Static and dynamic mechanical characteristic comparison research of v-type insulator string under gale condition

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Abstract. Application of V-type insulator string is most effective method in gale area to reduce wind deflection flashover, and dynamic characteristic of the V-type insulator string under action of pulse wind is an important factor to affect design of the V string. In order to clarify mechanical characteristic of the V-type insulator string under action of dynamic wind load, which is different to traditional rigid straight rod static mechanical method, finite element method is taken to calculate forcing of the V-type insulator string under action of pulse wind. Pulse wind speed time history with space relativity is considered and is converted to wind load time history, establishing non-linear finite element coupling model of insulator string – conductor, calculating mechanical characteristic of V-type insulator string under excitation of pulse wind, analyzing dynamic yield characteristic of the insulator under different angle of the V string, and providing theoretical basis for engineering design through comparison analysis between dynamic calculation result and static calculation result.

1. Introduction

Following rapid development of our national economy, power demand of the whole society is increasing. Because the energy bases of our country are mostly located at the west area, energy resource optimization and configuration within the whole country scope can be realized through "Transmitting electricity from western to eastern, mutual power supply between southern and northern, national wide interconnection".

In recent years, several windage yaw flashover accidents occurred in the power transmission line, therefore, the yaw flashover accident is an important safety hidden trouble for the normal operation of the grid, and it's not easy for the line to be reclosed after windage yaw accident, which seriously affects normal operation of the grid and causes great economic loss. Great windage yaw angle of the suspension insulator string is the direct reason for the windage yaw accident. Many newly constructed lines passing through the gale area, in order to reduce windage yaw of the insulator on the straight line tower, the V shaped insulator string is applied to reduce the windage yaw impact of the insulator. The V shaped suspension insulator string has been extensively applied in the domestic and foreign super-high voltage power transmission projects, which has many advantages of reducing size of the tower head, reducing steel consumption quantity, reducing width of the line corridor, saving cost of the line corridor, reducing filth accumulation on the insulator, increasing the self-cleaning capability, and preventing accident expansion during breakage of the insulator string etc. The V shaped insulator string can limit swing of the insulator. Since 2004, several string falling accident of the V shaped insulator string occurred in the power

transmission line in our country, for which the reason is as following: the leeward side of the V shaped insulator string is compressed under strong wind, which causes the ball head of the insulator extruding mutually with the socket-clevis eye, and the R shaped pin in the socket-clevis eye being abraded or deformed. All these problems lead the R shaped pin losing limitation function about the ball head, and the conductor falling.

In order to deeply learn the mechanical characteristic of the V shaped insulator string under strong wind, it is necessary to carry out mechanical analysis of the V shaped insulator under pulse action of gale. Forcing of the strain insulator string of the composition insulator in the 220kV line is studied in document[1]. Finite element analysis of the dynamic windage yaw angle of the suspension insulator string is studied in document[2].

This paper used the finite element method to calculate forcing of the V shaped insulator string under action of fluctuating wind. It is firstly simulated that the fluctuating wind speed time-history considering spatial correlation is converted into the wind load time-history, and then the finite element coupling model of the insulator string-power transmission line is established to calculate the stress distribution of the insulator string under excitation of fluctuating wind.

2. Calculation of wind load

It generally consists two parts in the time-history curve of wind: one is long period part, of which the value is often longer than 10 min; another is short period part, normally lasting several seconds. Because long period of wind is far greater than natural vibration period of the normal structure, the action of wind on the structure can be taken as static force action. Fluctuating wind is caused by the irregularity of wind, of which the strength is changed over time randomly. The period of fluctuating wind is very short, which will cause vibration of the structure. The horizontal fluctuating wind speed spectrum at tailwind direction applied in our country is Davenport spectrum. The fluctuating wind speed time-history at gale operation condition is obtained through calculation.

Wind speed at any height of the structure $v(z,t)$ may be amount of average wind speed $\overline{v}(z)$ and fluctuating wind speed $v_f(z,t)$, shown as formula (1). Simulation of wind mainly aims at fluctuating wind.

$$v(z,t)=\overline{v}(z)+v_f(z,t) \tag{1}$$

It is extensively acknowledge in wind engineering field that the horizontal fluctuating wind speed spectrum at tailwind direction is Davenport, which is also the wind speed spectrum applied in our national specification. The Davenport assumes that turbulent scale will change along height, and the spectrum density function is shown as formula (2).

$$S_v(\omega)=4K\overline{v}^2(10)\frac{x^2}{\omega\left(1+x^2\right)^{4/3}} \tag{2}$$

In which, $x=600\omega/\pi\overline{v}^2(10)$, $\omega\geq 0$ is frequency （rad/s）, $\overline{v}^2(10)$ is average wind speed (m/s) at height 10m away from ground, K is ratio which reflects roughness of ground.

