Mechanical stress distribution and risk assessment of 110 kV GIS insulator considering Al$_2$O$_3$ settlement

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Abstract: The growing application of gas insulated switchgear (GIS) in electric power system asks for higher reliability of epoxy (EP) insulators, thus it is important to seek effective methods to improve the operating reliability of GIS insulators. On the basis of the 110 kV GIS insulator, this study studied the aluminium oxide (Al$_2$O$_3$) settlement in the curing process and the stress distribution of the horizontally laid GIS. Besides, the risk coefficient was defined to evaluate the operating reliability of insulators laid by different methods (I–V). Some conclusions are shown below: the Al$_2$O$_3$ settlement in the curing process causes the insulator density to have a large variation from 2.13 to 2.32 g/cm$^3$. The Al$_2$O$_3$ content has a great influence on the mechanical performances of EP/Al$_2$O$_3$ system. The first principle stress is localised on the upper interface between the insulator and the conductor, which is the main threat to the mechanical damage of insulator. The laying method V appears to be optimal with a pretty low risk coefficient of 31.5. In actual application, for the horizontally laid GIS, the insulator should be laid with the mould gate downward to improve its mechanical reliability.

1 Introduction

Gas insulated switchgear (GIS) and gas insulated line (GIL) have been widely used in electric power system because of its high reliability and low footprint [1–5]. The GIS insulator is made of epoxy (EP)/aluminium oxide (Al$_2$O$_3$) composites that play the role of insulation and support in GIS. The reliability of GIS insulators is directly related to the safe and stable operation of the electric power system. A survey in China shows that mechanical failure accounts for a large proportion in all GIS faults, whose proportion reaches 39.3%, even higher than that of the insulation failure of 38.1% [6]. Therefore, it is important to conduct studies on improving the mechanical reliability of the GIS insulator.

Researchers at home and abroad have performed much work on the mechanical properties of high-voltage electrical equipment [7–13]. However, all the studies were based on an ideal assumption that the insulators were homogeneous. In industrial production, most of the EP resin casting products, especially the GIS insulators, are inhomogeneous via the Al$_2$O$_3$ settlement during the curing process. A sample test made by an insulator manufacturer shows that the density difference from top to bottom of the 110 kV GIS insulator is ~0.12 g/cm$^3$. Previous studies have shown that the Al$_2$O$_3$ content is closely related to the mechanical properties (elastic modulus, Poisson ratio, tensile strength, compressive strength and so on) of EP/Al$_2$O$_3$ composites [14–16]. The large density variation must have a significant effect on the mechanical performances of the GIS insulator.

On the basis of the 110 kV GIS insulator produced by Shandong Taikai High Voltage Switch Co. Ltd., the Al$_2$O$_3$ settlement in the curing process and the mechanical stress distribution of insulator in a horizontally laid GIS were studied in this paper. Since the density-dependent mechanical properties and mechanical stress distributions are directional, the mechanical reliability varies when the insulator is laid by different methods (I–V). To evaluate the mechanical reliability of the 110 kV GIS insulator, the risk coefficient is defined in this paper. The results show that the laying method V appears to be optimal with a low risk coefficient of 31.5. In application, for the horizontally laid GIS, an economical and practical approach to improve the mechanical reliability of the 110 kV GIS insulator is to keep the mould gate downward.

2 Experimental setup

2.1 Density measurement

In industrial production, the GIS/GIL insulators are produced by casting. A mixture of liquid EP and micro-sized Al$_2$O$_3$ particles is poured into an upright standing mould under a vacuum, as shown in Fig. 1a. Over 8 h are required to cure the EP/Al$_2$O$_3$ system at 130°C. The mass ratio of the EP matrix (CT 5531), curing agent (HY 5533) and micro-sized Al$_2$O$_3$ fillers is 100:38:330. Since the viscosity of EP/Al$_2$O$_3$ system is as low as 1 Pa s in the beginning, it is easy for the micro-sized Al$_2$O$_3$ particles to settle down via force gravity. As a result, the density of the EP/Al$_2$O$_3$ system varies in the direction of gravity and thus has a non-negligible influence on the mechanical properties of GIS insulators. To study the Al$_2$O$_3$ settlement in the curing process of the EP/Al$_2$O$_3$ system, some cylindrical samples were produced via casting, as shown in Fig. 1b. The length of the samples is 20 mm and the diameter is 10 mm. Next, a slicing machine was used to cut the samples into slices of 1 mm thickness. The density distribution of the cylindrical samples can be obtained by measuring the slice densities using the displacement method.

