Study on Mechanical Properties of Transmission Pipe Materials

Tianyu Zhou *
School of North China Electric Power University, Hebei, China

*Corresponding author e-mail: 867767069@qq.com

Abstract. To make the mechanical properties of the transmission pipeline material work effectively, the finite element analysis method was adopted. According to the national seismic code, GIL modal analysis and response spectrum analysis were carried out to obtain the mechanical vibration characteristics of GIL. The direction of GIL laying was inconsistent with the direction of seismic wave propagation. The results showed that the seismic excitation direction affected the GIL seismic response, and the insulator and conductor were weak parts of the GIL seismic response. In summary, changes in structure and material parameters significantly affect the seismic capacity of GIL. Under the premise of satisfying the electrical characteristics, reasonable selection of insulator and conductor parameters is beneficial to improve the overall seismic capacity of the GIL.

1. Introduction
Gas Insulated Transmission Lines (GIL) are a means of bulk electric power transmission at high and extra high voltage. GIL consists of tubular aluminium conductors encased in a metallic tube that is filled with a mixture of Nitrogen and Sulphur Hexafluoride gases for electrical insulation. The gas insulating medium is generally SF6 gas or a mixed gas of N2 and SF6. It has the advantages of small environmental hazard, small floor space, large conveying capacity, low line loss, low reliability, low maintenance cost and long service life. In solving special transmission problems in special climates, special environments or special sections, such transmission lines have great advantages [1]. Traditional overhead transmission lines have the disadvantages of large floor space, large insulation safety distance, harmful electromagnetic environment, and vulnerability to atmospheric environment. Transmission lines are used in important applications such as the intersection of overhead lines, the connection of overhead lines to GIL, the connection of rolling switchgear and high-voltage transformers in power plants. It has a wide range of development space and application prospects [2].

GIL technology was first applied to PSEG's Hudson power plant in New Jersey in 1972. Since then, major projects of GIL applications have emerged around the world. GIL has never had a major safety problem in its more than 40 years of operation and has a very high operational reliability. At present, electric power workers draw on the research results of GIS, and their electrical properties such as insulation performance and lightning protection grounding have been well studied systematically. Corresponding structural optimization guidelines and quantitative indicators have not been given. The lack of research on GIL mechanical vibration characteristics will definitely affect the safety of GIL operation, which has become an important constraint for the next development of GIL. Therefore, it is
of great significance to carry out research on mechanical vibration characteristics of GIL. This can provide theoretical basis and technical support for GIL design and safe and reliable operation.

2. Methodology

2.1. Seismic specification and seismic response spectrum
Earthquakes are a strong natural phenomenon. It is highly random and devastating. China is an earthquake-prone country. Therefore, the research on structural seismic response has been for a long time, and the corresponding seismic design specifications have been formed. After the Wenchuan earthquake, the domestic seismic code has been revised, which has improved the seismic requirements for electrical equipment. The current domestic seismic design specifications are: GB/T13549-2009 "High-voltage switchgear seismic performance test" and GB 50260-2013 "Power plant seismic design code". The current international seismic design specification is IEEE Std693-2005. The seismic design of the structure specified in China's seismic code requires analysis of the response spectrum. The response spectrum analysis is based on the vibration mode decomposition reaction spectrum theory. The mode decomposition theory is to decompose the seismic response of a structure into a superposition of the components of each mode. First, each mode corresponds to a seismic action. Then, the seismic response of each mode structure is superimposed by a combined method. Finally, the total structural seismic response value is obtained [3]. Seismic response spectrum refers to the maximum response of a group of medium-mass systems with different natural vibration periods and the same damping under earthquake action. The cycles are sorted and used to calculate multiple seismic records and obtain corresponding response spectra. A certain number of spectra are analyzed. Finally, a statistically significant response spectrum is given [4].

