Research on the Best Root Span of 500kV Substation Frame Based on Finite Element

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Abstract. A-shaped and steel tube structures have been widely applied when designing 500kV substation frame in China. While, compared with steel tube, angle steels have an advantage of easy-transporting, especially in oversea projects. However, researches on substation frame with angle steel were not enough. In order to find out the best root span of 500kV substation frame under similar engineering conditions, using the oversea project substation frame as an example, the substation frames with different root span have been detailed calculated, to find the best root span according to the cost of it. When the height of column is about 30m, the root suggestion value is 6.1m×3.1m. And then, the buckling analysis of the overall structure has been carried out by ANSYS, to find out that the weak part of the structure is in the middle of it. The structural adjustment is carried out for the weak part, including adjusting the web members and the chord members, to obtain a higher bearing capacity of the structure.

1. Introduction

Under the background of economic globalization and regional development, the implementation of the "The Belt and Road" strategy will effectively promote the construction of cross-border electricity and transmission channels, and actively carry out cooperation in upgrading regional power grid, has brought new rare opportunity for the development of energy and power industry [1]. The design of 500kV substation structure in domestic, mostly adopts heringbone column structure or steel pipe lattice structure, the angel steel lattice structure is lack of research [2-4]. In overseas projects, due to high costs, the angle steel has a great advantage for transportation. The angle of lattice substation frame is more suitable for the overseas market. Based on the background of this market, exploring the optimized root of steel lattice substation structure, saving substation structure steel consumption, it will have great economic significance.

2. Overview of the Project

The 500kV substation frame in Ethiopia was used as an example, the framework was 4 spans, 132.1m in length, 30.6m in height, 32m in span between beams, the height of ground wire column was 9.2m. Once in 50 years wind speed was 40m/s. The substation frame was shown in Fig. 1.

Reference [5] suggested that the general frame column root column was about 1/10~1/4 height of the frame, and the longitudinal root was generally bigger than the lateral root. The frames were calculated after root combination.
Summary information of frame with various roots by calculation, including material properties, the total amount of steel, displacement in the top of columns was shown in Table 1 [6-8]. In order to compare the amount of steel used in 21 different open frames, the data in the table was drawn, as shown in Fig. 2.

![Figure 1. The single line of substation frame.](image)

| R/(m×m) | T2/(t) | T1/(t) | s/(mm) |
|---------|--------|--------|--------|
| 3.4×3.1 | 53.09  | 76.01  | 197.00 |
| 3.8×3.1 | 49.24  | 72.16  | 195.25 |
| 3.8×3.4 | 49.53  | 72.45  | 195.32 |
| 4.4×3.1 | 44.45  | 67.38  | 197.86 |
| 4.4×3.4 | 44.63  | 67.55  | 197.98 |
| 4.4×3.8 | 44.75  | 67.62  | 198.43 |
| 5.1×3.1 | 40.96  | 63.88  | 197.64 |
| 5.1×3.4 | 41.16  | 64.08  | 196.41 |
| 5.1×3.8 | 41.78  | 64.65  | 195.59 |
| 5.1×4.4 | 43.37  | 66.25  | 195.71 |
| 6.1×3.1 | 38.94  | 61.82  | 198.25 |
| 6.1×3.4 | 39.19  | 62.06  | 196.96 |
| 6.1×3.8 | 39.92  | 62.79  | 195.80 |
| 6.1×4.4 | 40.53  | 63.41  | 194.84 |
| 6.1×5.1 | 41.53  | 64.40  | 195.29 |
| 7.7×3.1 | 38.98  | 61.85  | 194.24 |
| 7.7×3.4 | 39.93  | 62.80  | 197.66 |
| 7.7×3.8 | 40.24  | 63.11  | 197.41 |
| 7.7×4.4 | 40.62  | 63.50  | 195.74 |
| 7.7×5.1 | 41.74  | 64.62  | 194.79 |
| 7.7×6.1 | 43.47  | 66.34  | 195.13 |

R - root span; T2 - the amount of steel frame columns; T1 - the total steel quantity; s - the displacement of top column
As it could be seen from Fig. 2, the total amount of steel used in the framework showed a tendency to decrease first and then increase with the increase of root opening. For the same length to the root, the total amount of steel increased with the increase of root to short open; for the same short to the root, the total amount of steel to root for 3.4m~6.1m variation decreased greatly, the total amount of steel after 6.1m showed a slightly rising trend, but the change of relative small. As it could be seen from table 1, the root of 6.1m×3.1m substation frame used the minimum amount of steel.

