Postprint: Analysis of Causes and Retrofit Measures for Wind-Deflection Tripping of 750kV Transmission Lines

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Abstract

To identify the main causes of wind-induced swing flashover trips in 750kV transmission lines, the analytical method is employed to analyze the clearance distance at different angles after insulator wind swing, thereby identifying the wind swing angle that triggers line trips. Subsequently, the code-based method is utilized to calculate the wind swing angle, revealing that the wind swing safety margin for towers designed for a wind speed of 31m/s is merely 5°, and wind-induced swing flashover trips will occur when the on-site wind speed reaches 1.1 times the design wind speed. Simultaneously, through analysis of on-site monitored wind speed data, it is found that the maximum standard wind speed on site is 27.5m/s, while the maximum extreme wind speed reaches 40.5m/s, leading to the conclusion that the primary cause of wind-induced swing flashover trips is the extreme wind speed exceeding the design wind speed. Finally, for towers requiring retrofitting, the advantages and disadvantages of wind-resistant swing measures for transmission lines are analyzed, concluding that guy-type wind-resistant measures are recommended for 750kV transmission lines, with an analysis of guy selection also conducted. Wind-resistant retrofitting can enhance the wind resistance capability of 750kV transmission lines and improve the safe operation level of the power grid.

Full Text

Analysis of Causes and Research on Reform Measures for Wind-Induced Swing Tripping of 750kV Transmission Lines

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Abstract

To identify the main causes of wind-induced swing tripping in 750kV transmission lines, the analytical method was employed to analyze the clearance distance of insulators at different angles after wind deflection, thereby determining the critical wind deflection angle that triggers line tripping. Subsequently, the procedural method was used to calculate the wind deflection angle, revealing that the safety margin for wind deflection of towers designed for a wind speed of 31 m/s is only 5°; wind-induced swing tripping would occur when the on-site wind speed reaches 1.1 times the design wind speed. Concurrently, analysis of field-monitored wind data indicated that the maximum standard wind speed on site was 27.5 m/s, while the maximum extreme wind speed reached 40.5 m/s, leading to the conclusion that the primary cause of wind-induced swing tripping was the extreme wind speed exceeding the design wind speed. Finally, the advantages and disadvantages of various wind deflection prevention measures for transmission lines were analyzed for towers requiring modification, concluding that wind-resistant guy wire measures are recommended for 750kV transmission lines, with an analysis of the selection criteria for such guy wires. These windproof modifications are beneficial for enhancing the wind resistance capacity of 750kV transmission lines and improving the safe operation level of the power grid.

Keywords: wind deflection, tripping, hazard wind angle, standard wind speed, maximum wind speed, wind guy wire

1 Introduction

Xinjiang’ s terrain features the Altai Mountains to the north, the Karakoram Mountains to the south, and the Tianshan Mountains across its central region, with the Tarim Basin and Junggar Basin located to the south and north of the Tianshan range respectively. This topography of three major mountain ranges and two large basins creates eight major wind zones in Xinjiang [1-4]. Consequently, Xinjiang experiences numerous wind-induced transmission line tripping incidents. For example, from the night of April 22 to April 24, 2014, under the influence of strong cold air from Siberia, northern Xinjiang, the Tianshan mountain area, and Hami experienced sandstorms and high winds. Most areas in northern and eastern Xinjiang experienced heavy frost and northwest winds of approximately level 6, with instantaneous maximum wind forces reaching above level 12 in the “Thirty Li” and “Hundred Li” wind zones. By 18:00 on April 24, a total of 51 transmission lines of 110kV and above within Xinjiang

Company had tripped 70 times (with 35 lines experiencing fault outages), including 16 110kV lines tripping 20 times, 15 220kV lines tripping 26 times, and 3 750kV lines tripping 7 times (with the Tianzhong DC line and Hatian Line I accompanying outages). This caused severe impacts on the normal operation of the Xinjiang power grid, necessitating analysis of the causes of wind-induced swing tripping and the development of targeted preventive measures.