2.2. Classical strength theory
The vibration response characteristics of the three-phase GIL can be found by response spectrum analysis. Using the strength theory and the simulation results, the seismic capacity of the three-phase GIL can be evaluated and the design of the GIL can be optimized [5, 6]. The commonly used strength theory is as follows:

The first is the strength theory (maximum tensile stress theory).

\[ \sigma_1 \leq [\sigma] \] \hspace{1cm} (1)

In the formula, \( \sigma_1 \) is the maximum principal stress. \( [\sigma] \) is the allowable stress. The first strength theory states that the maximum tensile stress causes the material to break, that is to say, the material breaks when the maximum tensile stress reaches the limit that the material can withstand.

Second strength theory (maximum tensile strain theory)

\[ [\sigma_1 - m(\sigma_2 + \sigma_3)] \leq [\sigma] \] \hspace{1cm} (2)

In the formula, \( \sigma_1 \) is the maximum principal stress. \( \sigma_2 \) is the second principal stress. \( \sigma_3 \) is the minimum principal stress. \( [\sigma] \) is the allowable stress. The second strength theory states that the maximum tensile strain causes the material to break. The material breaks when the maximum tensile strain reaches the limit that the material can withstand.

Third strength theory (maximum shear stress theory)

\[ (\sigma_1 - \sigma_3) \leq [\sigma] \] \hspace{1cm} (3)

In the formula, \( \sigma_1 \) is the maximum principal stress. \( \sigma_3 \) is the minimum principal stress. \( [\sigma] \) is the allowable stress. The third strength theory states that the maximum shear stress causes the material to
yield. When the maximum shear stress reaches the limit that the material can withstand, the material yields and is further deformed by significant plastic deformation.

Fourth strength theory (shape change specific energy theory)

\[
\frac{1}{2}\left((\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right) \leq [\sigma]
\]  

In the formula, \(\sigma_1\) is the maximum principal stress. \(\sigma_2\) is the second principal stress. \(\sigma_3\) is the minimum principal stress. \([\sigma]\) is the allowable stress. The fourth strength theory holds that the yielding of the material is caused by the distortion energy density. When the shape change ratio reaches a certain limit value, the material yields, and further significant plastic deformation occurs to cause damage.

Brittle materials such as concrete, cast iron, stone, etc. are generally broken in fracture form, so the first and second strength theories should be used. Plastic materials such as lead, carbon steel, copper, etc. are usually destroyed in the form of plastic flow, so the third and fourth strength theories should be used. The conductors, casings, sections, and epoxy insulators in the three-phase GIL are all plastic materials. The evaluation of the seismic capacity of GIL should mainly refer to the third and fourth strength theories.

3. Results and discussion

3.1. Effect of excitation direction on vibration characteristics of GIL

The response spectrum analysis was performed on the three-phase GIL linear unit section. The X-direction excitation, the Z-direction excitation, the Y-direction excitation, and the XY-direction excitation are input separately. The seismic intensity is 6 degrees. The corresponding response spectrum response results are shown in Table 1.

| Table 1. Response spectrum result |
|----------------------------------|
|                                  |
| Displacement response (mm)       |
| X excitation (H)                 |
| Y excitation (V)                 |
| XY excitation                    |
| Z excitation (axis H)            |
| X                               |
| Y                               |
| Z                               |
| Z excitation (axis H)            |
| X                               |
| Y                               |
| Z                               |
| Stress response (MPa)            |
| X                               |
| Y                               |
| Z                               |
| Equivalent stress (MPa)         |
| X                               |
| Y                               |
| Z                               |

In Table 1, H is the horizontal direction and V is the vertical direction. \(C_1\) is the position at which the insulator contacts the conductor, and \(C_2\) is the position at which the insulator contacts the outer casing. The comparisons of the GIL vibration responses for each seismic excitation input are shown in Figure 1 and Figure 2:

![Figure 1. Displacement response in different directions of excitation](image-url)
As can be seen from Figure 1 and Figure 2, the maximum stress occurrence position is where the Y-direction insulator contacts the outer casing/conductor. When excited by an earthquake, the maximum value of the displacement response of the GIL structure and the maximum value of the stress response are $Y>X>Z$. The displacement and stress response of the horizontal excitation perpendicular to the GIL axis is the most severe. The displacement and stress response caused by the horizontal excitation in the Z direction is minimal. When the seismic intensity reaches or exceeds 7 degrees, the insulator will undergo shear damage. The Z-direction seismic response characteristics of GIL are basically unaffected by the direction of seismic excitation input.