3. Buckling Analysis of Substation

The finite element software ANSYS is used to analyze the buckling of the structure in order to have the further study about the mechanical properties of the structure [9-10]. On this basis, according to the results of the analysis, for the deficiency of the original structure, the frame was further adjusted, to achieve a more reasonable state.

Use the root of 6.1m×3.1m substation frame as an example. In ANSYS, first, defined material properties, defined the two kinds of material attributes including Q235 and Q345; second, defined the material section, created the key points and then connected point by line, assign section; third, mesh poles, applied wire load and wind load, and then solve, buckling analysis; the result could be seen finally. The model built in ANSYS was shown in Fig. 3~4.

The structure was solved, then buckling analysis was carried out, and the result was shown in table 2.
Table 2 result of buckling analysis

| Set | Buckling Factors |
|-----|------------------|
| 1   | 4.577            |
| 2   | 4.599            |
| 3   | 4.639            |
| 4   | 4.715            |
| 5   | 4.743            |

First and second buckling modes are shown in Fig. 5~6.

Buckling was generally based on the first mode, the more the set went, the smaller probability of occurrence, so the middle frame had the highest risk. According to Table 2, the buckling factor of the first buckling mode was 4.577, which means that when the load was increased to the original 4.577 times, the buckling of the structure occurred in the middle of the frame.

As Fig. 5~Fig. 6 could be seen, although the structure without buckling the overall shape, showed no large waves shape, it could be seen that the weak points of structure mainly occurred in the middle of the frame, and the other local modal structure was good, no obvious yield, indicating that the middle of the structure was relatively weak, the section of frame was too small, should be increased so that the section stress of the whole structure was more balanced.

![Figure 5. First buckling mode](image1)

![Figure 6. Second buckling modes](image2)

4. Adjust the Structure

In the original structure, the middle part of the frame columns were L160×14mm, and the size of the web members were L63×5mm, in the process of structural adjustment, the section of the web members were adjusted firstly, and then the chord members were adjusted.

4.1. Adjust the web members.

Because the size of the bottom of the web members were L75×6 mm, the middle of the belly bar should be not be bigger than the bottom of the web members, so middle of the web members were took in order L63×5, L70×5, L70×6 and L75×6, analyzed the buckling of the structure by ANSYS, the buckling factors were shown in table 3.
Table 3 results of the structural buckling analysis under different sections of web members

| Set | L63×5 (mm) | L70×5 (mm) | L70×6 (mm) | L75×6 (mm) |
|-----|------------|------------|------------|------------|
| 1   | 4.577      | 4.582      | 4.584      | 4.588      |
| 2   | 4.599      | 4.603      | 4.604      | 4.608      |
| 3   | 4.639      | 4.644      | 4.646      | 4.650      |
| 4   | 4.715      | 4.720      | 4.722      | 4.725      |
| 5   | 4.743      | 4.746      | 4.747      | 4.750      |
| 6   | 4.781      | 4.786      | 4.788      | 4.792      |
| 7   | 4.832      | 4.834      | 4.835      | 4.837      |
| 8   | 4.856      | 4.858      | 4.857      | 4.858      |
| 9   | 4.876      | 4.878      | 4.879      | 4.880      |
| 10  | 4.897      | 4.898      | 4.898      | 4.899      |

Data was processed in Table 3, and the first buckling factors were extracted in substation structures with different web members, as shown in Fig. 7~ Fig. 8.

