Discussion on the Value of Wind-induced Vibration Coefficient of Independent Steel Tube Lightning Rod Structure Design

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Abstract. This study compared the reliability of the ISTLRs (independent steel tube lightning rod) whose structure was designed using WIVC (wind-induced vibration coefficient) in DL/T 5457-2012, GB50009-2012 and AR method. Based on the assembly diagram of the lightning rod in the lightning rod replacement project in a 220kV substation, the finite element model was established in ANSYS Workbench. The three WIVCs were substituted into the HD (horizontal displacement) of the structure design, and the reliability of structure designed from the three was compared. Suggestions were made on the value of the WIVC when designing an ISTLR structure.

1. Introduction

The reasons for lightning rod break accidents can be summarized as the following points[1][2][3]: 1) material properties, such as material defects, fatigue, etc., 2) Variable wind load. 3) Harsh climatic conditions, including low temperature, environmental corrosion, and frost heaving of cracked water. 4) Unreasonable structural design. 5) Construction techniques, such as welding stress concentration. However, no one questioned the value of the WIVC. The WIVC will affect the reliability of the structure. LONG H et al.[4] conducted a time-history analysis of the model on the 1000kV UHV transmission steel tube tower using the AR autoregressive model to simulate the pulsating wind load, and calculated the WIVC of each section of the tower and the cross-arm. Kang W[5] used the AR method in 2018 to study the WIVCs of lightning rods with different structure types. (table 2) This paper attempts to compare the reliability of structure designed from the three WIVCs and gives suggestions for the structural design of ISTLR.

2. Engineering background

The outdoor power distribution equipment bracket of a 220kV substation was seriously old. Some brackets have exposed reinforced bar, cracks, and even equipment misalignment and tilting. In the substation, there were 15 lightning rods on the gantries and two 30m high independent ones. Among them, the lightning rods on the gantries had serious corrosion problems, and some of them had been tilted. According to the lightning protection calculation, 14 lightning rods on the gantries and two independent ones were removed, and 11 new 35m high independent lightning rods were built, (Fig. 1) using Q235B steel; and one lightning rod on the gantry was retained.
3. Establishment of the finite element model
A solid model of an ISTLR was established from Fig 1. The bottom of the lightning rod is fixed. The lightning rod is a high-rise structure, and the wind load is its design control load. The modal analysis of the structure shows that the HD of the first 10th mode is only 8.06mm (9th and 10th order). It can be seen that the HD of the ISTLR under the seismic load is much smaller than the wind load. Ensuring local stability[6], the wind-induced HD is the control condition for the design of independent steel tube structure. According to DL/T 5457-2012, the top 5m of the lightning rod is the tip part, therefore, 30m is the top of the support part. Only the HD of the top of the support not exceeding H/70 is the design control condition of the serviceability limit state.

4. HD by deferent WIVCs
4.1. WIVCs in GB50009-2012
WIVC($\beta_z$) in GB50009-2012[7] was calculated as table 1 and shown in table 3.

4.2. WIVCs in DL /T 5457-2012
It stipulates that the WIVC of an ISTLR is 2.0 in item 4.4.2 of DL /T 5457-2012.

Table 1. Calculation formula of WIVC in GB50009-2012

| $\beta_z$ | $R$ | $\phi_1(z)$ |
|----------|-----|-------------|
| $1 + 2g_{10}B_z\sqrt{1 + R^2}$ | $\pi x_1^2 \sqrt{6x_1 (1 + x_1^2)}^{4/3}$ | $-1.047 \left(\frac{z}{H}\right)^3 + 2.2465 \left(\frac{z}{H}\right)^2 - 0.224 \frac{z}{H}$

(see fig 3.)

| $x_1 = \frac{30f_1}{k_w\omega_0}$ | $k_w = 1.0$ | $k = 0.910$ | $\rho_z = \frac{10\sqrt{H + 60e^{-H/60} - 60}}{H}$

