Stress Simulation Study on a Novel Combination String of Transmission Line Insulators

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Abstract. The insulator string mainly plays a role of fixing wire and preventing the current from returning to the ground in the power transmission and transformation project. In order to compress the corridor width of the transmission line and make it convenient for breaking line, we proposed a novel structure in which the V-type fittings and the tensile insulator string are optimally combined. In this paper, the mathematical model of mechanical analysis for the structure is established. According to the equilibrium conditions of space force system, the factors affecting the stress of the structure are analysed. In addition, a simulation model is built in the finite element analysis software. The stress distributions of the new structure by setting two installation angles are calculated and the special parts with weak mechanical properties in the new structure are explored based on the generated stress cloud diagram. We compare the maximum value of the von Mises equivalent stress in the two arrangements. A conclusion of better than 45° at a mounting arrangement angle of 50° was obtained. The research results provide a theoretical reference for further optimization design and installation of the combined structure in the future.

1. Introduction
In recent years, the scale of power grids has been expanding, and the corresponding demand for transmission corridors has been increasing. The cost of resettlement of original residents in the corridors has become quite high, which has become the main reason for restricting the development of power grids. The determination of the width of corridor is closely related to the structure of the line insulator. The commonly used structures of transmission line insulator string are I-type and V-type. Although I-type suspension string has a shorter length than the V-type suspension string using the cross arm, I-type suspension string will occupy more line corridor width. The tensile string is subjected to a large tension and the design of the tower is relatively high. Therefore, it is necessary to develop a new type of insulator string structure to break through the limitations. The V-type suspension string has the advantage of compressing the width of the transmission corridor, and the tensile string is convenient for breaking the line. Combining the advantages, an optimized structure is proposed in which the tensile string is attached to the bottom of the V-type fittings. It can solve the problem that the width of the corridor existing in the overhead transmission line is widened and the suspension string is not convenient for the line to break. The combination string adopts a V-type...
fitting, and two I-type tensile strings are butt-joined to form a V-type composite insulator string. The mechanical strength of the proposed composite structure is one of the main problems. If the structural design is unreasonable, causing a certain stress to exceed the allowable value of the material, if the weak parts such as the contact between the parts are damaged, the whole combination string will be broken, resulting in power failure of the line and even damage to surrounding buildings, humans and animals.

Therefore, according to the new structure of the V-type combination insulator string, the mathematical model of the combined string static force is established. The equation is proposed according to the equilibrium condition of the space force system, and the internal force expression of the combined structure is derived, then the influencing factors of the stress of the structure were analyzed. Based on the finite element principle, the static simulation is carried out. Comparing the equivalent stress values of various components with two installation angles, the more reasonable arrangement and the weak points of the structure are summarized, which provides a theoretical basis and reference for further optimization design and installation arrangement of the structural string.

2. Mathematical model of V-type combination insulator strings

The proposed V-type combined insulator string structure is shown in figure 1, both ends of the upper V-type fittings and the cross arm are hooked to the cross arm by bolts, V-type fittings are arranged at a certain angle, docking two tensile insulator strings under the lower link plate. Compared with the original tensile insulator strings, the force point on the cross arm is transferred to the lower link plate of the V-type fittings of the current V-type combination insulator strings structure, so the lower link plate of the structure is a key component.

Schematic diagram of the force of the V-type combination insulator strings (as shown in figure 2), in the figure, the two points A and B are the hanging points on the cross arm of the V-type fittings, the installation layout angles are $\alpha_1$ and $\alpha_2$, respectively. The internal forces on both sides of the V-type fittings are $S_1$ and $S_2$. Points E and $E_1$ are the convergence points of the resultant force The V-type combination insulator strings is subjected to the lateral force $T$, and is subjected to the vertical force $G$ and the tensions $P$ and $Q$ of the wires at both ends. In the three-dimensional coordinate system, the X axis represents the direction of the transmission line, the Y axis represents the horizontal direction of the vertical line, and the Z axis represents the vertical direction of the vertical line.

Figure 1. Schematic diagram of the overall structure of the insulator combination strings.

Due to the different span on the left and right of the transmission line, the loads $P$ and $Q$ applied by the wires at both ends of the V-type insulator string are inevitably unequal, and the entire structure is subjected to an unbalanced load in the X-axis direction.
According to the balance condition of the space force system, the equilibrium equations are established in the three directions of X, Y and Z respectively:

\[
\begin{align*}
-S \cos \alpha_1 + S \cos \alpha_2 + T &= 0 \\
-(S_1 \sin \alpha_1 + S_2 \sin \alpha_2) \cdot \sin \theta + (Q - P) &= 0 \\
(S_1 \sin \alpha_1 + S_2 \sin \alpha_2) \cdot \cos \theta - G &= 0
\end{align*}
\]

