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Unbalanced tension analysis for UHV transmission towers in heavy icing areas

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ABSTRACT

Unbalanced tension is one of the most important controlling loads for the design of transmission towers in cold regions. It can be caused in some cases including non-uniform accreted ice, broken wires, ice shedding and galloping. Firstly, for the comparison of the unbalanced tensions and the inclinations of the suspension strings, the FEA method and the constant conductor length method were applied. The results by two methods are approximately well agreed. With the consideration of some design parameters of the transmission line, a seven continuous span FEA model of conductors and insulators was established. Secondly, under different load cases, the tensions and the unbalanced tensions of conductors were analyzed for the UHV suspension tower and tension tower in heavy icing areas. It shows that the load modes and the eccentricity of the accreted ice, as well as the wind velocity only have little effect on the unbalanced tensions. The transforming density method and 10 m/s of wind velocity are proposed for the analysis of the unbalanced tensions. When there are no elevation difference and span difference, the unbalanced tension of the UHV suspension tower increases with the ice thickness, the span length and the icing rate, and the calculated values for different ice thickness are lower than those of regulations. With the increasing of the elevation difference and the span difference, the ratios of the unbalanced tensions with and without elevation difference as well as span difference increase. However, the ratios of the unbalanced tensions with and without elevation difference as well as span difference decrease with the ice thickness. For tension towers, variations of the elevation difference and the span difference have little effect on the unbalanced tensions. Lastly, the calculated values of the unbalanced tension percentages of UHV transmission towers were compared with those of applicable regulations, some suggestions on the unbalanced tension values were proposed.

1. Introduction

Unbalanced tension is one of the most important controlling loads for the design of transmission towers in cold regions. Unbalanced tensions can be caused in some cases, including non-uniform accreted ice, broken wires, ice shedding and galloping, etc. As a normal type of load in icing areas, the non-uniform accreted ice may induce longitudinal unbalanced tensions in two adjacent spans of the suspension tower or tension tower. The suspension tower will be subjected to bending moment or torsional moment, which is the main reason for damage or collapse of suspension towers. After the collapse of a suspension tower, suspension towers at the two adjacent sides will bear much higher unbalanced tensions and impact loads, and the cascades in transmission lines may be induced.

In recent years, some researchers and designers have been focused on the study of the unbalanced tensions under non-uniform accreted ice (David B. Campbell, 1970; John D. Mozer et al., 1977; Yuan, 2010). Liao et al. (2006) computed the unbalanced tensions for the 1000 kV UHV suspension tower in light icing areas. For UHV suspension towers in plain areas, hill areas and mountain areas, some advices for the determination of the unbalanced tension values were proposed. In the report by China Power Engineering Consulting Group Cooperation (2008), a seven continuous span conductor model was established. Unbalanced tensions for the 220 kV–750 kV suspension towers and tension towers were calculated with ice thickness of 10 mm to 50 mm. Based on the constant conductor length method, Zhang and Liu (2009) developed a program for the analysis of the unbalanced tensions in continuous spans. Unbalanced tensions and inclinations of suspension strings were calculated for suspension towers in light icing areas. It is concluded that the unbalanced tension values calculated by the Design Code of 110 kV–750 kV Overhead Transmission Lines (National Energy Administration, 2010) are relatively low for some cases, and the unbalanced tension values should be enhanced for suspension towers in the transmission lines not higher than 500 kV. Cheng and Xue (2011) studied the effects of some design parameters on the unbalanced tensions. The design parameters include safety coefficient of conductors, length of

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suspension strings, span numbers, span difference and elevation difference.

After the serious ice disaster in South China in 2008, in order to ensure the anti-bending and anti-torsion capacity of transmission towers, the Technical Code for Designing of Overhead Transmission Line in Medium & Heavy Icing Area (China Electricity Council, 2009) was revised, and the unbalanced tension percentages and icing rates in two adjacent sides of transmission towers were regulated. The ratio of the unbalanced tension to the maximum working tension of conductors is defined as the unbalanced tension percentage. This code is suitable for 110 kV–750 kV transmission lines, however regulations or suggestions on the unbalanced tension values for UHV transmission towers were not mentioned.

For the calculation of unbalanced tension in IEC 60826(International Electrotechnical Commission, 2003), the two adjacent spans are loaded with accreted ice of $0.7g_R$ and $0.28\ g_R$. g_R is the reference ice weight accreted on the conductors. That means the icing rates of the two adjacent spans are constant values. However, in the Technical Code for Designing of Overhead Transmission Line in Medium & Heavy Icing Area (China Electricity Council, 2009), the icing rates are varied for different transmission line classes or different types of towers.