As it could be seen from table 3, with the increase of section, the first buckling factor of the structure increased slightly, which indicated that the bearing capacity of the structure increased just a little. This characteristic also had the same performance in the 3D3S calculation, that is, when the section of the web members changes, the displacement of the structure varied slightly.

From Fig. 7~ Fig. 8, increasing section of the middle web members, buckling factor of the structure increased very slightly, the bearing capacity of the structure had not been significantly improved.

4.2. Adjust the chord members.

Because the bottom chord section of the frame was L180×16. The middle chord size should not be greater than the bottom chord, so middle chord members were took in order L160×14, L160×14.5, L160×15, L160×15.5, L160×16 and L180×16, analyzed the buckling of the structure by ANSYS. The buckling factors were shown in table 4.
Table 4: Results of the structural buckling analysis under different sections of chord members

| Set   | L160×14 (mm) | L160×14.5 (mm) | L160×15 (mm) | L160×15.5 (mm) | L160×16 (mm) | L180×16 (mm) |
|-------|--------------|----------------|--------------|----------------|--------------|--------------|
| 1     | 4.577        | 4.962          | 4.956        | 4.949          | 4.943        | 4.919        |
| 2     | 4.599        | 4.962          | 4.959        | 4.956          | 4.954        | 4.944        |
| 3     | 4.639        | 4.988          | 5.077        | 5.070          | 5.063        | 5.038        |
| 4     | 4.715        | 5.065          | 5.088        | 5.091          | 5.093        | 5.103        |
| 5     | 4.743        | 5.084          | 5.308        | 5.305          | 5.302        | 5.276        |
| 6     | 4.781        | 5.086          | 5.313        | 5.310          | 5.303        | 5.292        |
| 7     | 4.832        | 5.100          | 5.317        | 5.332          | 5.339        | 5.357        |
| 8     | 4.856        | 5.133          | 5.402        | 5.405          | 5.407        | 5.383        |
| 9     | 4.876        | 5.222          | 5.421        | 5.416          | 5.409        | 5.385        |
| 10    | 4.897        | 5.255          | 5.423        | 5.419          | 5.412        | 5.405        |

Data was processed in Table 3, and the first buckling factors were extracted in substation structures with different chord members, as shown in Fig. 9~Fig. 10.

As shown in Fig. 10, it could be seen that when the section of the chord increased from L160×14 to L160×14.5, the buckling factor increased significantly, but when the section continued increased from L160×14.5 to L180×16, the buckling factors showed a slight downward trend. Take Table 4 and Fig. 9~Fig. 10 into consideration, when the middle chord section from L160×14 increased to L160×14.5, the bearing capacity of the structure was improved obviously, and when the middle chord section continued to increase from L160×14.5 to L180×16, the bearing capacity of this structure decreased gradually.

Based on the data above, the whole bearing capacity of the structure could be effectively improved by using L160×14.5 in the middle part of the frame. Considering the angle with the L160×14.5 for abnormal section, specialized production may make the total cost of the substation frame increased. The final measure of structural adjustment was that the section of the middle chord members was not changed, which is L160×14.

Figure 9: Buckling factors of different chord members substations
Figure 10: First buckling factors of substation frame with different chord members

5. Conclusion
Take Ethiopia 500kV substation frame as the research object, the total amount of steel was detailed calculated in different root substation frame, and the eigenvalue buckling of the structure was analyzed by ANSYS. Adjust the web members and the chord members to obtain a higher structural bearing capacity. Based on the work, the following conclusions were made:
1. when the height of the frame column was about 30m, the root suggestion value was 6.1m×3.1m, as the longer root was 1/5 column height, and the short root was 1/10 column height, the substation frame had the minimum amount of steel and better mechanical properties.

2. The bearing capacity of the substation frame was not improved obviously when the web members reinforced. When the chord members section increased, the bearing capacity of the structures showed first increased and then decreased. When the middle chord section was L160×14.5, the bearing capacity of the structure reached the maximum value. Taking into account the production requirements, the adjustment could maintain the original section.

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