The first two conclusions are the same as those of the relevant literature. Therefore, it has a certain universal significance. The displacement and stress response in the Y direction are the largest. The reason is that the nonlinearity of the structure in this direction and the structural rigidity in the Y direction are smaller than the X and Z directions. In the vibration response caused by seismic excitation in all directions, the maximum value of the vibration response is mainly distributed in the middle of the conductor and the contact of the insulator with the conductor and the outer casing. The mechanical strength of epoxy resin is an order of magnitude smaller than that of steel and lead. It can be determined that the insulator and the conductor are weak points in the seismic response of the GIL structure.

The shortcomings of the existing response spectrum analysis are as follows: The effects of sliding bearings or sliding insulators are not considered. Since the contact surfaces of each structure are Bonded, the influence of the damping effect is not considered. Only the response of the intermediate three-phase GIL linear unit segment is considered, and the seismic response problem of the unit segments at both ends of the straight-line segment is not performed. The seismic response of the GIL is not analyzed for long pipelines considering the traveling wave effect.

### 3.2 Influence of seismic intensity on vibration characteristics of GIL

As can be seen from the analysis of Figures 1 and 2, the response of the GIL in the X and Y directions is the most severe. Generally, the vertical excitation is 50%-75% of the horizontal excitation. To explore the vibration response of the GIL in the worst case, the excitation direction is chosen to be XY and the horizontal excitation and vertical excitation amplitude are equal. At this time, the results of GIL reaction spectrum analysis under different seismic intensities are shown in Table 2.

**Table 2. Response spectrum analysis results under different seismic intensities**

|                | 6 degrees | 7 degrees | 8 degrees | 9 degrees |
|----------------|-----------|-----------|-----------|-----------|
| Displacement response (mm) |           |           |           |           |
| X              | 2.90      | 5.75      | 11.46     | 22.86     |
| Y              | 6.45      | 8.14      | 11.51     | 18.27     |
| Z              | 0.31      | 0.36      | 0.46      | 0.65      |
| Stress response (MPa) |           |           |           |           |
| X              | 11.76     | 12.84     | 15.03     | 19.39     |
| Y              | 22.30     | 28.11     | 39.84     | 62.98     |
| Z              | 8.42      | 9.68      | 12.22     | 17.29     |
| Equivalent stress (MPa) |           |           |           |           |
|                | 23.10     | 28.30     | 38.77     | 59.66     |
The comparisons of GIL vibration responses at different seismic intensities are shown in Figure 3 and Figure 4:

**Figure 3.** Displacement response at different intensities

When the seismic excitation is less than 8 degrees, the maximum displacement response of the GIL structure is Y>X>Z. When the seismic excitation is greater than 8 degrees, the maximum displacement response of the GIL structure is X>Y>Z. The displacement response of the GIL Z direction (axial) is basically stable with the increase of seismic intensity:

**Figure 4.** Stress response at different intensities

The stress response of GIL is significantly positively correlated with the seismic intensity. When the seismic intensity reaches or exceeds 7 degrees, the insulator will undergo shear damage. When the intensity reaches 9 degrees, the insulator will also undergo tensile damage. The equivalent stress is in accordance with the fourth strength theory, and the allowable stress of the epoxy resin is 25 MPa. Comparing with the equivalent stress values in the table, the three-phase GIL can withstand a magnitude 6 earthquake.

