Research on Scale Model of Typical Tension String of UHVDC Transmission Lines under Ice-Shedding Loads

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Abstract—Tension insulator string is one of the important components of transmission lines and it needs to have enough mechanical strength to transfer the load between conductors and towers. However, due to the large size of the tension insulator strings, it is usually impossible to carry out the true type experiments. In this paper, the dimensional analysis was adopted to establish the mapping scale models of typical tension strings, namely 8N42-50100-55P at first. Then, the load scaling ratios of three typical tension insulator strings were obtained based on the results of the ice shedding calculation on an actual UHVDC transmission lines. Finally, the dynamic experiments of the scale tension insulator strings were carried out to access the feasible of technical route and to provide a technical support for the following research.

1. Introduction

Tension insulator string is an important component for connecting wires and transmission towers, need to have sufficient mechanical strength to transfer the wire load to the transmission tower, while each of the fittings disposed in the tension insulator string should ensure sufficient freedom and reliability. However UHV DC transmission line across a wide area, miles long, complicated way of regional climate conditions, operating conditions in some areas are very harsh, the line will encounter various security challenges during operation. For example, the tensioned panel (LT4-220J-280/2000/1000) of tension insulator string in a newly built ±800kV UHV DC project is severely bent, as shown in Figure 1.

The line ice shedding jump is one of the challenges faced by tension insulator strings. At present, relevant studies in China and abroad mainly focus on electrical and mechanical theory research. Kumosa et al. simulated icing by hanging heavy objects, and carried out experiments on different ice removal conditions on a section of 2-speed transmission line, the finite element method was used to simulate
the nonlinear dynamic response of the transmission line after ice removal.[5] Roberge and his collaborators systematically combed the accidents caused by wet snow and the physical properties of wet snow.[6] Wankowicz et al. conducted a large number of failure tests of transmission line components on a decommissioned transmission line, use ADINA to simulate its test process, it is found that the elastic wave propagation caused by the failure impact of components plays an important role in the formation of dynamic tension peak value of overhead lines. [7] Research on Dynamic Characteristics of Tensioned Insulator Strings in China, Han Junke analyzed the influence of tower-line coupling effect, de-icing position and span length of tension section on the dynamic characteristics of conductor / ground wire de-icing jump by finite element analysis method, and proposed the value of longitudinal unbalanced tension under de-icing jump conditions of ultra-high voltage multi-circuit transmission lines on the same tower. [8] Li Li et al. used composite element method to simulate icing in finite element simulation, and used element birth and death method to simulate de-icing. The dynamic effect of different de-icing conditions on transmission tower was studied. [9] By establishing the finite element model of transmission line and the multi-string insulator parallel model of tension string, Fu Guanjun et al. simulated and calculated the maximum dynamic mechanical load of tension string under various dynamic operating conditions under different parallel string arrangement, and gave the recommended selection scheme of composite insulator tension string on UHVDC transmission line[10].

The ice shedding jump of tension insulator string is a multi-field and multi-factor coupling system, which shows complex and rich nonlinear behavior. [11,12] However, the current research mostly focuses on the influence of dynamic load on conductors and towers, and usually ignores its influence on fittings. [13] For the problems such as the dynamic characteristics of the tensile insulator string existing in the metal fittings of UHV transmission lines, there is still a lack of relevant basic research results, and there are few research results that can be used for reference.

In this paper, the mapping scale models of 8N42-50100-55P typical insulator string types are established by dimensional analysis for the first time. The load scaling ratios of three typical tension insulator strings are obtained based on the input conditions of a typical tension section conductor of an actual UHVDC line under the condition of ice shedding and line jumping. Finally, the rationality of the research technical route is verified by the dynamic load test of the tension insulator string, which provides technical support for the follow-up study of the tension insulator string.

2. Dimensional analysis
The dimensional analysis method is divided into dimensional harmony principle and Π theorem. The principle of dimensional harmony is applicable to relatively simple problems. The unknown number of relevant variables is not more than 4 ~ 5. The Π theorem has universal applicability.[14]

2.1 Dimension concordant principle
The solution of dimensional harmony principle must be consistent with the dimensions of physical equations reflecting objective laws. Its importance lies in:

1. A equation should be harmonious in dimension, only the same dimension can be added or subtracted. So it can be used to test the correctness and completeness of the formula.
2. It can be used to determine the physical quantity index in the formula.
3. It can be used to explore physical laws and establish the structural forms of physical equations.

