlling the resin viscosity, particle size, centrifugal force, centrifugal time, etc. In 2006, Kato et al. fabricated FGM spacers with epoxy and TiO$_2$ fillers (average diameter: 8.7 μm) using the centrifugation method. Simulations and tests showed that the E-field strength at the triple junction of the FGM insulator was weakened by ∼20% and the flashover voltage was improved by ∼69% in 0.4 MPa SF$_6$ gas compared with the uniform insulator [9]. In 2012, Hayakawa et al. [30] fabricated GLP-FGM and U-FGM spacers in disk type. Fig. 3 shows the concept and schematic illustration of fabricating GLP-FGM and U-FGM spacers. Fig. 4 presents the relative permittivity distributions of GLP-FGM and U-FGM spacers. The maximum E-field strength can be reduced by ∼12% with the coaxial-type U-FGM. Compared with the lamination method, the permittivity distributions of GLP-FGM and U-FGM spacers fabricated by the centrifugation method are continuous, and no interface can be observed. However, the controllability of the centrifugation method is weak; it is difficult to fabricate an FGM spacer with an optimal permittivity distribution. To bring this method into practical application, further research on the flow process of epoxy/filler systems is desired.

3.2.2 Three-dimensional (3D) Printing technology: The 3D printing technique is considered a novel and promising method for preparing d-FGM insulating spacers [31]. Fig. 5 shows two types of 3D printers and their working principles. In 2016, Kurimoto et al. [32] printed a conical insulating spacer layer by layer, as shown in Fig. 5a. The liquid ultraviolet (UV)-cured-acrylic resin with alumina fillers was poured onto the resin tray and irradiated with a scanning UV light through the transparent bottom of the tray. By elevating the building support plate step by step, the resin was cured layer by layer until the spacer was built up. In 2008, they printed a two-layered permittivity-graded insulator using unfilled and alumina-filled UV-cured resins [33]. In 2019, Zhang and co-workers printed a non-uniform conductivity spacer by fused deposition modelling, as shown in Fig. 5b [34]. Acrylonitrile butadiene styrene (ABS), polylactic acid, ABS/carbon black composites, and PLA/graphene composites were chosen as printing materials, which were heated, extruded and deposited under 3D control, forming a non-uniform spacer point by point. The flashover voltage improvement of the non-uniform conductivity insulator was verified both in SF$_6$ and vacuum under DC voltages. In 0.3 MPa SF$_6$, the flashover voltage was 23.8% enhanced for the non-uniform ABS insulator, and 16% enhanced for the non-uniform PLA insulator. In vacuum, the flashover voltage was increased by 19.1% for the non-uniform ABS sample, and 20.9% for the non-uniform PLA sample. Since the 3D-printed spacers are built by continuous accumulation of material units (layers or points), this method has the potential to fabricate FGM spacers with any designed permittivity and conductivity distributions inside. However, some technical obstacles must be overcome before industrial application, e.g. limited printing materials, difficult dielectric property adjustment, and uncertain mechanical performances.

3.2.3 Flexible mixture casting (FMC) method: The flexible mixture casting (FMC) method was proposed by Hayakawa et al. [35] to fabricate ε-FGM spacers, as shown in Fig. 6. The high-ε resin was prepared by filling the epoxy resin with high-ε SrTiO$_3$ particles, and the low-ε resin was prepared by filling epoxy resin with low-ε SiO$_2$ particles. Two resins were mixed by a blender, and the mixing ratio was continuously and flexibly controlled by the
injection speeds of the high-\(\varepsilon\) and low-\(\varepsilon\) resins. The mixture was introduced into a casting mould and accumulated in layers with a controlled mixing ratio. After resin injection, the spacer was put into an oven and cured for 15 h at 80°C.

Fig. 7 shows the \(\varepsilon\)-FGM spacer model fabricated by the FMC method. The stacked resin distribution implies that a permittivity gradient was formed. Compared with the centrifugation method, the FMC method can be used to fabricate FGM insulators with designed permittivity and conductivity distributions, thereby maximising the E-field relaxation effect. However, there will be many interfaces composed of neighbouring resins, so the mechanical and dielectric properties of the interfaces should be improved before application.