2 Wind Deflection Accident Description

This section describes a 750kV wind-induced swing tripping accident. At 09:01 and 11:18 on April 23, the 750kV Tuhu Line I tripped twice, with both reclosing attempts failing. Both faults were caused by discharge between the grading ring on the conductor side and the crossarm after wind deflection of phase B (left side phase) at tower #326 of Tuhu Line I. The fault location was designed for a high-wind meteorological zone with a design wind speed of 31 m/s. Tower #326 is a ZB131P type suspension tower with a nominal height of 36 m. The conductor and ground wire types are LGJK-310/50 and JLB20A-100 respectively, with side-phase and middle-phase string configurations of I-string and V-string respectively, and side-phase and middle-phase insulator models of 1×FXBW-750/210 and 2×FXBW-750/210 respectively.

3 Analysis of 750kV Transmission Line Wind Deflection Issues

3.1 Analysis of Electrical Clearance Distance After Wind Deflection

The diameter of the insulator’ s shed is much larger than that of the grading ring. During the equivalent process, the primary considerations are the influence of the grading ring and the conductor bundle support device. The simplified equivalent diagram is shown in [Figure 2: see original paper].

The insulator string design for tower #326 is illustrated in [Figure 1: see original paper]. As shown in the figure, influenced by the bundle conductors and grading ring, the entire insulator string must be recalculated as a line when computing the electrical clearance distance after wind deflection, as significant errors would otherwise occur [5-6]. Therefore, it is necessary to re-equivalent the model after the insulator string suspends the conductor. Since the diameters of the bundle conductors and grading ring are much larger than those of the insulator sheds, the influence of the grading ring and conductor bundle support device must be considered in the equivalent process.

The ZB231P type tower head dimensions are shown in [Figure 3: see original paper]. Based on the equivalent diagram of the insulator string, the air gap distance between the insulator string and the tower during wind deflection is illustrated in [Figure 4: see original paper].

As shown in [Figure 4: see original paper], after wind deflection, the grading ring will discharge to the tower body first when the insulator string reaches tripping conditions [7-8]. Drawing a circle from the point on the grading ring nearest to the tower body, the tangent point with the tower body represents the closest distance, indicated by the right angle in the figure. From the ZB231P tower parameters, the sum of angle a and angle c is 81°, and L1 can be determined from the simplified insulator string parameters as 7.3 m. The triangular relationship in the figure yields the calculation formula for the nearest distance between the conductor and tower body during wind deflection:

$$d_1 = \sin c \cdot L$$

Based on the previous analysis of the distance between the conductor and tower crossarm after wind deflection, the calculation formula for L3 is:

$$L_3 = L_1^2 + L_2^2 - 2L_1L_2 \cos c$$

As shown in [Figure 4: see original paper], for ZB231P type towers, the sum of angle e and angle f is constant at 111°. Using oblique triangle solutions, angle e can be determined, and then angle f and L3 can be used to calculate the nearest distance between the conductor and tower body:

$$d_2 = \sin f \cdot L_3 - r$$

Based on the structural parameters of ZB231P type towers and the aforementioned calculation method, the air gap distances at different wind deflection angles are calculated and presented in .

**** Relationship between electrical clearance distance and wind deflection angle for ZB231P type tower conductors (for 40 m tower height) (units: mm)

3.2 Calculation of Maximum Allowable Wind Speed

According to GB50545 "Design Code for 110～750kV Overhead Transmission Lines,"the minimum clearance distance between live parts and tower components for 750kV lines at altitudes above 100 m is 1.9 m.

Per code requirements, the standard values of horizontal wind load and reference wind pressure for conductors and ground wires should be [9]:

$$W_X = \alpha\beta_c\mu_z\mu_{sc}dL_PB\sin^2\theta$$

$$W_0 = V^2/1600$$

where W_X is the horizontal wind load perpendicular to the conductor direction (kN); α is the wind pressure non-uniformity coefficient, taken as 0.65; β_c is the conductor wind load adjustment coefficient, taken as 0.9; μ_z is the wind pressure height variation coefficient, determined according to at the reference height of 10 m; μ_{sc} is the conductor shape coefficient, taken as 1.2 when diameter is less than 17 mm or under icing conditions (regardless of diameter), and 1.1 when diameter is greater than or equal to 17 mm; d is the conductor outer diameter (for bundle conductors, use the sum of all sub-conductor outer diameters) (m); L_P is the tower' s horizontal span (m); B is the wind load increase coefficient under icing conditions, taken as 1.1 for 5 mm icing design and 1.2 for 10 mm icing design; θ is the angle between wind direction and conductor direction (°); and V is the wind speed at the reference height of 10 m (m/s).