2.2 Π theorem
The Π theorem is the theoretical core of dimensional analysis. Any physical law can always be expressed as a determined functional relationship. [15] For a certain type of physical problems, if there are n independent variables \(b_1, b_2, \ldots, b_n\). Then the physical quantity \(b\) is the \(n\) function of this independent variable, that is,

\[
b = f(b_1, b_2, \ldots, b_n)
\]

(1)

Independent variables \(b_1, b_2, \ldots, b_n\), the number of selected basic units is \(m\), which are \(X_1, X_2, \ldots, X_m\), the dimensional equation of physical quantity \(b\) can be expressed as:
Taking logarithm of the above equation:

\[ \ln[b] = a_1 \ln X_1 + a_2 \ln X_2 + \cdots + a_m \ln X_m \]

(3)

If \( \ln X_1, \ln X_2, \ldots, \ln X_m \) is the 'orthogonal basis' of m-dimensional space, then \( b_1, b_2, \ldots, b_m \) is the projection of 'vector' \( \ln[b] \), or its 'component'. Therefore, the dimensional equation can be simplified as:

\[ \ln[a] \sim (a_1, a_2, \ldots, +a_m) \]

(4)

The so-called dimensional independence of several physical quantities means that the dimensionless form cannot be formed by the product of their power. Expression in vector language means that the 'vector' of their dimensions is linearly independent. There are at most m linearly independent vectors in m-dimensional space. m vectors \( b_{1i}, b_{2i}, \ldots, b_{ni} \) \((i = 1, 2, \ldots, m)\) The condition of linear independence is:

\[
\begin{vmatrix}
b_{11} & b_{12} & \cdots & b_{1n} \\
b_{21} & b_{22} & \cdots & b_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
b_{m1} & b_{m2} & \cdots & b_{mn}
\end{vmatrix} \neq 0
\]

(5)

Therefore, \( \Pi \) theorem can be expressed as setting that the content of a physical problem involves n independent variable physical quantities, including physical constants \( b_1, b_2, \ldots, b_k \). If there are m basic variables in the selected unit system, then \( n - m \) dimensionless variables \( \Pi_1, \Pi_2, \ldots, \Pi_{n-m} \) can be formed, and the functional relationship between physical variables \( f(b_1, b_2, \ldots, b_n) = 0 \), which can be expressed as the corresponding dimensionless form \( f(\Pi_1, \Pi_2, \ldots, \Pi_{n-m}) = 0 \).

In the case of \( n - m \), if the dimensions are independent of each other, they cannot form a dimension of one. If they are not independent, they may also form a dimension of one.

2.3 Complete similarity, incomplete similarity, scale law

2.3.1 Complete similarity, incomplete similarity

From the above function, we can see the relationship between all the basic quantities of the problem:

\[ b = f(b_1, b_2, \ldots, b_k, b_{k+1}, \ldots, b_n) \]

(6)

Let \( b \) be the dependent variable to be determined, \( b_1, b_2, \ldots, b_k \) is an independent variable. Independent variables can be divided into independent dimensions of the basic dimensions \( b_1, b_2, \ldots, b_k \), and independent variables \( b_{k+1}, \ldots, b_n \). The dimension of \( b_n \) can be expressed as a power function of the basic dimension, known as the derived dimension. If \( n = 0 \), all independent variables are independent, and if \( k = 0 \), all independent variables are dimensionless.

Introducing dimensionless expressions:

\[ \Pi = \Phi(\Pi_1, \Pi_2, \ldots, \Pi_n) \]

(7)

Dimensionless parameters can be used the power function of \( b_1, b_2, \ldots, b_k \) and \( b_{k+1}, \ldots, b_n \), that is:

\[ \Pi_i = \frac{b}{b_{k+1} \cdots b_{k+n}^{\alpha_i}} \quad i = 1, \ldots, n \]

(8)

Clear physical meaning for function \( f \), meet formula (7),(8).

According to the \( \Pi \) theorem, dimensionless \( \Pi_1, \Pi_2, \ldots, \Pi_n \) is called similarity parameter. If some physical problems \( \Pi_1, \Pi_2, \ldots, \Pi_n \) are the same, then these physical problems are similar. The concept of similarity in physics can be used to study a single problem. Therefore, if some physical problems are different in size but have the characteristics of similar transformation in time or space, this situation is called self-similarity, that is, similar parameters remain constant in the transformation process. The self-similarity of a physical problem has an intermediate progressive characteristic, that is, when the initial
and boundary conditions are almost constant, the entire physical system is still in an intermediate state, far from the final equilibrium state.

