Research on P-Δ Effect Increase Coefficient of Independent Steel Tube Lightning Rods in Substation

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Abstract. To optimize the design method of ISTLR (independent steel tube lightning rod) in substations, ANSYS was used to investigate increase coefficient (called P-Δ Effect increase coefficient) of top HD (horizontal displacement) of ISTLRs under wind load when considering P-Δ Effect compared with that not considering. The results show that the P-Δ Effect increase coefficient is about 1.05. Therefore, the HD of the top can be calculated without considering the P-Δ Effect when designing the structure of the ISTLRs. It can be multiplied by the P-Δ Effect increase coefficient 1.05 and controlled by not exceeding the limit value H/70 of the norm.

1. Introduction
Lightning rods prevent the power distribution devices in substations from being damaged by lightning. They can be classified into independent lightning rods and non-independent lightning rods according to their structure. Independent lightning rods can be classified into five types according to the different materials and structural forms: latticed steel structure, independent steel tube structure, guyed steel mast structure, STCC structure and RC ring rod structure. ISTLRs have become the preferred structural form of independent lightning rods in substation because of their small land occupation, clear structure concept, light weight, excellent flexibility and many other advantages. The material mechanics method cannot consider the P-Δ Effect because of the enormous amount of calculation. And the FE (finite element) software is too expensive for the majority of design institutes. Based on the problems in the design of 35m lightning rods in a 220kV substation, in this paper, the ANSYS FE analysis is used to calculate the top HD of lightning rods of different heights under different basic wind pressures, trying to find out the P-Δ Effect increase coefficient of the independent lightning rod design, to design the ISTLRs structure by the material mechanics method.

2. Literature Review of P-Δ Effect of Steel Structure
Li D et al.[1] proposed a simplified P-Δ method for petrochemical equipment supporting steel structure frame in 2007 by using ANSYS. Gong C[2] analysed the influence of P-Δ Effect on the structural design of steel portal frame on the concrete column in 2009. Zhou J et al[3] compared the second-order analysis method of the plane unbraced frame between Chinese and American norms in 2009. Liu X[4] used the FE method to obtain the influence law of the P-Δ Effect of the structure under the design load for the high-rise frame structure with inclined supports used in the T30 hotel building in 2014. The second-order effect coefficients are used to consider the influence of the P-Δ Effect on the steel frame structure in 5.1.6 and 5.4.2 of GB 50017-2017[5]. However, there is currently no P-Δ Effect analysis for ISTLR structure.
3. Original design

3.1. Project overview
The outdoor power distribution equipment bracket of a 220kV substation is seriously old. It is in the area with seismic fortification intensity of 6th degree. Some brackets have exposed reinforced bar, cracks, and even equipment misalignment and tilting. There were 15 lightning rods on the gantries, (Fig. 1) and two independent 30m high ones in the station. Among them, the lightning rods have serious corrosion problems, and some of them have been tilted. According to the lightning protection calculation, in the project, 14 lightning rods on the gantries and two independent ones were removed, 11 new 35m independent lightning rods were built, and one lightning rod on a gantry was retained.

3.2. Static analysis of 35m ISTLR structure
According to the Design Basic Wind Speed Distribution Map of Coastal of China Southern Power Grid (2017 Edition), the basic wind pressure is 0.77 kPa. Independent steel tube structure (Fig. 2(a)) was used for the lightning rods in the substation, using Q235B steel. The ANSYS model was established, and the bottom fixed constraint was applied. The wind load was calculated according to the GB50009-2012[6] and converted to act on the outer surface of the lightning rod steel tube for static analysis. According to the 6.5.3 of the DL/T 5457-2012[7], the HD of the top 5m, as the tip part, is excluded. The HD at the height of 30m is 416.7mm, which is less than the specification required 428.6mm. (i.e., H/70), while considering the P-Δ Effect, its HD is 434.2mm, which has slightly exceeded the specification limit. At this point, the maximum von-Mises equivalent stress of the tube body is only 105.57 MPa, which is only 2/3 of the specification limit (150.8 MPa).

3.3. 35m ISTLR structure mode analysis
The structure is subjected to mode analysis, and the first ten modes are only 8.06 mm (nine, ten orders). It can be seen that the HD value of the independent tube lightning rod under seismic load is much smaller than that under the wind load.

3.4. Design control condition
GB50135-2006[8] stipulates that the sectional seismic strength calculation of structural members can be omitted in the area with seismic fortification intensity of 6th degree. According to the static analysis and modal analysis, it can be seen that under the premise of ensuring local stability[9], the wind-induced HD is the control condition for the design of independent tube structure.