**** Wind pressure height variation coefficient μ_z

The standard value of wind load for insulator strings should be:

$$W_t = W_0 \mu_z B A_1$$

where W_t is the standard wind load value for the insulator string (kN), and A_1 is the calculated wind pressure area for the insulator string (m²).

For simplified calculation, the insulator string and conductor are assumed to be rigid bodies that do not bend or deform under wind; wind pressure is treated as a static force uniformly applied to the conductor and insulator string. The static force analysis diagram when the conductor reaches equilibrium under wind load is shown in [Figure 5: see original paper].

The wind deflection angle Φ calculation formula based on the force analysis diagram shown in [Figure 5: see original paper] is:

$$\Phi = \arctan\left(\frac{F_d + \frac{1}{2}F_j}{G_d + \frac{1}{2}G_j}\right)$$

where F_d is the horizontal wind load perpendicular to the conductor direction (N), F_j is the insulator string wind load (N), G_d is the conductor vertical load (N), and G_j is the insulator string gravity load (N).

Based on the previously calculated allowable wind deflection angle without tripping, and using an average span of 500 m with conductor parameters shown in , the allowable wind speed values for ZB231P type towers at different heights under power frequency and switching overvoltage conditions are calculated and presented in and .

**** Conductor types for different line sections

**** Allowable wind speed values for different tower types without tripping

**** Allowable wind speed values for successful reclosing of different tower types

4 Analysis of Wind Deflection Trip Causes

First, analyzing the wind speed values monitored by the micro-meteorological monitoring device during tripping, the micro-meteorological monitoring data for tower #297 on April 23 is shown in [Figure 6: see original paper]. The figure indicates a maximum standard wind speed of 27.5 m/s, maximum wind speed of 29.2 m/s, and maximum extreme wind speed of 40.5 m/s.

Based on the previous analysis, ZP231P type towers would not experience wind-induced swing tripping when the standard wind speed is less than 34 m/s. However, actual wind-induced swing tripping occurred on site, demonstrating that using standard wind speed to calculate transmission line wind deflection angles yields underestimations that do not match field conditions.

According to the line’ s force analysis during wind deflection, for ZB231P type towers, the electrical clearance distance will be less than 1.9 m when the wind deflection angle reaches 61°. With a span of 500 m, ZB231P type towers will experience discharge at a wind speed of 33 m/s, with conductor wind pressure reaching 78.682 kN.

As shown in [Figure 4: see original paper], when the wind deflection angle increases from 0° to 61°, the conductor moves a distance of 9.276 m. Based on wind load calculations, the average acceleration during movement is 78,682/4,824/2 = 8.16 m/s^2. The rising time can thus be calculated as 1.51 s. Since wind speed cannot increase directly from 0 m/s to 33 m/s, and some wind deflection angle may already exist during the wind speed increase process, although previous wind speeds may not reach the discharge requirement, if a gust occurs at this moment, reaching the discharge distance requires only a very short time. Therefore, the cause of line tripping is excessive instantaneous wind speed.

According to showing allowable wind speed values for successful reclosing of different tower types and the standard wind speed values monitored during the accident shown in [Figure 6: see original paper], the allowable wind speed for successful reclosing after wind-induced swing tripping is 26 m/s, while the standard wind speed monitored on site was approximately 28 m/s, making successful reclosing difficult.

5 Solutions for 750kV Line Wind Deflection Issues

5.1 Adding Vertical Hangers to Side-Phase Crossarms

Installing vertical hangers can increase the air gap distance when the insulator string deflects under wind [10-11], with the effect shown in [Figure 7: see original paper].

Based on the previous calculation method for the windproof tower head modification effect, for ZB231P type towers, adding a 1 m vertical hanger increases the allowable wind deflection angle to 66°, equivalent to preventing tripping at 1.2 times the design wind speed.