A physical problem contains the number of independent variables, whether less than n. For example, the independent variable $b_n$, if the corresponding dimensionless dependent variable $\Pi_n$ is large or small, then the independent variable is non-basic and can be omitted. When the dependent variable $\Pi_n$ tends to be zero or infinite and other similar dependent variables remain unchanged, this conclusion is completely correct if there is a finite, nonzero function $\Phi$. Assuming that this condition can be satisfied, the function $\Phi$ can be replaced by the function $\Phi_1$ of $\Pi_{n-1}$ independent variables, namely:

$$\Pi = \Phi_1(\Pi_1, \Pi_2, \ldots, \Pi_{n-1})$$

(9)

$\Phi_1$ is the finite value in the $\Phi_n$ function when $\Pi_n$ tends to zero (or infinity). The dependent variable $\Pi_n$ is called complete self-similarity or the first kind of self-similarity.

On the other hand, considering that when $\Pi_n \to 0$ or $\Pi_n \to \infty$, the function $\Phi$ tends to zero or infinite, and the dependent variable $\Pi_n$ will remain constant, then the function $\Phi$ can be expressed by power function relation,

$$\Pi = \Pi_n^\gamma \Phi_1(\Pi_1, \Pi_2, \ldots, \Pi_{n-1})$$

(10)

In the formula $\gamma$ is a constant, whether the dependent variable $\Pi_n$ is small or large, its value is different. Variable $\Pi_1, \Pi_2, \ldots, \Pi_{n-1}$ is still the independent variable of physical problems, and $\gamma$ is the function of $n-1$. In this case, there are the following relationships within the required precision range:

$$\Pi^* = \Phi_1(\Pi_1, \Pi_2, \ldots, \Pi_{n-1})$$

(11)

Among them,

$$\Pi^* = \frac{\Pi}{\Pi_n^\gamma} = \frac{b}{b_1^{\gamma-\gamma_n} \ldots b_k^{\gamma-\gamma_n} b_n^\gamma}$$

(12)

In this case, the dependent variable $\Pi n$ is not completely similar, or is called the second kind of similarity.

$\gamma$ is a power index of completely similar phenomena, and its value is unknown. However, by comparing the relationship between the experimental data and the assumed similarity types, the nature of the physical problem can be determined, whether it is completely similar or not. If the determination is not completely similar, it is necessary to obtain the $\gamma$ value from the analysis of the experimental data.

2.3.2 Scale law
Scale is to represent variables $x$ and $y$ in the form of power function, namely:

$$y = A \cdot x^\beta$$

(13)

$A$ and $\beta$ are constants. There is such a simple functional relation in mathematical models of various problems, and it occurs in nature, such as physical, engineering, and even economic problems[16].

3. Dimension Calculation of Dynamic Characteristics of Tension Insulator String

3.1 Main physical quantities
According to the dimensional analysis theory, the main factors affecting the dynamic characteristics of the conductor tension insulator string are the length of the fitting string, the horizontal and vertical span of the line, and the load change of the conductor. The corresponding basic dimensions are as follows:

(1) The length of the fitting string
The length of fitting string refers to the length of all fittings and insulators connected, unit m, denoted as $S$.

(2) Wind speed
Wind speed refers to the relative wind speed of the environment around the fitting string. Unit m/s, denoted as $V$.

(3) The load change of the conductor
The change of load acting on the connection position after conductor ice shedding jumps, unit kg/m/s², denoted as $F$.

(4) The load response of the fitting string

The load response of the fitting string after ice shedding jump, unit kg/(s²·m), denoted as $F_R$.

3.2 Dimensional analysis

According to the theory of dimensional analysis, the equation of dimensional analysis is

$$f'(S, S_3, F, F_R) = 0$$

$S$ is the length of the fitting string, $S_3$ is the horizontal and vertical span of the line, $F$ is the load change of the conductor, $F_R$ is the load response of the fitting string.

The basic dimensions involved therefore include length, quality, and time. Dimensions can be listed in the MKSA system as shown in table 1.

| Table.1 Parameters of Reaction Wall |
|-----------------------------------|
| Dimensional | $S$ | $V$ | $F$ | $F_R$ |
| $L$       | 1   | 1   | 1   | -1    |
| $M$       | 0   | 0   | 1   | 1     |
| $t$       | 0   | -1  | -2  | -2    |

According to Π theorem, a dimensionless product Π can be constructed by four influencing factors and three basic dimensions.