The cosine stage superposition method is applied to simulate the fluctuating wind speed time-history of several points, the fluctuating wind speed at tailwind direction can be simulated by formula (3).

$$\tilde{v}_j(t) = \sum_{m=1}^{j} \sum_{i=1}^{N} \left| H_{jm}(\omega_i) \right| \sqrt{2\Delta\omega} \cos\left(\omega_i t + \theta_{mi}\right)$$

(3)

In which, $\tilde{v}_j(t)$ is the fluctuating wind speed of j point at height direction of the high-rise structure, N is isodisperse of the frequency scope in the wind speed spectrum, $\Delta\omega$ is increment of round frequency, θ_{mi} is the random number distributed in the section of $[0, 2\pi]$, $H_{jm}(\omega_i)$ is an element of the lower triangular matrix $[H]$. This matrix is obtained through Cholesky decomposition of the spectrum density function. The spectrum density function matrix $[S]_{j\times j}$ is shown as formula (4).

$$[S(n)] = \begin{bmatrix} S_{11}(n) & ... & S_{1j}(n) \\ ... & ... & ... \\ S_{j1}(n) & ... & S_{jj}(n) \end{bmatrix}$$

(4)

In which, $S_{xx}(n)$ is auto-power spectrum of wind speed at x point, $S_{xy}(n)$ is mutual-power spectrum of wind speed at x point and y point.

Calculation height of reference wind speed takes 10m, and roughness of the ground is considered as B category. Designed basic wind speed is 33m/s（10m high）, and average height of the conductor is calculated as 30m, which is converted to wind speed at this location as 39.34m/s. According to the fluctuating wind spectrum generated from the Davenport spectrum, the fluctuating wind speed time-history curve is shown as Fig.1.
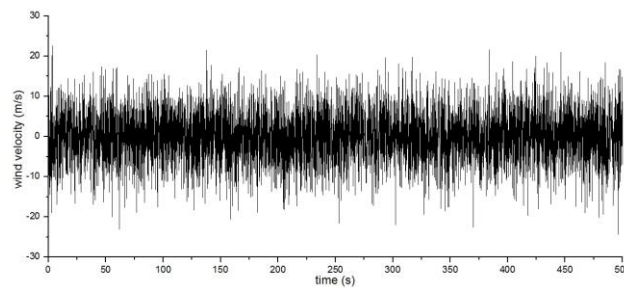

Figure 1. Time-history curve of high wind

Wind load of the split conductor is specified in IEC60826 Design code of overhead power transmission line that: wind load of the split conductor equals to the split number multiplying by wind load of the single conductor, and shield effect of the split conductor is neglected.

3. Value calculation model
The basic formulas such as balance equation of the suspension chain line and so on, are derived from documents [3-4], and one iterative algorithm is constructed. On such base, documents [5-6] apply the finite element method to derive the rigidity matrix of the suspension chain line unit for analysing the plane and the space suspension rope structure. The basic dynamic movement equation is as following:

$$M\ddot{u} + C\dot{u} + Ku = F \tag{5}$$

In which, M is quality matrix of the structure, K is rigidity matrix, C is damping matrix, $\ddot{u}$ is acceleration vector, $\dot{u}$ is speed vector, u is displacement vector, F is load vector.

The movement equilibrium equation is constant coefficient two order linear ordinary differential equation set, which can be solved theoretically with the standard solution using in the constant differential equation set. However, for the actual dynamic analysis of finite element, two value solution methods are generally applied, i.e., vibration model superposition method and direct integration method.

As the conductor belongs to the flexible structure, the geometrical non-linear issue of great displacement and small deformation shall be considered during analysis process. At same time, initial static balance position of the conductor system is initial condition for analysis of static force and dynamic force, which has a significant impact on the calculation results, therefore, we firstly carried out the static balance analysis of the conductor system. The calculation model is established according to the assembly figure of the insulator string.