2.2 Mechanical property measurement

Owing to the Al$_2$O$_3$ settlement, the density of the EP/Al$_2$O$_3$ system varies in the direction of gravity. According to the measured density distribution, samples with different Al$_2$O$_3$ contents were fabricated to test their mechanical properties. The densities of samples were 2.14, 2.19, 2.24, 2.29 and 2.34 g/cm$^3$. Fig. 2 shows the samples for the tensile and compressive tests. The samples for the tensile tests were dumbbell shaped, and the samples for the compressive tests were cylinder shaped. The elastic modulus and Poisson ratio of different samples were also measured to provide the simulation parameters of the mechanical stress distribution.
3 Simulation model

3.1 Al₂O₃ settlement

The settlement of micro-sized Al₂O₃ particles is controlled by the following equations [17]:

\[ m \frac{d^2v}{dt} = mg - F_v - F_b \quad (1) \]

\[ m = \frac{\pi}{6} D_f^3 \rho_f \quad (2) \]

\[ F_b = \frac{\pi}{6} D_f^3 (\rho_f - \rho_{ep})g \quad (3) \]

\[ F_v = 3\pi \eta D_f v_t \quad (4) \]

where \( m \) is the mass of Al₂O₃ particles, kg; \( g \) is the gravitational acceleration, m/s²; \( F_b \) is the buoyancy, N; \( F_v \) is the viscous force, N; \( D_f \) is the grain diameter of Al₂O₃ particles, m; \( \rho_{ep} \) and \( \rho_f \) are the densities of EP resin and Al₂O₃ particles, respectively, kg/m³; \( \eta \) is the viscosity of the EP/Al₂O₃ system, Pa·s; and \( v_t \) is the velocity of Al₂O₃ particles at time \( t \).

The Al₂O₃ particles hit the terminal velocity after a brief acceleration, and the free settling velocity \( v_0 \) can be obtained by setting \( dv/dt = 0 \) [17]

\[ v_0 = \frac{gD_f^2 (\rho_f - \rho_{ep})}{18\eta} \quad (5) \]

Considering the interaction between Al₂O₃ particles, the hindered settling velocity \( v \) can be described by the following equation [17]:

\[ v = v_0 (1 - C/n)^m \quad (6) \]

where \( n \) is the measured coefficient, which is set to 2.22. \( C \) is the Al₂O₃ concentration, whose initial value is set to \( 7.95 \times 10^{11} \) m⁻³.

Fig. 3 shows the Al₂O₃ diameter distribution and the measured viscosity of the EP/Al₂O₃ system during the curing process at 130°C. Fig. 3a shows that the Al₂O₃ diameter has a large variation from 1 to 60 µm. According to (5), the larger particles should have larger settling velocity than the smaller ones. Fig. 3b shows that the viscosity of the EP/Al₂O₃ system increases with the passage of curing time. According to (5), the settling velocity of Al₂O₃ particles decreases as the viscosity of the EP/Al₂O₃ system increases. After \( \sim 70 \) min, the viscosity of pure EP resin reaches 20 Pa·s and the Al₂O₃ settlement becomes slow enough to be neglected. As a result, the simulation time of gravity settling is set to 70 min in this paper. Moreover, the viscosity of the EP/Al₂O₃ system increases with the Al₂O₃ content. The viscosity of the EP/Al₂O₃ system can be described as:

\[ \eta = \eta_0 (1 - C/C_{max})^{-m} \quad (7) \]

where \( \eta_0 \) is the viscosity of the pure EP resin, Pa·s; \( C_{max} \) is the maximum Al₂O₃ concentration, m⁻³; and \( m \) is the correction coefficient, which can be obtained by fitting the data in Fig. 3b.