Solving algebraic equations

$$\begin{bmatrix} 1 & 1 & 1 & -1 \\ 0 & 0 & 1 & 1 \\ 0 & -1 & -2 & -2 \end{bmatrix} \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \end{bmatrix} = \begin{bmatrix} -1 \\ 1 \\ -2 \end{bmatrix}$$

(15)

Solution of the equation

$$\begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \end{bmatrix} = \begin{bmatrix} -2 \\ 0 \\ 1 \end{bmatrix}$$

(16)

We can get the following formula

$$F_R = \frac{FL^2}{3}$$

(17)

3.3 Scale model calculation

In this paper, 8N42 - 50100 - 55P typical tensile insulator string is used for calculation and research, as shown in Fig. 2. The fitting model is scaled by 1/3 of the original fitting size. The insulator string model is connected by several 200 mm long extension rods. The total length of fitting and insulator model is controlled within 12 m. 8N42-50100-55P is a four-way double hanging point tension string of disk suspension insulator. The tension insulator string adopts 6×JL1/G2A-1250/100-84/19 aluminum strand with wire splitting distance of 500 mm. 60 550kN glass insulators per insulator string, 4 insulator strings horizontally arranged, 1000mm spacing.
Based on the typical tension section parameters of an actual UHVDC line, according to the line layout, the height and span of each tower hanging point in the tension section are determined, and the tension section model is finally established. The section of tension section is shown in Figure 3. The tension section is arranged by tension tower - tangent tower - tangent tower - tension tower. The span is 290m-380m-210m and the height difference is 10m-84m-70m. The specific parameters are shown in Tab. 2. This study mainly studies the dynamic characteristics of the tensile string at position 5505 #
Table 2. Parameters of Tension Section

| Parameter               | Value                  |
|-------------------------|------------------------|
| Divided conductor       | 6×JL1/G2A-1250/100     |
| Design wind speed       | 30 m/s                 |
| Design icing thickness  | 20 mm                  |
| Spacing                 | 290 m—380 m—210 m      |
| Height difference       | 10 m—84 m—70 m         |

There is a hinge relationship between the components in the tension string. The ice shedding jump motion of the conductor will make the components in the tension string rotate relatively and bear complex tension, compression, bending and torsion loads. The bending deformation of transmission tower structure has little effect on the dynamic response of conductor under ice-shedding. Therefore, in the initial configuration of tension string, the influence of transmission tower is ignored, and the space fixed point is used to replace the hanging point of transmission tower. In the model, only the conductor and tension string are considered, and the coupling effect of suspension insulator string and tower is ignored.

The input condition of the true model is the uniform de-icing jump time history load of the tension gear under the condition of 25 mm icing shown in Figure 3. The boundary condition of the scaled model is 1/27 of the true model. Figure 4 is the vertical displacement time history curve and the tension time history curve corresponding to the connection point between the conductor and the tension string during the ice-shedding process of the real model conductor.

In this paper, the large size trapezoidal tension coupling plate with tension string is taken as the research object. The explicit nonlinear dynamic analysis method is used to solve the proportional relationship between the scale tension coupling plate and the true tension coupling plate. Time-history curves of stress along the line direction and perpendicular to the surface direction of the connecting hole on the insulator side of the tensioned coupling plate under three de-icing conditions and the stress nephograms of each coupling plate are compared as follows.
Fig. 5 Time History Curves of Force Vertical to Plate (Direction A) and of Force Along the Tension (Direction B) of Tension Plate for 8N42-50100-55P

Fig. 6 Nephogram of Tension Plate LT4-220J-280/2000/1000

| Model of tension string | Tension Plate | Force Vertical to Plate | Force Along the Tension |
|-------------------------|---------------|-------------------------|-------------------------|
|                         |               | Real model | scale model | Real model | scale model |
| 8N42-50100-55P          | LT4-220J-280/2000/1000 | 329195   | 36393       | 1177275   | 133729       |

It can be seen from the stress time-history curves and stress nephograms of the scaled models of the tensile joint plates that when the fitting model is scaled by 1/3 of the original size and the load is scaled by 1/27 of the original value, the response of the joint plate is reduced to 1/9 of the original response, which is basically consistent with the theoretical analysis. It can be seen from the stress nephogram of the real tension plate that the stress distribution extends from the connecting hole and the weight reducing hole to the surrounding, forming a trapezoidal loading area. The stress nephogram of the scale model can only reflect the position of the maximum stress, and cannot fully display the stress distribution of the tension plate.

