Design and Development of 220kV SF6 Gas Insulated GIS Actual Testing Platform

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Abstract: To simulate the performance parameters of SF6 gas insulated AC GIS equipment under normal and failure condition in the laboratory environment, and the development trend of characteristic parameters such as partial discharge and SF6 gas decomposition can be monitored periodically and quantitatively, the 220kV SF6 gas insulated GIS type test platform is designed and developed. The test platform is in accordance with GIS specifications used in substation, including gas insulated circuit breaker and other typical GIS equipment. The external voltage is realized by the series resonant circuit. The paper starts from the design of the GIS bus and the solid insulation structure, and the three-dimensional E-field distribution characteristics of the solid insulator are simulated and analyzed. The hardware installation of the partial discharge measurement and SF6 gas decomposition monitoring on GIS model test platform are discussed. Through design and development of 220kV SF6 gas insulated GIS type test platform, the feasibility of the structure design of GIS bus and the solid insulation are verified, it provides theoretical and practical basis for the operation and maintenance of SF6 gas insulated GIS equipment.

1. INTRODUCTION
GIS equipment is widely used in the substations of various voltage levels, which has many advantages, such as less land occupation, easy maintenance, high reliability and so on. The operation inspection data over years show that GIS equipment is prone to the pipeline partial discharge, the flash-over of solid insulation parts and other accidents, which are caused by metal particles inside GIS pipes, insulation defects of insulation parts and so on. High field strength and high temperature physical environment caused by the above accidents will lead to the decomposition of SF6 gas[1]. At present, the operation status of GIS equipment is evaluated by partial discharge monitoring and the SF6 decomposition gas monitoring devices, but it is difficult to set up insulation defect in GIS equipment running on site of substation, quantitatively analyze its partial discharge characteristics, regularly and quantitatively track and monitor decomposition characteristics of SF6 gas. In view of this, the 220kV SF6 GIS test platform for gas insulation is designed under the laboratory conditions, which includes key equipment such as the circuit breaker, dis-connector, voltage and current transformer, lightning arrester, etc. The whole GIS true type test platform is applied with the series resonant circuit to apply voltage, and SF6 gas insulation is used for the resonant device to realize compact design[2]. The test platform is consistent with the specification of GIS for substation.

Starting from the structural design of GIS central bus and the solid insulation part, 3D E-field distribution characteristics of the solid insulation parts are simulated and analyzed in this paper. The
GIS true test platform has passed the AC withstand voltage test of whole machine, and the UHF sensor is installed on the test platform, and the vibration sensor unit is installed near the circuit breaker. On the other hand, the installation of the basin insulator and the support insulator solid insulator is completed at the main interval of GIS true type test platform. Through the design and development of the 220kv SF6 GIS true type test platform, series resonance circuit can be applied to the GIS true type test platform, and the feasibility of the structure design of GIS central bus and solid insulation parts can be verified on true type test platform, which can provide certain theoretical and practical basis for the operation and maintenance of the SF6 GIS equipment in service on site.

2. **OVERALL DESIGN OF GIS CENTER BUS AND PLATFORM**

2.1 GIS central bus design

Firstly, design of central bus is considered for 220kV SF6 GIS true type test platform, and the uniformity of electric field distribution and the control of maximum working field strength are mainly emphasized in design[3]. Range of outer diameter R1 of the center conductor shall be determined according to the allowable field strength $E_1$. Topological structure between the inner center conductor and the outer grounding metal flange of GIS true type test platform and the typical corona equalizing hardware are shown in Figure 1. In the design, the surface field strength of central conductor in the coaxial cylindrical electric field is mainly controlled as follows:

$$E = \frac{U_{th}}{r_1 \ln(r_2 / r_1)}$$

(1)

![Figure 1. Surface E-field distribution of conductor](image)

The design value of lightning impulse withstand voltage of 220kV SF6 GIS true type test platform is 550kV at 1.2/50μs, and the allowable lightning impulse field strength of conductor surface is 20kV/mm. Set the radius of the center conductor of the true type test platform $R_1=20$mm, and the radius of the shell $R_2=100$mm. Substitute the above data into equation (1) and the surface field strength of central conductor is about 17kV/mm, so true type test platform has high electrical safety insulation margin. Center conductor chamfer is shown in Figure 1. The electric field distribution is simulated by establishing the three-dimensional electric field calculation model. It can be seen from the figure that highest field strength of central conductor under applied voltage of 220kV is concentrated in the middle part of guide rod, and field strength value is about 3.56kV/mm, with high electrical safety margin.

2.2 Design of pot insulator

In 220kV SF6 GIS true type test platform, the solid insulator is mainly pot insulator. Design and calculation of high voltage electrical performance and electric field are mainly considered in the design and calculation. The field strength value of each part of the pot insulator shall be lower than the allowable field strength value, such as allowable field strength of the internal insert surface of the insulator, the allowable field strength of the tangent direction of the surface of the solid insulator, etc. the design situation of outer contour of the typical pot insulator is shown in Figure 2.
Figure 2. Outer outline design of basin insulator

It can be seen from the Figure that there are metal parts such as the center conductor, shield cover, etc. in the basin insulator, and basin body material is epoxy resin material. The shields effectively reduce electric field strength in three contact areas of the insulator, the metal conductor and SF6 gas. The SF6 gas pressure of the true type test platform GIS pipeline is kept at 0.45GPa, and the basin insulator can effectively divide the GIS pipeline into independent gas chambers to ensure gas pressure stability in each gas chamber.

