Study on the influence of insulator on the coupling effect of transmission tower-line system

Qingshui Gao¹,², Shi liu¹,², Yi Yang¹,² and Chu Zhang¹,²
¹Electric Power Research Institute of Guangdong Power Grid Co. Ltd, 510080 Guangzhou, P.R. China
²Guangdong Diankeyuan Energy Technology Co., Ltd, 510080, Guangzhou, P.R. China

Abstract. There is a coupling between transmission tower and lines. Traditionally, it is assumed that an insulator is in a tight connection with tower. In fact, both tight and loose connections exist. This paper studies the influence of connection state on system dynamics. The tower-line system rigged with the adjustable connection state of insulator was built. We used modal test method to study the coupling effect. The influence of the line is mainly in the longitudinal and torsional mode. It has less influence on the lateral mode. The damping increases for tower-line system and is the largest for loose connection state. The loose connected system’s first three modal frequencies are almost the same as that of the tower. However, the tight connected system’s longitudinal and torsional frequency decreases. The difference caused by connection state of insulator should be considered. Modelling method under different connection state should be different. The traditional finite element method can be used for tight connection. Under loose connection state, the insulator-line system can be regarded as a tuned mass damper attached to the tower.

1. Introduction
The span of large transmission tower is longer. The mass of the line is not negligible compared with the weight of transmission tower. The internal tension of line is also large, which has a great influence on the dynamic characteristics of transmission tower-line system. In [1], a strong coupling effect between the tower and the line for long span transmission tower was found. In [2], results show that the longitudinal natural frequency of transmission tower decreases with the increase of mass ratio of line / tower. In [3], the simplified vibration model considering the line in the form of an additional mass was adopted and the influence of line on tower-line coupling effect was researched. In [4-11], the multiple particle model was used to consider the influence of line on vibration mode and frequencies of high voltage large span transmission towers. In [12-13], the influence of insulators on the dynamic characteristics of transmission towers under different wind directions and velocities was discussed. The finite element method was used to set up the analysis model. All of the above models assumed that the insulator was tightly connected to the transmission tower. In fact, there are tight connection and loose connection between insulators and towers. The influence of the connection state between the insulator and the transmission tower was not considered.

A test rig was built to study the influence of insulator connection state on the dynamic characteristics of transmission tower-line system. The connection state of the insulator with the tower can be changed. The coupling effect of transmission tower-line system was studied by theory and
The results can provide guidance for vibration control design of transmission tower-line system.

2. Test method for tower-line system

Figure 1 shows the transmission tower-line system test rig. The tower is a cup type. Its height is 1.80 m, the head width is 0.80 m, and the root opening width is 0.40 m. The tower is composed of angle steel and flat steel. The cross section of the tower main body is square. The total weight of the transmission tower is 18.2 kg. The insulator is 0.13 m long. The connection state between insulators and towers can be changed.

![Figure 1. Transmission tower-line system test rig](image)

The transmission line adopts ZR-BVR type multi core copper wire cable with single layer plastic insulation. The cross-sectional area is 16 mm$^2$, and the unit length is 0.175 kg/m. It is 1.55 m away from the ground, the length of the single span is 5 m, and the sag is 0.50 m. One end of the line is hung on the insulator, and the other end is fixed on the wall.

We used the modal test method to research the dynamic characteristics of tower-line coupling system in case of two lines suspended in the tower. By applying impact force on the tower with a hammer, the frequency response function was obtained by the method of single point excitation and multi-point vibration measurement. The modal parameters of tower and tower-line system, such as frequency, damping and mode shape, were identified by the modal analysis software ME'scope.

3. Test results analysis

Figure 2 shows the frequency response function of tower without lines. Three peaks in the curve correspond to the longitudinal, the torsional and the transversal modes, respectively.

![Figure 2. Frequency response function of tower](image)

Table 1 shows the first three modal frequencies and damping of the tower and the tower-line coupling system. We found that

(1) The influence of the suspended lines is mainly in the longitudinal mode and the torsional mode. It has less influence on the lateral mode.
The modal damping increases for the tower-line system, especially in the longitudinal direction. The longitudinal modal damping under loose connection state is larger than that of tight connection state.

(3) The system first three modal frequencies are almost the same as that of the tower under the loose connection state. However, under the tight connection state, it leads to the decrease of the longitudinal and the torsional frequency.

Table 1. Modal parameters of tower and the tower-line coupling system

| Parameter | State  | Direction |
|-----------|--------|-----------|
|           |        | longitudinal | torsional | lateral |
| Frequency/ Hz | Tower | 12.25 | 25.25 | 26.9 |
| Damping    | Tight  | 10.63 | 13.63 | 26.9 |
|           | Loose  | 12.38 | 25.25 | 26.9 |

The tower-line coupling effect is different in different connection state between the insulator and the tower. Considering insulators only in tight connection state may lead to large modelling error.

4. Modelling of Insulator at different state

Modelling method should be different if the connection state between the insulator and the tower is different.

4.1 Tight connection state

In the finite element modelling of tower-line system, the beam-rod hybrid element and the cable element are used to model the tower and line, respectively.