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Fig. 1 Process of casting the 110 kV GIS insulator and cutting the cylindrical samples
(a) Casting insulator, (b) Cutting samples

Fig. 2 Samples for the tensile test and the compressive test
(a) Tensile test, (b) Compressive test

Fig. 3 Al₂O₃ diameter distribution and the measured viscosity of the EP/Al₂O₃ system
(a) Diameter distribution, (b) Viscosity variation
Fig. 4 shows the simulation model for the Al₂O₃ settlement in the EP/Al₂O₃ system. For cylindrical samples, a one-dimensional mathematical model can be set up to study the Al₂O₃ settlement process, as shown in Fig. 4a [18]. The cylinder is divided into n elements. For element i, the Al₂O₃ concentration can be calculated using the following equation:

\[ C[i] = C[i]_0 - dF_{in}[i] - F_{out}[i] \]  

(8)

where \( C[i] \) is the Al₂O₃ concentration of element i, m⁻³, and \( F_{in}[i] \) and \( F_{out}[i] \) are the inflow and outflow, respectively, of element i, m⁻³

\[ F_{in}[i + 1] = F_{out}[i] = \frac{C[i]v_dr}{L_{ele}} \]  

(9)

where \( dr \) is the time step, s, and \( L_{ele} \) is the size of elements, which is set to 0.001 m.

For the GIS insulator, as shown in Fig. 4b, the inflow and outflow of the boundary elements are slightly different because of the particle slippage on the inner surface of the mould. For element \([i, k]\), the outflow can be calculated using the following equation:

\[ F_{out}[i, k] = \frac{C[i, k]v_dr}{L_{ele}} \]  

(10)

where \( v_i \) is the tangential component of the terminal velocity, m/s.

3.2 Mechanical stress

Fig. 5 shows the local geometric structure of a horizontally laid 110 kV GIS. The diameter of the tank is 315 mm and the distance between the neighbouring insulators is 6 m. The conductor is hollow, with an outer diameter of 80 mm. The insulator is made of EP/Al₂O₃ composites, and the tank and conductor are both made of cast Al. Moreover, 0.4 MPa of sulphur hexafluoride is filled in the tank to improve the dielectric strength. This paper focuses on the static stress distribution, which is controlled by Hooke’s law [19, 20]

\[ \varepsilon_x = \frac{1}{E} [\sigma_x - \mu (\sigma_y + \sigma_z)] \]  

(11)

\[ \varepsilon_y = \frac{1}{E} [\sigma_y - \mu (\sigma_x + \sigma_z)] \]  

(12)

\[ \varepsilon_z = \frac{1}{E} [\sigma_z - \mu (\sigma_x + \sigma_y)] \]  

(13)

\[ \gamma_{xy} = \frac{2(1 + \mu)}{E} \tau_{xy} \]  

(14)

\[ \gamma_{xz} = \frac{2(1 + \mu)}{E} \tau_{xz} \]  

(15)

\[ \gamma_{yz} = \frac{2(1 + \mu)}{E} \tau_{yz} \]  

(16)

where \( \sigma \) and \( \tau \) are the normal and shear stress, respectively, N/m²; \( \varepsilon \) and \( \gamma \) are the normal and the shear strain, respectively; \( E \) is the elastic modulus, N/m²; and \( \mu \) is Poisson’s ratio.

Fig. 6 shows the geometric structure and a simplified bolting model of the 110 kV GIS insulator. As shown in Fig. 6a, there are 12 screw holes at the edge of insulators to allow the insulators to be bolted to the tank. The bolt model is M12, and the pre-tightening torque on the bolt is 85 N m. This paper makes an equivalent simplification of the insulator bolting model, as shown in Fig. 6b. Since there is no relative displacement on the contact interface between insulator and tank, the pre-tension force \( F_B \) is introduced to replace the bolts. After calculation, \( F_B \) is set to 4.6 × 10⁵ N.