5.2 Using Wind-Resistant Cables

Wind-resistant cable installation is shown in [Figure 8: see original paper]. Compared with traditional counterweight methods, this solution reduces impact on the tower and does not require power outage for installation. Relative to the measure of converting I-strings to V-strings, the wind-resistant cable solution does not require changing the tower crossarm structure, resulting in lower comprehensive costs. Field application demonstrates that this device can limit wind deflection angles within a safe range and effectively prevent conductor discharge to the tower under strong winds.

5.3 Installing Wind-Resistant Guys on Side Phases

Inspired by the use of wind-resistant guys on 220kV lines in Xinjiang' s high-wind zones, consideration is being given to applying wind-resistant guys on side phases of 750kV lines.

5.4 Selection of Wind Deflection Prevention Measures for Xinjiang Grid

Based on the aforementioned wind deflection prevention measures, the vertical hanger addition method requires tower modification, resulting in long outage times and extensive construction work. Wind-resistant cables lack operational experience on 750kV lines, and after installation, they form a straight line that can cause excessive force on the crossarm when the insulator string contacts the cable, potentially causing damage; currently, they can only be used on lines of 220kV and below. Therefore, the method of installing wind-resistant guys on side phases was selected for the modification. However, as this is the first application of wind-resistant guys on 750kV lines, analysis of their force conditions during wind deflection is required.

(1) Optimization of allowable wind deflection angle and guy wire-to-vertical line angle. To ensure normal operation during wind deflection, the allowable wind deflection angle and the angle between the guy wire and vertical line should not be excessive. Additionally, since wind-resistant guys are only installed on some towers while others remain unmodified, the reclosing scenario after wind-induced swing tripping at unmodified locations must be considered. Therefore, locations with guy wires should account for switching overvoltage discharge issues, ensuring that the clearance distance after wind deflection exceeds the switching overvoltage discharge distance. According to reclosing success requirements, the allowable suspension string deflection angle is 30°, and the guy wire should reserve approximately 1.5 m of slack length.

(2) Force analysis after installing wind-resistant guys. The forces after installing wind-resistant guys are shown in [Figure 9: see original paper]. Taking ZB231P type towers as an example, with a normal span of 500 m and wind speed of 31 m/s, previous calculations indicate a conductor wind pressure of 89.37 kN and conductor vertical load of 49.88 kN. The calculated tension on the tower insulator is 136.03 kN, and the tension on the guy wire insulator is 83.63 kN, both within the insulator’ s tensile capacity. If checked against the extreme wind speed of 45 m/s, the tower insulator tension is calculated as 167.23 kN and the guy wire insulator tension as 103.71 kN. This shows that under extreme wind speed checking, the tower insulator tension approaches 82% of its normal service tension, posing a risk of insulator string breakage; it is recommended to use double insulator strings for tower insulators. The guy wire insulator tension remains within the acceptable range, allowing single-string connections.

(3) Installation of micro-meteorological monitoring devices. Since wind deflection angles during tripping are analyzed using wind speeds measured by micro-meteorological monitoring devices, these devices can effectively be used for accident prevention following incident analysis. It is recommended to increase micro-meteorological monitoring devices on the Tuhu line to improve understanding of wind conditions in this section and provide effective wind speed design basis for new line construction.

6 Conclusion

To analyze the main causes of wind-induced swing tripping in 750kV transmission lines, the analytical method was used to examine clearance distances of insulators at various angles after wind deflection, identifying the critical wind deflection angle that causes line tripping. The procedural method was then applied to calculate the wind deflection angle, revealing that the safety margin for towers designed for 31 m/s wind speed is only 5°, with wind-induced swing tripping occurring at 1.1 times the design wind speed. Analysis of field-monitored wind data showed maximum standard wind speeds of 27.5 m/s and maximum extreme wind speeds of 45 m/s, concluding that the primary cause of wind-induced swing tripping is extreme wind speed exceeding the design wind speed. Finally, the advantages and disadvantages of various wind deflection prevention measures were analyzed for towers requiring modification, concluding that wind-resistant guy wire measures are recommended for 750kV transmission lines, with analysis of guy wire selection criteria. These windproof modifications enhance the wind resistance of 750kV transmission lines and improve power grid safe operation levels.

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