4. Scale model test of dynamic characteristics of tension string

4.1 Test scheme

4.1.1 Test condition
One end of the test tensile insulator string is hinged with the reaction wall through a special connection device, and the other end is connected with the reaction steel frame fixed on the laboratory ground.
through cables to exert tension along the wire direction on the tensile insulator string. The reaction wall is L-shaped reinforced concrete shear wall with solid webs, the wall height is 9m, and the pitch between the studs is 500mm. MTS 244.41S High Performance Actuator is mounted on the side wall to impose a time-history load perpendicular to the direction of the tensioned insulator string. The maximum output of the actuator is 500kN, the maximum stroke is ±375 mm, and the operating frequency is 0.1~50 Hz, which can meet the requirements of test load and operating frequency. As shown in Figure 7.

![Figure 7 Schematic of Test](image)

**Fig.7 Schematic of Test**

**Table.4 Parameters of Reaction Wall**

| No. | Parameters                              | Parameter value        |
|-----|-----------------------------------------|------------------------|
| 1   | Type                                    | L-shaped solid abdomen |
|     | Length                                  | 5m+10.5m, 3.95m        |
| 2   | Height                                  | 6m+9m, 9m              |
|     | Thickness                                | 3m, 2.5m, 2.0m         |
| 3   | Top horizontal load                     | 1000kN/m               |
| 4   | Base moment                              | 9000kNm/m              |
| 5   | Maximum horizontal displacement of wall top | H/2500                   |
|     | Loading hole size                       | Inside diameter 69mm    |
|     | Distance between loading holes           | 500mm                  |
|     | Single hole bears load                  | 1000kN                 |
4.1.2 Test Model and Loading
In this paper, the dynamic test adopts the scale model of the above typical tensile insulator string. For the time displacement of vertical tension plate in the plane direction, the input time history is shown in Figure 9.

4.1.3 Monitoring location
Loading time history is measured and controlled by force sensor, and displacement time history of loading point is recorded by displacement meter. In this paper, multiple strain gauges are arranged at the tension plate to measure the stress distribution, stress and strain development of the tension plate. At the same time, strain gauges are arranged in other key parts of tension insulator string to observe the strain development law. The location of the strain gauges of the tension connecting plate is obtained.
from the finite element analysis results. The strain gauges are arranged in the parts with large strain. The preliminary layout scheme of the strain gauges of the tension plate of the tension insulator string model is shown in Figure 10.

The data of displacement and force load are collected by NI and MTS data acquisition system, the sampling frequency is 0.5Hz ~ 10MHz, and the excitation voltage is ±10V. Strain data collected by static data acquisition box.

Fig. 10 Decorate Position of Strain Gage on the Tension Plate

4.2 Test result
8N42-50100-55P model LT4-220J-280 / 2000 / 1000T tension plate displacement response curve and stress as shown in Figures 11 and Table 6.

Fig.11 LT4-220J-280 / 2000 / 1000T Coupling Displacement Response Curve
### Table 5 Stress value of monitoring point

| No. | Maximum strain ($\varepsilon_{\mu}$) | Stress (Mpa) |
|-----|-------------------------------------|--------------|
| 1   | 2120                                | 445.2        |
| 2   | /                                   | /            |
| 3   | /                                   | /            |
| 4   | 1293                                | 271.5        |
| 5   | /                                   | /            |
| 6   | 268                                 | 56.3         |
| 7   | 705                                 | 148.1        |
| 8   | 1720                                | 361.2        |
| 9   | 2105                                | 442.1        |
| 10  | /                                   | /            |
| 11  | /                                   | /            |
| 12  | /                                   | /            |
| 13  | /                                   | /            |

#### 4.3 Test conclusion

Based on the principle of dimensional analysis, the scaling model and experimental verification of the dynamic characteristics of the tensile string carried out, and the dimensionless product $\Pi$ of the dynamic response of tension string was obtained. The validity of the model is verified by experimental analysis.

#### 5. Conclusion

Based on the principle of dimensional analysis, the scaling model and experimental verification of the dynamic characteristics of the tension string were carried out, and the dimensionless product $\Pi$ of the dynamic response of tension string was obtained. When the fitting model is scaled by 1/3 of the original size and the load is scaled by 1/27 of the original value, the response of the panel is reduced to 1/9 of the original response. However, the stress nephogram can only reflect the position of the maximum stress, and cannot fully display the stress distribution of the coupling plate. Finally, the validity of the model is verified by experimental analysis.

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