In the case of tight connection, system stiffness matrix and mass matrix are established by combining the stiffness matrix $K_{i,i}$ and the mass matrix $M_{i,i}$ of the tower and line in the global coordinate system

$$K_{i,i} = \sum_{i=1}^{n_t} K^{(i)} + \sum_{j=1}^{n_l} K^{(j)}$$ \hspace{1cm} (1)

$$M_{i,i} = \sum_{i=1}^{n_t} M^{(i)} + \sum_{j=1}^{n_l} M^{(j)}$$

where $n_t, n_l$ are the element number of tower and line. The insulator is simulated by a bar element with prestress. Its stiffness matrix is

$$K = K_e + K_g + K_{\sigma}$$ \hspace{1cm} (2)

where $K_e$ is the elastic stiffness matrix, $K_g$ is the displacement nonlinear stiffness matrix, $K_{\sigma}$ is the stress nonlinear stiffness matrix. The elastic stiffness matrix and the displacement nonlinear stiffness matrix can be derived from the shape and material properties of the rod. The stress nonlinear stiffness matrix can be obtained from the prestress calculation model shown in Figure. 3. Assuming that the tensile force exerted by the line on the insulator is the gravity of the line between the two insulators, the corresponding stress can be calculated.
Table 2 shows the calculated frequencies of the tower and the tower-line coupling system under tight connection. By comparing the results of tables 1 and 2, we can find that

1. The calculated frequencies are the same as those obtained experimentally.
2. The influence of tower-line coupling effect on system modal frequencies in three directions is consistent with the experimental results. That is, the influence is mainly in the longitudinal and the torsional modes. The modal frequencies of these two modals are reduced.

| System                  | Longitudinal | Torsional | Lateral |
|-------------------------|--------------|-----------|---------|
| Tower/Hz                | 12.31        | 22.05     | 24.33   |
| Tower-line system/Hz    | 10.02        | 12.08     | 23.42   |

Suspension line has a comprehensive influence on the additional stiffness and additional mass of the tower. For longitudinal bending and torsional modes, the line increases system mass in the corresponding direction, while the additional stiffness caused by the tension of the line has a relatively small effect. It results the decrease of frequencies in the corresponding modes. In the transverse direction, the effect of additional stiffness compensates for the effect of additional mass, so that the line has little effect on the frequency.

### 4.2 Loose connection state

Under the loose connection state, insulators can be regarded as a pendulum suspended on transmission tower. The insulator-line system works like a kind of tuned mass damper (TMD) as shown in Figure 4.

Under the linear small angle assumption, the control force $F_{spd}$ generated by pendulum motion can be simplified to

$$F_{spd} = \frac{m_p g}{l} (x_p - x_i)$$

where $m_p$ is the weight of line, $g$ the acceleration of gravity, $x_p, x_i$ the displacement of pendulum and structure relative to ground, $l$ the length of the pendulum.

The equation of motion of pendulum is

$$m_p \ddot{x}_p + \frac{m_p g}{l} (x_p - x_i) = 0$$

When the damping is not considered, the motion equation of the structure is
\[ m_i \ddot{x}_i + k_i x_i = F_{\text{spd}} + f \]  

(5)

where \( f \) is external force, \( m_i, k_i \) are the mass and stiffness of the structure, respectively.

The equation of the structure with additional pendulum is

\[
\begin{bmatrix}
m_i & 0 \\
0 & m_p
\end{bmatrix}
\begin{bmatrix}
\ddot{x}_1 \\
\ddot{x}_p
\end{bmatrix}
+
\begin{bmatrix}
k_1 + k_2 & -k_2 \\
-k_2 & k_2
\end{bmatrix}
\begin{bmatrix}
x_1 \\
x_p
\end{bmatrix}
=
\begin{bmatrix}
f \\
0
\end{bmatrix}
\]  

(6)

where \( k_2 = m_p g / l \).

The two natural frequencies corresponding to the above systems are

\[
\omega_n^2 = \frac{\omega_1^2}{2} \left[ 1 + a \pm \sqrt{(1 + a)^2 - 4\left(\frac{\omega_2}{\omega_1}\right)^2} \right]
\]  

(7)

where \( \omega_1, \omega_2 \) are the natural frequencies of the structure and the pendulum, respectively.

\[
\omega_1^2 = \frac{k_1}{m_1}, \ \omega_2^2 = \frac{k_2}{m_p} \quad a = \left(1 + \frac{m_p}{m_1}\right)\left(\frac{\omega_2}{\omega_1}\right)^2
\]  

(8)

Taking the longitudinal vibration of the rig as the example, the corresponding frequencies are

\[ \omega_1 = 76.93 \text{ rad/s}, \ \omega_2 = 6.91 \text{ rad/s} \]  

(9)

From (8), we can find that

\[ \omega_2 \ll \omega_1, \ a \approx 0 \]  

(10)

Thus, the tower-line system natural frequency

\[ \omega_n \approx \omega_1 \]  

(11)

In case of loose connection of insulator, the natural frequencies of tower is less influenced by line.

When the tower vibrates under external excitation, the inertia mass of the TMD device (insulator-line system) absorbs the vibration energy of the controlled mode of the tower. The damping increases. Therefore, the system damping is larger if the insulator is loosely connected with tower.

5. Conclusions

The influence of connection state of insulator with tower on the dynamic characteristics of transmission tower-line system was studied by means of modal test and analysis.

The conclusions are as follows

(1) The connection state between insulator and tower has a certain effect on the dynamic characteristics of the tower-insulator-line system. Considering insulators only in tight connection state with tower is not appropriate. It may lead to large modelling error.

(2) Modelling method under tight connection state and loose connection state should be different. Under the tight connection state, the tower, insulator and line can be modelled by finite element method respectively. The system stiffness and mass matrices can be obtained by combining the stiffness and mass matrices of the tower, line and insulator in the global coordinate system. However, under loose connection state, the system composed of insulator and line can be regarded as a tuned mass damper attached to the tower.

(3) The influence of the lines is mainly in the longitudinal mode and the torsional mode. It has less influence on the lateral mode.

(4) The modal damping increases for the tower-line system, especially in the longitudinal direction. The modal damping under loose connection state is larger than that of tight connection state.

(5) Under the loose connection state, system first three modal frequencies are almost the same as that of the tower. However, under the tight connection state, it leads to the decrease of the longitudinal and the torsional frequency.
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