3.2.4 Magnetophoresis and electrophoresis methods: In addition to the abovementioned methods, the magnetophoresis and the electrophoresis methods have also been introduced to fabricate FGM. In 2016, Nardi et al. [36] prepared FGM samples by applying an external magnetic field on the suspension system of Fe\(_3\)O\(_4@\)TiO\(_2\) nanoparticles and epoxy resin using electrophoresis (i.e. DC voltage application), as shown in Fig. 8. Numerical simulations clarified that these graded composites can reduce the E-field strength at the triple junction by up to 45% compared with the conventional one. In 2018, Diaham et al. proposed an original method to structure FGM on metalised alumina DBC substrates by local handling of high-permittivity ceramic (SrTiO\(_3\)) particles in epoxy resin using electrophoresis (i.e. DC voltage application), as shown in Fig. 9 [37]. By applying FGM, an impressive attenuation of the field reinforcement at the triple point can be obtained, and the breakdown voltages were improved by ~70 and ~30% compared with neat epoxy and the homogeneous composite. The magnetophoresis and electrophoresis methods are similar to the centrifugation method, but more flexible and simpler; the permittivity distribution can be adjusted by controlling the electric/magnetic field distribution. Before practical application, further research into magnetic/electrostatic preparation and accurate control of magnetophoresis/electrophoresis are desired for fabricating large-scale and complex-shaped insulators.

4 Optimising dielectric parameter distributions of FGM insulators

With the development of fabrication techniques for FGM insulators, it becomes feasible to manufacture insulators with designed dielectric parameter distributions to maximise the E-field relaxation effect. Various optimisation methods have been developed to modify the distribution of dielectric parameters (conductivity and/or permittivity) in solid insulators while keeping insulators in simple contour form.

4.1 Iterative optimisation

In 2006, a computer-aided technique for optimising FGM solid insulators was proposed by Okubo et al. [38]. The optimal spatial distribution of permittivity was defined as ‘the distribution which can relax the field stress most effectively inside and around the insulator’. The E-field calculation was carried out with the finite element method (FEM), and the E-field optimisation in each FEM
where $\varepsilon_i$ and $\varepsilon_i'$ are the relative permittivity at $P_i$ before and after modification, respectively; $E_{ij}$ is the E-field strength at $P_i$; and $E_{0ij}$ is the objective value of the E-field strength. $\varepsilon_{\text{max}}$ and $\varepsilon_{\text{min}}$ are the limits of the relative permittivity, respectively. $\varepsilon_{\text{min}} = 4$, and $\varepsilon_{\text{max}}$ varies from 8 to 200. $C$ is the modification coefficient, whose initial value $C_0 = E_{0ij}/E_{\text{max}}$ in the first calculation. When $C$ is < 0.01, the variation range of $E_{\text{max}}$ is < 0.1 kV/mm, and the optimisation process stops.

Fig. 10a shows the optimal permittivity distribution of a rotationally symmetric cone-type FGM spacer, which is continuously and complexity graded in the bulk. Fig. 10b shows the E-field relaxation effect of the optimal FGM spacer. The E-field distortion in and around the spacer is significantly reduced by the optimal FGM spacer. A larger permittivity range leads to a better E-field relaxation effect.

Recently, the authors’ team developed a relatively simple method to optimise the dielectric parameter distribution [40]. The non-uniform E-field distribution along the insulator surface is considered the key factor that triggers surface flashovers. The insulation margin of the insulator bulk is so large that there is no need to optimise the E-field distribution inside the insulator, and the optimisation objective can be set as the surface E-field distribution.

The following multi-objective design is presented to improve the insulation performance of the gas–solid insulation system. The iterative method is simple and effective, but the semi-empirical formula for adjusting the permittivity distribution is not suitable for all cases.