All the components of GIS must withstand their weights; thus, the gravity force is applied to all of them. A surface pressure of 0.4 MPa is applied on the inner surface of the tank and the surfaces of the insulator and the conductor. A surface pressure of 0.1 MPa is applied on the outer surface of the tank and the edge of the insulator. The fixed constraint is applied on the two ends of the tank because only the stress distribution on the insulator is concerned in this paper.

Table 1 shows the mechanical parameters of EP/Al₂O₃ composites and cast Al in the mechanical stress simulation.

4 Results and discussion

4.1 Density distribution

Fig. 7a shows the comparison between the simulated and measured density distributions of the cylindrical sample. The simulation result is found to be in good agreement with the measurement data. The simulation result is found to be in good agreement with the measurement data. The existing deviation is within the acceptable error range. The maximum density at the bottom of the sample reaches 2.29 g/cm³, whereas the minimum density at the top is as low as 2.12 g/cm³. In the middle region, the sample density is ~2.24 g/cm³, which does not change significantly with position. On the basis of this finding, the cylindrical samples for the compressive tests must be extracted from the middle region to keep the sample density uniform. The comparison in Fig. 7a proved the validity of the mathematical model for the Al₂O₃ settlement simulation. As a result, the simulated density distribution in the GIS insulator should also be reliable, as shown in Fig. 7b. The
maximum density of the insulator is 2.32 g/cm$^3$, which appears at the bottom edge of the insulator and the upper interface between insulator and conductor. The minimum density of the insulator is 2.13 g/cm$^3$, which appears at the top edge of the insulator and the lower interface between the insulator and the conductor. Many papers have stated that the Al$_2$O$_3$ content is closely related to the mechanical properties of EP/Al$_2$O$_3$ composites. The large density variation in the 110 kV GIS insulator must have a significant effect on the mechanical properties of the GIS insulator.

4.2 Mechanical property

Fig. 8a shows the elastic modulus and Poisson ratio of the EP/Al$_2$O$_3$ system with different Al$_2$O$_3$ contents. As the sample density increases from 2.14 to 2.34 g/cm$^3$, the elastic modulus of the EP/Al$_2$O$_3$ system has an obvious growth from 8000 to 12,400 MPa, whereas the Poisson ratio barely changes. Fig. 8b shows the tensile and compressive strengths of the EP/Al$_2$O$_3$ system with different Al$_2$O$_3$ contents. As the sample density increases from 2.14 to 2.34 g/cm$^3$, the compressive strength of the EP/Al$_2$O$_3$ system has a linear growth, and the tensile strength of the EP/Al$_2$O$_3$ system increases first and then decreases. The maximum tensile strength is ~85 MPa when the sample density is ~2.24 g/cm$^3$.

4.3 Stress distribution and laying method

Without considering the density variation, the stress distribution of the insulator in the horizontally laid 110 kV GIS can be simulated by setting the insulator density to 2.24 g/cm$^3$. Fig. 9 shows the mechanical stress distribution of the 110 kV GIS insulator. In the decomposition of stress, there must exist one inclined section.
where the shear stress reaches zero. Under this circumstance, the stress can be decomposed into three principle stresses, which are named first, second and third principle stresses in order of numeric value. Usually, the positive first principle stress is tensile, and the negative third principle stress is compressive. Fig. 9a presents the first principle stress distribution, indicating that the tensile stress is localised on the upper interface between the insulator and the conductor. The maximum first principle stress is \( \sim 27 \) MPa. Fig. 9b presents the third principle stress distribution; the compressive stress is localised in two regions: (i) the edge of the insulator, which is caused by the bolt pre-tension force on the flange and (ii) the lower interface between the insulator and the conductor. The maximum third principle stress is \( \sim 29 \) MPa.