(1)

\[
S_1 = \frac{\left[(Q - P)^2 + G^2\right]^{1/2} + T \sin \alpha_2 / \cos \alpha_2}{\sin \alpha_1 \cos \alpha_1 / \cos \alpha_2 + \sin \alpha_1}
\]

(2)

\[
S_2 = \frac{\left[(Q - P)^2 + G^2\right]^{1/2} - T \sin \alpha_1 / \cos \alpha_1}{\sin \alpha_1 \cos \alpha_1 / \cos \alpha_2 + \sin \alpha_2}
\]

(3)

Assume that the cross-arm installation is horizontal, i.e., \( \alpha_1 = \alpha_2 = \alpha \), then

\[
S_1 = \frac{\left[(Q - P)^2 + G^2\right]^{1/2} + T \tan \alpha}{2 \sin \alpha}
\]

(4)

\[
S_2 = \frac{\left[(Q - P)^2 + G^2\right]^{1/2} - T \tan \alpha}{2 \sin \alpha}
\]

(5)

The stress on the upper part of the V-type combination insulator string structure AE and BE segments are related to the internal forces \( S_1 \) and \( S_2 \), respectively. Equations (4) and (5) show that the internal forces \( S_1 \) and \( S_2 \) are independent of the off-angle \( \theta \) and are related to the arrangement angle \( \alpha \), the forces \( P, Q, T, \) and \( G \). In the case where the external force is constant, the change in the arrangement angle \( \alpha \) affects the magnitude of the stress on the components on the line segments AE and BE. The stress on the lower link plate is mainly related to the forces \( P, Q, T \) and \( G \). In the simulation analysis, the off-angle \( \theta \) of the load \( P \) and \( Q \) imbalance due to the different span is not considered. In addition, since the tensile insulator string in the lower part of the V-type combination insulator string has been mounted, it is necessary to ignore the structure of the lower end tensile insulation string when constructing the three-dimensional model for simulation analysis, only need to apply an equivalent load on the lower link plate.

3. Simulation study of V-type combination insulator strings

3.1. Modelling and parameter settings
The optimized structure of the V-type combination insulator strings (as shown in figure 3), The V-type fitting strings has four U-type hanging rings, two extension rings, two lengths of 2000.0 mm, a cross-
sectional area of 19.7×36.0 mm$^2$ connecting rods, and two link plates. The two link plates are physically connected by a right-angle hanging board. This paper used the software Solidworks to physically model each component according to Power Fittings Manual. The fixed pin and the thread on the bolt do not affect the overall force, so it is simplified. After the modeling and assembly, the solid model was imported into the ANSYS workbench using the interface technology of Solidworks and ANSYS workbench for static simulation analysis. The required part numbers and related mechanical properties are shown in table 1.

![Figure 3. Schematic diagram of three-dimensional model of combined insulator string structure.](image)

| Component                  | Model     | Material | density (kg m$^{-3}$) | Young's modulus (GPa) | Poisson's ratio |
|---------------------------|-----------|----------|-----------------------|------------------------|-----------------|
| U-type Hanging Ring       | U-1290    | 1035     | 7.85e3                | 2.12e11                | 0.31            |
| Extension Ring            | PH-12120  | 1035     | 7.85e3                | 2.12e11                | 0.31            |
| Bolts                     | M18/M24   | 1035     | 7.85e3                | 2.12e11                | 0.31            |
| Right-angle Hanging Board | Z-12100   | A3       | 7.83e3                | 2.06e11                | 0.30            |
| Link Plate                | L-12-70/400 | A3     | 7.83e3                | 2.06e11                | 0.30            |

3.2. Calculation of V-type combination insulator strings

In the static analysis, the small deformation theory is adopted, and the direction of the force after the deformation of the object is not considered, and the general motion method and the time option are ignored, and the original classical equation is:

$$ [M](\ddot{x}) + [C](\dot{x}) + [K](x) = \{F(t)\} $$

Can be simplified to:

$$ [K]\{x\} = \{F\} $$

$$ [M] $$ is the mass matrix, $$ [C] $$ is the damping matrix, $$ [K] $$ is the stiffness coefficient matrix, $$ \{F\} $$ is the force vector; $$ \{x\} $$ is the node displacement vector. In the calculation, the assumed material is in the linear elastic phase, that is, no yielding occurs, and Hooke's law is satisfied.

$$ \sigma = Ex\{x\} $$

The model import software was built. After meshing, a total of 1514219 nodes and 582134 cells were obtained. The average mass of the whole grid was 0.813. In combination with the actual situation of the hanging net, the constraint is set at the uppermost bolt cylinder of the V-type fitting string, the equivalent load of a 220kV line span of 600m is applied to the two ends of the lower joint plate (as
shown in figure. 4), wherein the horizontal component after load decomposition is $P=Q=35097\text{N}$, and the load vertical component $G=6660\text{N}$. The size of the installation arrangement angle $\alpha$ is adjusted, and the von Mises stress is calculated separately, and the calculation results are shown in figure. 5 and figure. 6, respectively.