With the development of the UHV transmission projects, the UHV transmission lines cannot be avoided to pass the heavy icing areas. The XiangJiaBa-ShangHai ±800 kV DC transmission line in operation has passed heavy icing areas in Southwest China. The YaAn-NanJing 1000 kV AC transmission line in consideration will pass the icing areas with 20 mm accreted ice in Southwest China. According to the design conditions of the UHV transmission lines, it is noted that the ice thickness referred in this paper is the design ice thickness with a return period of 100 years.

Until recently, few studies have dealt with the unbalanced tensions for the UHV transmission towers in heavy icing areas. Numerical simulations using nonlinear finite element analysis (FEA) are useful to study the unbalanced tensions for UHV transmission towers. In this paper, a seven continuous span conductor-string model in UHV transmission line was developed. Some design parameters were considered in the FEA model, which included the loading mode of accreted ice, the eccentricity of accreted ice, the wind velocity, the ice thickness, the icing rate, the span length, the elevation difference and the span difference. Parametric study on the unbalanced tensions and the unbalanced tension percentages was performed. Based on the analysis results, the unbalanced tension values were determined for the UHV transmission towers in heavy icing areas. This study should be useful for ensuring the safety and reliability of UHV transmission towers in heavy icing areas.

2. Analysis model

2.1. FEA model

A conductor-string FEA model was established in the ANSYS software (Yan et al., 2010; Yang et al., 2009, 2010a, 2010b, 2010c). Two basic assumptions were set in this model. Firstly, it is assumed that the support structures at the end of the line system are dead-end structures and can be considered to be rigid during the analysis. The effect of longitudinal stiffness of towers was ignored. Secondly, it is also assumed that the material of the conductors and insulators remains elastic under ice loads.

Suspension strings are pinned to the cross arms by U type ring, and suspension strings can freely rotate around the longitudinal direction and the transversal direction of transmission lines. The real behavior of the suspension strings is more like a chain of rigid links (Fekr and McClure, 1998). So the suspension strings were modeled with LINK8 (ANSYS, Inc., 2009) bar element. The conductors were simulated by LINK10 (ANSYS, Inc., 2009) cable element. The effect of the initial tension on the mechanical characteristics of conductors can be considered in LINK10. The element stiffness matrix $[K]$ can be derived and presented in Eq. (1).

$$[K] = [K_l] + [S_l] = \frac{A\cdot E}{L}\begin{bmatrix} 1 & 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} + \frac{T_0}{L}\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & -1 & 0 \\ 0 & 0 & 1 & 0 & 0 & -1 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & 1 & 0 \\ 0 & 0 & -1 & 0 & 0 & 1 \end{bmatrix} \tag{1}$$

Where $[K_l]$ and $[S_l]$ are the geometric stiffness matrix and the stress stiffness matrix, respectively. A is the area of the element section, E is the elastic modulus,$T_0$is the initial tension, L is the element length.

The initial tension of the link element can be realized by applying an initial strain or decreasing the temperature of the elements. The latter method was used for the FEA model. A very small initial tensile strain (such as 10^{-7}) was specified for each element of conductors in order to avoid singularities in the initial stiffness matrix of the cables. The equivalent temperature ΔT can be calculated by Eq. (2).

$$\Delta T = \frac{T_0}{\alpha\cdot E_c\cdot A_c} \tag{2}$$

Where T_0 is the initial tension of conductor, E_c is the elastic modulus of conductor, α is the linear expansibility of conductor, A_c is the section area of conductor.

Before the unbalanced tension analysis under the load case with non-uniform accreted ice, the form-finding analysis of conductors was carried out. Firstly, the initial tensions of the conductors can be determined according to the ruling span of the actual transmission line section. The ruling span can be calculated by the method in the Design manual for high-voltage transmission lines of electric power engineering (North-East Electric Power Design Institute of State Power Corporation of China, 2002). Then the parabolic geometry models of the conductors were obtained on the basis of tension-sag formula. The geometrical forms of the conductors were updated repetitively through nonlinear static analysis, and the form-finding process was terminated when the deformations of the conductors were close to zero.

2.2. Verification of the analysis model

The unbalanced tension was commonly calculated by the method based on the constant length of conductors in an individual strained line section. In this method, the stress state equations of conductors and the force equilibrium principle were applied, and the mathematical model of the conductor tension as well as the string inclination was established under non-uniform accreted ice. Finally, a program was developed for the analysis of the conductor tension and the unbalanced tension.

In order to verify the accuracy of the FEA model used in this study, the results calculated by the FEA model were compared with those by the constant conductor length method in Zhang and Liu (2009). Zhang and Liu (2009) model is a classical model and widely used for the calculation of the unbalanced tension. Some results by this model have been adopted by some Chinese standards. But in Zhang and Liu