### 4.2 Topology optimisation

Topology optimisation is usually used in the field of structural mechanics to improve the mechanical performances by optimising the material distribution for given design space, loads and other conditions. Recently, Zhang and co-workers introduced the topology optimisation method to optimise the FGM insulator point by point [41]. The spatial distribution of the relative permittivity in an FGM insulator (area $I$) is represented by the variable density method.

$$\varepsilon(r, z) = (\varepsilon_{\text{max}} - \varepsilon_0)\rho_{\text{design}} + \varepsilon_0 (r, z) \in \Omega_I$$

where $\rho_{\text{design}}$ is the control variable and $\varepsilon_{\text{max}}$ and $\varepsilon_0$ is the maximum and minimum relative permittivity of the FGM insulator. The following multi-objective design is presented to improve the uniformity of the E-field distribution.
\[ \min f = (1 - q)f_1 + qf_2 \]
\[ \begin{align*}
\text{s.t.} \\
10^{-9} \leq \rho^p \leq 1 \\
0 \leq \int \rho \, d\Omega \leq \gamma A, \, \Omega \in \Omega_i 
\end{align*} \]

where \( A \) is the cross-section area of the spacer; \( q \) is a weighting parameter balancing \( f_1 \) and \( f_2 \); and \( f_1 \) and \( f_2 \) are assigned to control the uniformity and reliability of the permittivity distribution, respectively.

\[ f_1 = \frac{1}{C_{\text{ref}}} \int \left| \frac{E - E_{\text{mean}}^1}{\sigma} \right|^2 \, d\Omega, \, \Omega \in \Omega_i \cup \Omega_{II} \]
\[ f_2 = h_{\text{max}} \frac{A}{\rho_{\text{design}}} \int \left| \nabla \rho \right|^2 \, d\Omega, \, \Omega \in \Omega_{II} \]

The global convergent method of moving asymptotes (GCMMA) was used to solve this design problem. Fig. 13 shows the permittivity and E-field distributions after optimisation. The E-field concentration at the triple junction point is relaxed by the FGM insulator, and a larger permittivity range leads to a better field relaxation effect.

### 4.3 Particle swarm optimisation (PSO)

PSO is a kind of intelligent searching optimisation algorithm involving simulating the group cooperation behaviours of birds foraging. The PSO method has the advantages of simple concept, easy realisation with only a few tuning parameters and so on. In 2015, Qasim and Gupta [42] introduced the PSO method to modify the spatial distribution of the permittivity in a spacer. The optimisation objective is shown as follows and was solved by the PSO algorithm:

\[ \min F(\varepsilon) = \omega(\varepsilon) \cdot \max (E_i) + (1 - \omega) \cdot \text{stddev}(E_j) \]
\[ \forall i \in \{ \text{the total polygons} \} \]
\[ \forall j \in \{ \text{node points inside insulator} \} \]

where \( E_i \) is the E-field of polygon \( i \) in and around the insulator; \( E_j \) is the E-field of node point \( j \) inside the insulator; \( \omega \) is a vector of permittivity values of polygons inside the insulator; and \( \omega \) is a weighing factor.

After optimisation, the maximum E-field in the spacer with a pareto-optimal permittivity distribution is significantly reduced, as shown in Fig. 14. However, the E-field distribution is not non-monotonic, which may be addressed by a choice of smaller polygons at the cost of greatly increasing the calculation burden.

Recently, the researcher applied this technique to uniform the E-field distribution in a cable termination by using a stress control tube, obtaining an optimised permittivity gradation as shown in Fig. 15 [43]. The maximum E-field is relaxed by \( \sim 62\% \), and the field utilisation factor is improved to \( \sim 67\% \).

To optimise the dielectric parameter distributions, the correct object should first be determined. Currently, most researchers are concerned with the norm of the E-field inside and around the insulator. However, in a gas-solid system, the insulation weakness point is usually the gas–solid interface instead of the insulator bulk. There are tangential and normal E-field components along the gas–solid interface, so their weighting factors during the flashover inducement and development processes are critical for the optimisation. Moreover, the mechanical performances of FGM insulators should also be considered in future optimisation work.

### 5 Surface FGM (SFGM) insulator for compact GIS/GIL

At present, FGM insulation design mainly involves controlling the spatial gradient distribution of the dielectric constant or conductivity in solid insulation structures, thus effectively suppressing E-field distortions, and ultimately improving the flashover voltage of gas-solid insulation systems [24]. However,
FGM insulators are faced with the problems of optimisation of the spatial distribution of dielectric parameters, complex fabrication processes and low efficiency in industrial applications. Therefore, novel gradient modification methods are urgently needed [22]. The concept of SFGMs was proposed to form functionally graded spatial distribution of dielectric parameters, complex fabrication treatment, which means regulating the dielectric parameter distributions on the insulator surface [44].