We operated the windage yaw analysis of the insulator-fitting-conductor system under the condition of static wind and strong wind respectively, selecting the horizontal span as 500m, the vertical span as 500m and height difference of two spans of the conductor as 0m. We chose the length of whole composite insulator string being 11.0m, and composite insulator being 550kN. The model of the V shaped insulator string is shown as Fig.2. The conductor applied for mechanical calculation was 6×JL/G3A-1000/45-72/7.
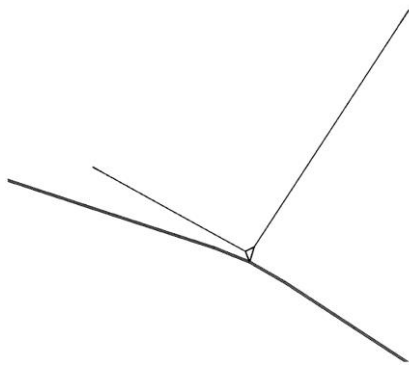

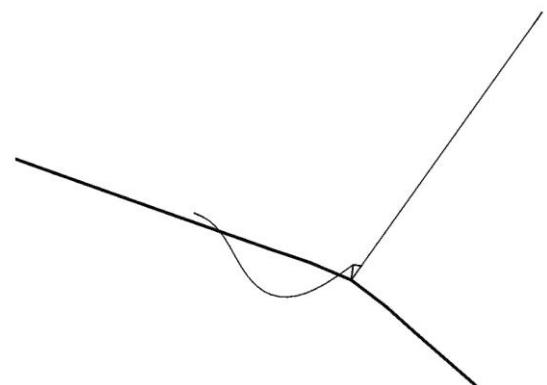**Figure 2.** Numerical calculation model of V-shaped insulator string

Figure 3. Buckling deformation of V-shaped insulator string under high wind

4. Static force calculation of V shaped insulator string

Static wind speed applied for calculation is 39.34m/s.

When angle of the V shaped string is 100° and the V shaped string is single connected, forcing of the insulator at the upwind side of the V shaped string under action of calm wind is 148.94kN, and forcing of the single connected insulator at leeward side of the V shaped string is -0.08kN.

When angle of the V shaped string is 110° and the V shaped string is single connected, forcing of the insulator at upwind side of the V shaped string under action of calm wind is 151.27kN and forcing of the single connected insulator at leeward side of the V shaped string is 7.01kN.

When angle of the V shaped string is 120° and the V shaped string is single connected, forcing of the insulator at upwind side of the V shaped string under action of calm wind is 159.03kN and forcing of the single connected insulator at leeward side of the V shaped string is 22.57kN.

When angle under action of calm wind is 100°, the single connected insulator at leeward side is placed at critical status for bending. When angles are 110° and 120°, there is no possibility for bending.

5. Mechanical characteristic of insulator string under action of fluctuating wind
Under action of fluctuating wind with the speed being 39.34m/s, the fluctuating wind spectrum was generated according to Davenport spectrum, and the time-history curve of fluctuating wind speed was shown as Fig.1. We calculated the mechanical characteristic of the V shaped string under action of fluctuating wind, when the fluctuating wind caused the insulator at leeward side bending, the deformation figure of the V shaped insulator string is shown as Fig.3.

5.1 Calculation Results When Angle of V Shaped String is 100° and V Shaped String is Single Connected
The force time-history curve of the single connected insulator at upwind side of the V shaped action under action of fluctuating action is shown as Fig.4, maximum value is 256.21kN, which is 1.72 times of static force calculation value.

Force time-history curve of the single connected insulator at leeward side of the V shaped string under action of fluctuating wind is shown as Fig.5, maximum value is 87.35kN. Bending phenomenon occurs in the insulator. Calculation time is 500s, and time step length is 0.1s. During 5000 time steps, the insulator at leeward wind side of the large V shaped string is unloaded at no 2786 time step.
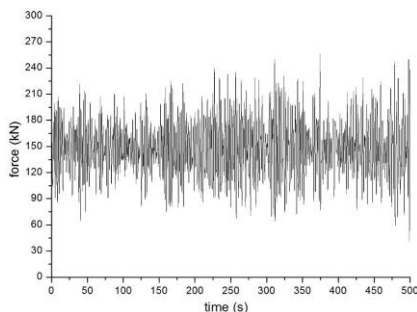

Figure 4. Force time-history curve of single-string insulators at windward side of V-string
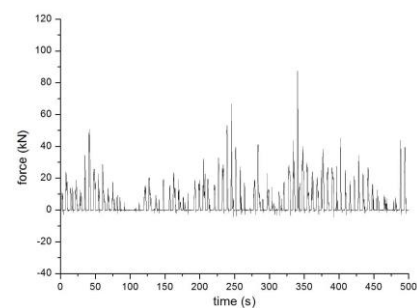

Figure 5. Force time-history curve of single-string insulators at leeward side of V-string

5.2 Calculation Result When Angle of V Shaped String is 110° and V Shaped String is Single Connected
The force time-history curve of the single connected insulator at upwind side of the V shaped action under action of fluctuating action is shown as Fig.6, maximum value is 252.81kN, which is 1.67 times of static force calculation value.