2.3 Overall design of test platform

The 3D FEM calculation model is established for the key position of 220kV SF6 GIS true type test platform. The voltage value during operation of the true type test platform is applied, and the local electric field strength is simulated and analyzed to obtain the electric field strength value at the key position of the solid insulation parts. The three-dimensional simulation model establishes the finite element calculation model based on the actual size of solid insulation parts in the GIS true test platform, and influence of high potential fittings on the surface electric field distribution of solid insulation parts is mainly considered in the simulation calculation[4].

Figure 3. 220kV SF6 Gas Insulated GIS Actual Platform

Figure 4. Three dimensional FEM model of testing platform
After design and calculation, overall layout of 220kV SF6 GIS true type test platform is shown in Figure 3. Real platform is constructed in strict accordance with the above drawings, with an overall length of 8.1m and the overall width of 4.5m. The maximum distance between the GIS gas outlet sleeve and the ground is 5.338m. The real test platform is designed and constructed according to the GIS equipment used in 220kV substation. The three-dimensional finite element simulation model of the test platform is shown in Figure 4. The main part of the drawing is GIS pipeline, which is divided into different gas chambers by pot insulator. An observation window is set up on the pipeline to detect the visible spark discharge in the GIS pipeline under high voltage condition, and an UHF sensor is installed here to measure the partial discharge in the pipeline. The power supply of whole true type test platform is the series resonance system, which can be boosted from power frequency 220V to 680kV, with rated current of 1.2A. The whole device is SF6 gas insulated, with high voltage generated by resonance circuit and adjustable frequency in the range of 18-300Hz. The compact design of the device overcomes the limitation of the traditional open series resonant high voltage generator due to corona loss, and its local discharge is lower than 2pC, and the series resonance coefficient is 45. The 220kV true test platform can effectively simulate the electrical stress and thermal stress that GIS equipment bears in actual operation. GIS equipment includes the pot insulator, tube bus insulation support and other insulation parts. It provides SF6 gas field fault gas and solid products of insulation parts fault for the physical and chemical analysis platform for the subsequent SF6 fault gas composition analysis and fault solid product element analysis.

3. Design Verification of Electric Field Distribution of Typical Solid Insulation Parts

3.1 Support Insulator
220kV SF6 gas insulated GIS true type test platform mainly includes the two types of typical solid insulation parts: support insulation part and pot insulator. Its main function is to realize the electrical isolation between GIS high potential central tube bus and grounding flange, which has the mechanical support function. The overall situation of the true type test platform is shown in Figure 5.
The insulation defects can be artificially set in GIS pipeline of the true type test platform, and the AC high voltage can be applied for long time to observe decomposition characteristics of SF6 gas and partial discharge characteristics of insulation defects. Therefore, the solid insulation parts in the platform are required to maintain the good insulation performance in the process of AC withstand voltage and long-time pressurization. It is necessary to carry out the three-dimensional electric field distribution of the true type test platform of GIS under complex operation condition. Figure 6 shows connection area between the end of GIS gas insulated bushing and the central guide rod. It can be seen the central guide rod, the metal shield structure of bushing and corona equalizing cover constitute the complex area. Metal shielding not only shields the electric field of GIS outgoing bushing, but also shields each other with the central guide rod, forming the low field strength area at the connection position[5-7]. The electric field intensity on surface of apple type grading ring is shown in Figure 7 under the operation condition of 220kV SF6 GIS true type test platform.

![Figure 7. Surface E-field distribution of apple type ring](image1)

Figure 7. Surface E-field distribution of apple type ring

![Figure 8. 3D E-field distribution of supporting insulator](image2)

Figure 8. 3D E-field distribution of supporting insulator

Figure 7 shows that apple type grading ring can effectively shield metal connection area between the sleeve and the central conductor. Maximum field strength area on surface appears at the chamfer of the grading hood, with a value of 17.9kV/mm, which is lower than the surface control field strength of the metal parts under the SF6 atmosphere of 20kV/mm. On the other hand, the solid support insulator is installed to fix the position and support the weight of the central conductor of GIS pipeline. The upper end of the support insulator is placed in the apple type grading ring, and lower end reduces the discharge probability of the apple type grading ring to the low potential flange by designing umbrella edge and increasing the creepage distance[8-10]. The three-dimensional E-field distribution of supporting insulator is shown in Figure. 8.
Figure 9. E-field distribution curve of support insulator

Figure 10. The outer outline of the basin insulator

Figure 11. E-field distribution on surface of basin insulator

Figure 8 shows that maximum field strength of supporting insulator is located at its upper end. According to distribution curve of electric field on the surface of the supporting insulator in Figure 9, the maximum field strength is about 8.086kV/mm, field strength at umbrella edge appears jumping phenomenon, and the voltage of the supporting insulator is basically linearly distributed, so the insulator can effectively realize the electrical isolation between the high-voltage central conductor and the grounding flange.