5.1 Concept of SFGM

In our previous study, equivalent circuits for conventional (Fig. 16a), surface \( \varepsilon \)-uniform (Fig. 16b) and \( \varepsilon \)-SFGM insulators (Fig. 16c) were introduced to qualitatively describe the working principle of SFGM by assuming that the equipotential lines were parallel to the top and bottom surfaces of insulators [45]. The conventional insulator has a uniform relative permittivity distribution of \( \varepsilon \approx 6.8 \) inside the bulk. By grading the thickness distribution of the high-permittivity layer (over 1000) layer in the radial direction, the \( \varepsilon \)-SFGM insulator can be obtained.

In Fig. 16a, an insulator is divided into \( n \) \((n \to \infty)\) slices in the height direction. Each slice \( j \) has a radius of \( r_j \) and a height of \( dL \), forming a capacitor. The conventional insulator can be approximately represented by a capacitor series of \( C_j \), whose value can be described as

\[
C_j = \frac{\varepsilon_0 \varepsilon_r r_j^2}{dL} \quad (13)
\]

According to circuit theory, the E-field strength in each slice can be calculated by the following equation, which indicates that the E-field is inversely proportional to the square radius of a slice and the distribution is extremely uneven.

\[
E_i^n = \frac{dV_i}{dL} = \frac{I_{1a}}{2 \pi \varepsilon \varepsilon_0 d} \cdot \frac{1}{r_i^2} \quad (14)
\]

In Fig. 16b, each slice \( i \) of the surface layer of the surface \( \varepsilon \)-uniform insulator can be regarded as a capacitor in a cylindrical ring shape with a radius of \( r_i \), a thickness of \( d \) and a height of \( dl \). When the capacitance of the surface capacitor \( C_{si} \) is much higher than that of the bulk capacitor \( C_i \), the surface \( \varepsilon \)-uniform insulator can be approximately represented by a capacitor series of \( C_{si} \). The E-field strength in each slice can be calculated by,

\[
E_i^b = \frac{dV_i}{dL} = \frac{I_{1b}}{4 \pi \varepsilon_0 \varepsilon_r d} \cdot \frac{1}{r_i} \quad (15)
\]

From the above equation, the E-field of the surface \( \varepsilon \)-uniform insulator is inversely proportional to the radius of a slice, and the E-field distribution is more uniform than that of the conventional insulator.

By grading the thickness of the high-permittivity surface layer in the form of an inverse proportional function \((d(r_i) = \text{const}/r_i)\), a \( \varepsilon \)-SFGM insulator can be obtained, as shown in Fig. 16c. The E-field can be calculated by

\[
E_i^c = \frac{I_{1c}}{4 \pi \varepsilon_0 \varepsilon_r d(r_i)} \cdot \frac{1}{r_i} = \frac{\text{const} \cdot I_{1c}}{4 \pi \varepsilon_0 \varepsilon_r d} \quad (16)
\]

In this case, the E-field distribution along the \( \varepsilon \)-SFGM insulator surface is ideally uniform. Although this model does not consider the influence of the stray capacitance, it can help easily understand the working principle of the SFGM insulator.

5.2 Fabrication of SFGM insulators

5.2.1 Dip coating method: Miyaji applied the dip coating method to fabricate SFGM insulators with localised conductive layers, as shown in Fig. 17 [46]. They chose \( \sigma \)-SFGM insulators instead of \( \varepsilon \)-SFGM insulators to relax AC E-field concentrations because it is difficult to prepare huge-permittivity (over 1000) coatings. An alternative approach is to reduce the complex impedances of the surface layer by applying high-conductivity coatings. Although the AC E-field distribution was uniformed, high-conductivity coatings
may cause unacceptable conduction loss. Moreover, the conductivity gradient was not continuous, and E-field distortions could be generated between the gradients.