Force time-history curve of the single connected insulator at leeward side of the V shaped string under action of fluctuating wind is shown as Fig.7, maximum value is 81.31kN. Bending phenomenon occurs in the insulator. Calculation time is 500s, time step length is 0.1s. During 5000 time steps, the insulator at leeward wind side of the large V shaped string is unloaded at no 1143 time step.
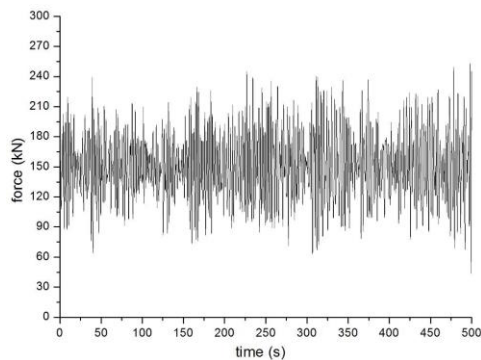
FIGURE 6. Force time-history curve of single-string insulators at windward side of V-string
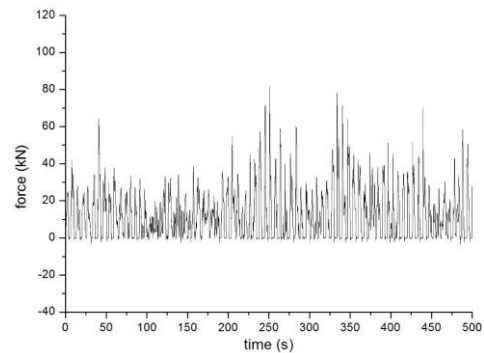

FIGURE 7. Force time-history curve of single-string insulators at leeward side of V-string

5.3 Calculation Result When Angle of V Shaped String is 120° and V Shaped String is Single Connected
The force time-history curve of the single connected insulator at upwind side of the V shaped action under action of fluctuating action is shown as Fig.8, maximum value is 269.12kN, which is 1.69 times of static force calculation value.

Force time-history curve of the single connected insulator at leeward side of the V shaped string under action of fluctuating wind is shown as Fig.9, maximum value is 98.02kN. Bending phenomenon occurs in the insulator. Calculation time is 500s, time step length is 0.1s. During 5000 time steps, the insulator at leeward wind side of the large V shaped string is unloaded at no 309 time step.
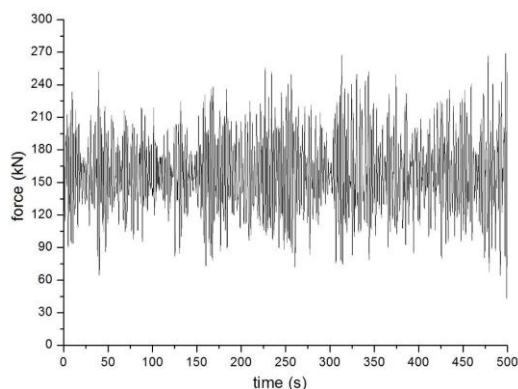

Figure 8. Force time-history curve of single-string insulators at windward side of V-string
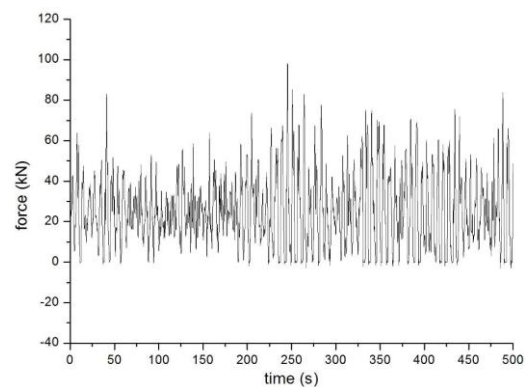

Figure 9. Force time-history curve of single-string insulators at leeward side of V-string

6. Conclusion
The following conclusions were obtained through calculation results.

Value calculation can effectively simulate forcing process of the V shaped insulator under action of calm wind and fluctuating wind, and obtained the corresponding mechanical characteristic.

With the same angle and same wind speed, the maximum forcing of the single connected insulator at upwind side of the V shaped string under action of fluctuating wind is about 1.8 times forcing under action of calm wind.

Unloading times of the V shaped insulator string at leeward side under action of fluctuating wind can reflect bending condition of the insulator.

The V shaped insulator string can effectively inhibit windage yaw flashover fault under action of general wind load. However, in gale area, dynamic bending of the insulator at leeward wind side of the V shaped insulator string caused by strong fluctuating wind will cause fatigue of the insulator, which shall be considered in the design of V shaped insulator string.

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