By analyzing the response results of the three-phase GIL response spectrum, the maximum displacement response in the GIL is located in the middle of the conductor. The maximum equivalent stress response is at the location where the insulator is in contact with the housing/conductor. The main influencing factors of structural vibration response are insulator and conductor parameters, namely structural cross-sectional area and elastic modulus. The conductor cross section is determined by the transmission capacity and the overall insulation design of the GIL. The cross section of the insulator allows for a small number of optimized adjustments when the insulation requirements are met. To improve the vibration response characteristics of GIL, it is necessary to investigate the relationship between the insulator section, the insulator elastic modulus, the insulator distance from the end face, the conductor thickness, the conductor elastic modulus and the GIL structure response.
3.3. Analysis of results
According to the response spectrum analysis of seismic response of 220kV GIL in actual engineering, the vibration and seismic performance of GIL were obtained. The research shows that the GIL seismic response can be effectively analyzed by simulation and response spectrum analysis, which can meet the requirements of general UHV GIL seismic design. It can provide a powerful reference for GIL actual engineering. The direction of seismic excitation will have an impact on the GIL seismic response.

To improve the seismic capacity, the direction of GIL laying should be avoided to be consistent with the direction of the seismic wave propagation in the area. Studies on the modes of excitation and seismic response spectra show that insulators and conductors are weak parts of the physical structure of GIL. The calculation results show that the 220kV GIL can withstand the seismic intensity of 6 degrees. However, for seismic intensity of 7 degrees and above, it is possible to damage. According to the analysis of the weak parts of GIL, the change of structural parameters can significantly affect the seismic capacity of GIL. In the simulation, by selecting the key structural parameters, the maximum GIL equivalent stress response can be reduced by 17% at 6 degrees seismic intensity. Under the premise of satisfying the electrical characteristics, reasonable selection of insulator and conductor parameters is beneficial to improve the overall seismic capacity of the GIL and ensure the safe and reliable operation of the transmission system.

4. Conclusion
GIL mechanical vibration characteristics were studied and simulated. The following conclusions are obtained: The finite element numerical calculation method is adopted. According to the response spectrum analysis of seismic response of 220kV GIL in actual engineering, the seismic performance of GIL was obtained. The study found that the direction of seismic excitation will have an impact on the GIL seismic response. To improve the seismic capacity, the direction of GIL laying should be avoided to be consistent with the direction of the earthquake-prone waves in the area. The GIL three-dimensional finite element model is used to study the mode characteristics and seismic response spectrum excitation characteristics. The study found that insulators and conductors are weak parts of the physical structure of the GIL. Their structural parameter changes can significantly affect the seismic capacity of GIL. Under the premise of satisfying the electrical characteristics, reasonable selection of insulator and conductor parameters is beneficial to improve the overall seismic capacity of the GIL. Therefore, the safety and reliability of the transmission system is guaranteed.

References
[1] Peng L, Zhibing L, Qian S. Research on insulation design of UHV gas-insulated metal-enclosed transmission line. Power System Technology, 2015, 39(11): 3305-3312.
[2] Douglass D, Chisholm W, Davidson G, et al. Real-time overhead transmission-line monitoring for dynamic rating. IEEE Transactions on Power Delivery, 2016, 31(3): 921-927.
[3] Proctor J L, Brunton S L, Kutz J N. Dynamic mode decomposition with control. SIAM Journal on Applied Dynamical Systems, 2016, 15(1): 142-161.
[4] Adanur S, Altunisik A C, Soyluk K, et al. Multiple-support seismic response of bosporus suspension bridge for various random vibration methods. Case Studies in Structural Engineering, 2016, 5: 54-67.
[5] Kolupaev V A. Formulations of Classical Strength Hypotheses//Equivalent Stress Concept for Limit State Analysis. Springer, Cham, 2018: 89-99.
[6] Klinkhamer F R, Mistele T. Classical stability of higher-derivative q-theory in the four-form-field-strength realization. International Journal of Modern Physics A, 2017, 32(16): 1750090.