### 5.2.2 Magnetron sputtering method:

To fabricate \( \varepsilon \)-SFGM insulators for AC E-field relaxation, the magnetron sputtering method was proposed to deposit huge-permittivity BaTiO\(_3\) layers on insulator surfaces [47]. The E-field relaxation effect of the surface \( \varepsilon \)-uniform insulator has a ‘saturation effect’. As shown in Fig. 18, the maximum E-field strength declines with increasing the permittivity and thickness of the sputtering layer and finally reaches a stable value when the product of the sputtering layer permittivity and thickness is high enough [45]. To maximise the E-field relaxation effect of the \( \varepsilon \)-SFGM insulator, the iterative method was used to optimise the thickness distribution of the sputtering layer, as shown in Fig. 19 [48]. After four iterations, the thickness distribution of the sputtering layer converges to the optimal solution; and a continuous sputtering method was used to fabricate the optimal \( \varepsilon \)-SFGM insulator. During sputtering, the sputtering time and the layer thickness distributions were controlled by a rotating mask with a designed gap above the insulator. Compared with the conventional insulator, the maximum E-field of the optimal \( \varepsilon \)-SFGM insulator was reduced by \( \sim 70\% \), and the AC flashover voltage was improved by \( \sim 20\% \) in air. Compared with the dip coating method, the \( \varepsilon \)-SFGM insulator fabricated by the magnetron sputtering method had a much lower conduction loss due to the huge-permittivity layer. In addition, the thickness distribution of the sputtering layer was continuous and optimal, thus exhibiting a better E-field relaxation effect. However, both the dip coating and sputtering methods are faced with the problem of long-term interface stability. Future research should focus on enhancing the binding ability and interfacial compatibility between the sputtering layer and the insulator before practical application.

### 5.2.3 Gradient fluorination method:

Under a DC voltage, the conductivity distribution of the dielectric materials determines the steady-state E-field distribution. Thus, the design of surface conductivity distribution provides an idea for DC E-field control. The fluorination treatment is simple and efficient in improving the surface conductivity and other electrical parameters of polymers [49, 50]. As shown in Fig. 20 the thickness of the fluorination layer and the surface conductivity of epoxy increase with the fluorination time and the fluorination temperature. The gradient fluorination method was thus proposed by the authors’ team to fabricate \( \varepsilon \)-SFGM insulators with a continuous surface conductivity gradient [51, 52]. During fluorination, a heater was placed on the insulator top to form a continuous temperature gradient, controlling the distribution of fluorination rate and regulating the thickness distribution of the fluorination layer, as shown in Fig. 21a. By changing the temperature distribution and the fluorination time, continuous \( \varepsilon \)-SFGM insulators with different surface conductivity gradients can be fabricated, as shown in Fig. 21b. An obvious E-field reduction can be observed at the triple junction point of the SFGM insulator, as shown in Fig. 21c. The DC flashover voltage of the \( \varepsilon \)-SFGM insulator was improved up to \( \sim 33\% \) in air compared with the conventional insulator. Compared with the coating and the sputtering methods, SFGM insulators fabricated by the gradient fluorination method have no interface problems. However, the relationship among the surface conductivity, fluorination time and fluorination temperature is complicated and influenced by some external factors. Accurate control of the temperature distribution during fluorination is also critical for obtaining the optimal surface conductivity gradient. After solving the above problems, \( \varepsilon \)-SFGM insulators fabricated by the gradient fluorination method can be brought into practical application.

### 6 Conclusions

Suppressing the E-field distortion at gas-solid interfaces is the key of the insulation design to reduce flashovers and further promote the compactness of high-voltage gas insulated equipment. FGM for relaxing E-field concentrations has been developed for decades,
are faced with the problems of long-term interface reliability. The future development of SFGM insulators should be carried out from three aspects: optimisation design, material preparation and performance evaluation. In the aspect of optimisation design, SFGM insulators should have continuous and optimal gradients to maximise the E-field regulation effect and minimise the loss power; in the aspect of material preparation, novel surface treatment techniques should be proposed for modifying the surface dielectric parameters and enhancing the interface binding ability and interfacial compatibility before practical application; (3) in the aspect of performance evaluation, a performance evaluation system for SFGM insulators should be established and perfected considering actual working conditions.

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