3.2 Basin insulator

The actual outer contour structure of pot insulator is shown in Figure 10. According to actual structure, a three-dimensional model is established to simulate electric field. The calculation results are shown in Figure 11. From the simulation results, it can be seen that the local field strength concentration area of typical insulating parts in GIS true type test platform mainly occurs in the contact part between solid insulating medium and high potential metal, and the position where the maximum field strength appears has the typical characteristics, that is to say, the maximum field strength along the surface of pot insulator appears in the contact area between solid insulating parts and high potential[11,12]. And the maximum field strength of the basin surface is 10.8kV/mm, which is lower than requirement of 20kV/mm control field strength under SF6 gas insulation condition. Therefore, the electric field simulation calculation shows that the electric field strength at key position of 220kV SF6 GIS true type test platform can meet electric field design requirements.
4. COMMISSIONING OF 220KV GIS TRUE TEST PLATFORM

Based on the reasonable design of the central conductor and the basin insulator of 220kV SF6 GIS true type test platform, AC withstand voltage test is carried out for the GIS true type interval, which includes circuit breaker, the dis-connector, the arrester, the voltage and the current transformer.

As shown in Figure 12, the true type interval of GIS is in the overall situation. In actual voltage withstand test, grounding switch is in the off state, and the arrester, voltage transformer and the GIS tube bus are isolated through the isolation switch. When the circuit breaker is on and off, the voltage withstand test is carried out for the whole GIS true interval. During the test, the resonance frequency \( f \), the quality factor \( Q \) and the current value \( I \) of the whole series resonant circuit are focused on. During the test, two-stage step-up technology is adopted: after power frequency 220V voltage of distribution transformer is increased to 10kV, voltage is increased to 100kV through the series resonance technology[13]. The actual value of power frequency voltage is 212.8V, and the reactance value in the series resonance circuit is \( L=720h \). The voltage applied to the true type interval of GIS is 20~110kV, and the step is 10kV.

Through actual withstand voltage test, it is found that when the circuit breaker is closed, resonance frequency of the whole circuit reaches \( f_1=123.11Hz \). When the circuit breaker is open, the resonance frequency of the circuit reaches \( f_2=136.83Hz \). When the series resonance circuit reaches resonance state, the relationship between reactance value \( L \), the capacitance value \( C \) and resonance frequency \( f \) is characterized by formula (2):

\[
C=(2\pi f)^2 \frac{1}{L}
\]

Substituting values of \( L \) and \( f \) into formula (2) to calculate that when circuit breaker is closed, \( C_1=2.3212nF \), and when the circuit breaker is open, \( C_2=1.8791nF \). In addition, the current \( I_c \) of the high voltage side of the excitation transformer and the series reactor is calculated by formula (3), namely:

\[
I_c = I_L = 2\pi f C_x U_s
\]

Where \( C_x \) is in nF and \( U_s \) is in kV.

![Figure 13. Relationship between quality factor of resonant circuit and GIS pipeline voltage](image-url)
Figure 14. Relationship between transformer current and GIS pipeline voltage

Figure 13 shows that for the actual GIS interval, the GIS pipeline voltage value and loop quality factor $Q$ basically show a linear relationship, and the $Q$ value changes between 20 and 45. Because $U_C/Q = u$, where $u$ is the output voltage value of the excitation transformer, it shows that the output voltage value of excitation transformer is basically constant, and the difference between opening and closing conditions of the circuit breaker is that the circuit load capacitance value is different. Figure 14 shows that with the increase of GIS pipeline voltage value, current value at the low voltage side of excitation transformer presents an increasing trend, and there is saturation effect.

5. CONCLUSION

Starting from the structural design of the GIS central bus and solid insulation parts, this paper analyzes the three-dimensional E-field distribution characteristics of the solid insulation parts, discusses the commissioning results of GIS true test platform, and draws the following conclusions:

(1) The radius of center conductor of true type test platform is $R_1=20$mm, the radius of shell is $R_2=100$mm, and the surface field strength of conductor is about 17kV/mm. Therefore, there is high electrical safety insulation margin between the center conductor of true type test platform and the grounding flange;

(2) The maximum field strength of the supporting insulator is located at upper end, which is about value of 8.086kV/mm; maximum field strength of the basin insulator along the surface appears in the contact area between the solid insulator and the high potential, and the maximum field strength of basin surface is 10.8kV/mm, which is lower than requirement of 20kV/mm control field strength in SF6 gas insulation environment;

(3) In true type test platform, voltage value of GIS pipeline and loop quality factor $Q$ basically show the linear relationship, and the $Q$ value changes between 20 and 45. Because $U_C/Q = u$, where $u$ is the output voltage value of excitation transformer, it shows that the output voltage value of excitation transformer basically remains constant. With the increase of GIS pipeline voltage value, the current value of excitation transformer at the low-voltage side shows increasing trend, and there is saturation effect.

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