Obviously, both the density-dependent mechanical properties and the stress distributions of the 110 kV GIS insulator are not symmetrical, but are directional. For the horizontally laid GIS, the laying method must have a non-negligible effect on the mechanical reliability of insulators. Fig. 10 shows the diagram of five insulator laying methods. In the first method, the insulator is placed to keep the mould gate upward. In the following four methods, the insulator is turned counterclockwise by 45°, 90°, 135° and 180°. To quantify the mechanical reliability of insulators, the first and third risk coefficients are defined as given below:

\[
\beta_1 = \max \left( \frac{\sigma_1}{\sigma_t} \right) \quad (17)
\]

\[
\beta_3 = \max \left( \frac{\sigma_3}{\sigma_{bc}} \right) \quad (18)
\]

where \( \beta_1 \) and \( \beta_3 \) are the first and third risk coefficients, respectively; \( \sigma_1 \) and \( \sigma_3 \) are the first and third principle stresses, respectively, MPa; \( \sigma_t \) is the tensile strength, MPa; and \( \sigma_{bc} \) is the compressive strength, MPa.

Fig. 11 presents the risk coefficients of insulators laid by different methods. Evidently, the first risk coefficient is much higher than the third risk coefficient, indicating that most of the insulator mechanical damages are caused by tensile stress because the compressive strength of insulator is much higher than the tensile strength. Therefore, most of the manufacturers only focus on the tensile strength of insulators. In the process of turning the insulator counterclockwise from the method I to method V, the first risk coefficient has a downward trend. The laying method V appears to be optimal, with a pretty low risk coefficient of 31.5.
Since the maximum first risk coefficient determines whether the insulator is damaged or not, this paper only focuses on the tensile stress and tensile strength distributions on the 110 kV GIS insulator. Fig. 12 shows the first principle stress and tensile strength distributions on the interface between the insulator and the conductor. The maximum first principle stress is observed on the upper interface, regardless of the method used to lay the insulator. When turning the mould gate of the insulator from upward (the method I) to downward (method V), the maximum first principle stress decreases from 32.6 to 25.3 MPa. It can be inferred that the lower elastic modulus of the insulator may be helpful to reduce the first interface stress concentration. Moreover, for different laying methods, the tensile strength of the insulator at the upper interface may be helpful to reduce the tensile stress concentration on the upper interface. This method is the worst situation because the insulator is at high risk of having tensile damage. In method III, as shown in Fig. 12b, the tensile stress of the insulator reaches a maximum on the upper interface; thus, the first risk coefficient has an obvious drop compared with method I. In method V, as shown in Fig. 12c, though the tensile strength of the insulator on the upper interface is only 80 MPa, the greatly reduced first principle stress causes the first risk coefficient to reach as low as 31.5. In application, for the horizontally laid GIS, the insulator should be laid with the mould gate downward to improve its mechanical reliability.

5 Conclusions

This paper investigated the density distribution and mechanical performance of 110 kV GIS insulator considering Al$_2$O$_3$ settlement. The main summary can be described as follows:

i. The Al$_2$O$_3$ settlement in the curing process of the insulator results in a large density variation from 2.13 to 2.32 g/cm$^3$. The maximum density of the insulator is found at the bottom edge of the insulator and the upper interface between the insulator and the conductor. The minimum density of the insulator is found at the top edge of the insulator and the lower interface between the insulator and the conductor.

ii. The Al$_2$O$_3$ content has a great influence on the mechanical properties of the EP/Al$_2$O$_3$ system. The elastic modulus of the EP/Al$_2$O$_3$ system increases with the Al$_2$O$_3$ content, but the Poisson ratio barely changes. The compressive strength of the EP/Al$_2$O$_3$ system has a linear growth with the Al$_2$O$_3$ content, and the tensile strength increases first and then decreases.

iii. The first principle stress is located on the upper interface between the insulator and the conductor, and the third principle stress is located on the insulator edge and the lower interface between the insulator and the conductor. The first principle stress concentration is a primary threat to the mechanical reliability of the 110 kV GIS insulator.

iv. Laying method V appears to be optimal, exhibiting a low risk coefficient of 31.5. In application, for the horizontally laid GIS, the insulator should be laid with the mould gate downward to improve its mechanical reliability.

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