3.3. Results and analysis

When the combined insulator string is mounted, the stress is mainly distributed on the inner side of the U-shaped loop and the extension ring contact, the bolt holes of the joint plate, and the respective bolts are sheared. The connecting rod is hardly affected by external force. When the angle $\alpha$ is set to 45°, the maximum stress of the entire structure appears at the position where the lower link plate is subjected to the load, and its value is 123.55 MPa. The link plate is the main component of the entire structure to withstand the external force. The second bolt from bottom to top is subjected to the highest stress. The maximum value is 80.436Mpa. The main reason is that the bolt has the largest external force $G$ and small contact area compared with other bolts. It is in line with the actual situation. Since the contact between the U-type loop and the extension ring belongs to the point contact of the contact area with a small contact area, the maximum stress value between the two appears on the inner side of the extension ring, and its value is 119.03 MPa, which needs attention. Although there is a stress
concentration phenomenon, since the maximum stress that occurs is less than the yield strength of the material used, this arrangement is to meet the strength requirements.

(a) (b) (c) (d)

Figure 6. Stress cloud diagram with angle $\alpha=50^\circ$.

Adjust the arrangement angle $\alpha=50^\circ$, other conditions are unchanged, and calculate again. The overall stress distribution of the V-type composite insulator string is approximately the same as that at 45°, and the maximum stress is still 123.55Mpa on the link plate structure. The maximum stress is approximated by the stress at the position of the two bolt holes at the lower end of the joint plate. Related to $P$, $Q$, $G$, the stress on the lower link plate is independent of the angle of arrangement. However, in this arrangement, the maximum stress value when the U-type loop is in contact with the inside of the extension ring is 99.76 MPa, which is 16.19% lower than that at 45°. In combination with the force analysis of the second section, it is known that when the arrangement angle $\alpha$ is increased to 50°, the internal forces $S_1$ and $S_2$ on the V-type fitting string are reduced, so that the stress at this point is lowered. The position of the bolt subjected to the maximum stress has not changed, and its value is reduced by 1.373 MPa, which is approximately the same as that of $\alpha=45^\circ$. It is again confirmed that the maximum stress of the bolt is related to the vertical force $G$.

Table 2. Distribution of maximum stress values at different arrangement angles.

| Arrangement angle(°) | Maximum stress value (Mpa) |
|----------------------|---------------------------|
|                      | Bolts   | Link plate | Connecting ring |
| 45                   | 80.436  | 123.55     | 119.03           |
| 50                   | 79.063  | 123.55     | 99.76            |

Comprehensive comparison of the maximum stress values at the two mounting arrangements (as shown in table 2). When the arrangement angle $\alpha$ is adjusted from 45° to 50°, only the stress values on both sides of the V-type fitting string are greatly changed, and the stress values at the remaining positions are approximately the same. Most notably, the maximum stress on the connecting ring and the U-ring decreased by 16.19%, which is consistent with the results of the second section of the overall force analysis. In summary, in the two common arrangement angles, the arrangement angle of 50° is better, and the U-type loop and the connecting ring are weak points of the structure. The lower link plate is also the weak point of the whole structure. It is not only affected by the vertical force $G$ but also by the horizontal direction forces $P$ and $Q$. Therefore, the combined insulator string structure requires a higher strength of the joint plate. Under this condition, although the maximum stress value is less than the yield limit of the material, the safety factor is generally low. With the development of computer technology, the numerical calculation based on the finite element principle provides a
convenient and quick method for the pure theoretical calculation of the pre-stress analysis of the design string structure of the power industry.

4. Conclusion
1) The calculated stress distribution of the V-type composite insulator string is in accordance with the mathematical model analysis and the actual situation, and is mainly distributed on the inner side of the U-type loop and the extension ring contact, the bolt holes of the joint plate, and the bolts are sheared.
2) The stress value between the loops of the V-type composite insulator string structure is related to the internal forces $S_1$ and $S_2$ on the V-type fitting. From the source, it is equivalent to the load components $P$, $Q$, $G$, $T$ and the mounting arrangement angle $a$, related. In the case of the same load, from the maximum stress value between the hanging rings under the two common mounting arrangement angles of the comparison, the mounting arrangement angle $a$ is better than 45° when taken at 50°.
3) When the load horizontal component $P=Q=35097N$ and the load vertical component $G=6660N$, the V-type composite insulator string structure satisfies the structural strength requirement, but the safety factor is not high. It is recommended that the lower link plate be used with a larger load breaking model or a stronger material to increase the safety factor.

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