3.5. Defects of the original design
According to the description in section 3.2, the original design of the 35m ISTLR has the following two defects:
• GD-3 and GD-4 are used as the bracket part, and their diameter does not meet the “not less than 150mm” recommended by the specification.

• The original structural design has not considered the P-Δ Effect. Its top displacement has exceeded the specification limit of H/70, after considering the P-Δ Effect.

The reason for the first defect is that the designer does not fully understand that the "The diameter of bracket part is not less than 150 mm" recommended by the specification means that resonance is prevented by preventing the natural frequency of the tip and the bracket portion from approaching. The second defect was caused by the designer using the material mechanics method, not considering the P-Δ Effect to design its top HD. Only FE analysis can solve the P-Δ Effect. But it is not convenient to repeatedly change the shape of the lightning rod in the FE software to meet the norms. Therefore, the author tries to find out the P-Δ Effect increase coefficient through a lot of calculations, to achieve the purpose of the structural design of the ISTLR by material mechanics method avoiding P-Δ Effect calculation.

4. Research on P-Δ Effect increase coefficient

At present, in addition to the 750kV, 1000kV and other ultra-high voltage outdoor substations in which lightning rods are too high and have to choose the lattice structure, the general 500kV (inclusive) and below substations adopt ISTLRs. The usual ISTLRs have heights of 25m, 30m, 35m, 55m, etc. The author selected 25m, 35m, 45m, 55m, 60m ISTLRs at a basic wind pressure of 0.2~1.2. In the meantime, when the P-Δ Effect is considered and not, the top HD is calculated. (Fig. 3) The independent lightning rod of 35 m is a combination of GD-3 and GD-4 into a 152 outer diameter steel tube from the original design of Fig. 2(a) and further improved, as shown in Fig. 2(b). The calculated data example is shown in Table 1.

Fig. 3 draws the following conclusions:

• The P-Δ Effect increase coefficient of 25m~60m ISTLRs is between 1.04 and 1.05.

• With the increase of the basic wind pressure, the P-Δ Effect increase coefficient of the ISTLR structure has a slight decrease trend, but it is not obvious. Therefore, it can be considered that the basic wind pressure does not affect the P-Δ Effect increase coefficient of the ISTLR structure.

![Figure 2. Assembly drawing of the 35m ISTLR](image-url)
Table 1. P-Δ Effect increase coefficient of 35m independent lightning rods

| Basic wind pressure | No P-Δ Effect | P-Δ Effect | P-Δ Effect increase coefficient |
|---------------------|---------------|------------|--------------------------------|
| 1.200               | 593.920       | 617.690    | 1.040                          |
| 1.100               | 544.380       | 566.200    | 1.040                          |
| 1.000               | 500.980       | 521.130    | 1.040                          |
| 0.900               | 461.210       | 479.910    | 1.041                          |
| 0.800               | 410.380       | 427.000    | 1.040                          |
| 0.700               | 379.820       | 395.570    | 1.041                          |
| 0.600               | 314.910       | 327.680    | 1.041                          |
| 0.500               | 268.530       | 279.430    | 1.041                          |
| 0.400               | 225.050       | 234.180    | 1.041                          |
| 0.300               | 187.600       | 195.200    | 1.041                          |
| 0.200               | 139.820       | 145.660    | 1.042                          |

Fig3. P-Δ Effect increase coefficient of ISTLRs of different heights
5. Conclusions and recommendations
Based on the design defects of the 35m ISTLR in a 220kV substation, ANSYS FE software was used to calculate the structure of 25m, 35m, 45m, 55m, and 60m ISTLRs. It is concluded that the P-Δ Effect increase coefficient of 25m~60m ISTLRs can be taken as 1.05. This study facilitated the structural analysis of ISTLRs.

The P-Δ Effect increase coefficient proposed in this paper is based on the reasonable structural design. Therefore, it must be judged by experienced structural engineers. There are still the following issues in the text that require further study:

- The P-Δ Effect increase coefficient of ISTLRs higher than 60m.
- A more accurate study of P-Δ Effect increase coefficient of ISTLRs.

Due to limited knowledge of authors, the P-Δ Effect increase coefficient of ISTLRs proposed in this paper still requires more in-depth research and verification by the majority of design peers and researchers, in order to find an increase coefficient that is both accurate and safe enough.

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