$\rho_x = \frac{10\sqrt{B + 50e^{-B/50} - 50}}{B}$

$f_1 = 0.6038$ | $\omega_0 = 0.77$ | $\mu_x = \left(\frac{z}{10}\right)^{0.30}$

$\mu_x = \frac{a_1 H}{35}$ | $H = 35m$. | $B$: Diameter of the tube
Fig 2. The HD of the lightning rod using the WIVC in the AR method (considering the P-Δ effect)

Table 2. WIVC in the AR method (by Kang W)

| Height (m) | Undamped | Damping coefficient = 0.02 |
|------------|----------|----------------------------|
| 34.75      | 2.86     | 2.27                       |
| 32         | 2.62     | 2.11                       |
| 28.875     | 2.38     | 1.93                       |
| 25.625     | 2.16     | 1.77                       |
| 22         | 2.17     | 1.75                       |
| 18         | 1.87     | 1.54                       |
| 14         | 1.71     | 1.43                       |
| 10         | 1.42     | 1.25                       |
| 6          | 1.19     | 1.11                       |
| 2          | 1.04     | 1.02                       |
Table 3. Comparison of WIVCs of the 35m independent lightning rod

| Segment height (m) | AR method (based on Table 2.) | DL / T 5457-2012 | GB50009-2012 |
|-------------------|--------------------------------|------------------|--------------|
| 34                | 2.510                          | 2.00             | 3.41         |
| 31.5              | 2.331                          | 2.00             | 3.14         |
| 28.5              | 2.133                          | 2.00             | 2.89         |
| 25.5              | 1.965                          | 2.00             | 2.64         |
| 21.5              | 1.928                          | 2.00             | 2.29         |
| 16.5              | 1.654                          | 2.00             | 1.87         |
| 11                | 1.394                          | 2.00             | 1.46         |
| 4                 | 1.09                           | 2.00             | 1.09         |

4.3. WIVCs in the AR method
WIVC in the AR method by Kang W is as table 2. According to the GB50009-2012, the damping coefficient of the steel structure is 0.01. The average values of the undamped and damping coefficient 0.02 were calculated from table 2. Afterward, the WIVCs between the adjacent segment heights were obtained by linear interpolation.

Table 4. HD of the lightning rod at 30m (mm)

| WIVC | P-Δ effect off | P-Δ effect on |
|------|----------------|---------------|
| DL / T 5457-2012 | 376.77         | 389.15        |
| AR method        | 384.28         | 396.86        |
| GB50009-2012     | 495.38         | 511.44        |

Fig 3. Fit Polynomial of $\phi_1(z)$
5. Conclusions and recommendations

Through the comparison of the WIVCs in table 3 and HD of the structural support of the 35m independent lightning rod in table 4, the conclusion is drawn:

- The WIVC of AR method is smaller than GB50009-2012 WIVC at any height, less than DL/T 5457-2012 WIVC at about 26m, and more than it at 26m or higher place.
- The displacement of the lightning rod at the height of 30m obtained by the WIVC of the AR method is about 2% greater than the displacement obtained by the WIVC of DL/T 5457-2012, and about 29% less than the displacement obtained by the WIVC of GB50009-2012.

Therefore, the WIVC in DL/T 5457-2012 is too small, which is not suitable for the structural design of today's independent lightning rods; although GB 50068-2018 is implemented on April 1, 2019. [8]

The partial factor of the live load was increased from 1.4 to 1.5, but the live load partial factor only affects the design of the ultimate limit state, and does not affect the allowable value of the HD of the top of the lightning rod support during serviceability limit state design. When designing the ISTLR structure in a substation, the WIVC should be calculated by the method in GB50009-2012. Moreover, the author suggests taking 2.62 for the whole tube, which is calculated equivalent to the top HD.

There are still the following issues that require further study:

- The reliability of structure designed from AR method WIVC test by wind tunnel experiment.
- The effect of the connection between the rod segments on the HD of the lightning rod.
- The simplified values of the WIVC of ISTLRs of different heights.

Due to limited knowledge of authors, the design proposals presented in this paper still require more in-depth research and optimization by design peers and researchers.

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