Research on General Design and Application of Double-circuit T-Connection Tower In 110kV

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Abstract: Based on the investigation results and the current general design of state grid, this paper reasonably planned the design conditions of the tower. Taking the general design module as the basic tower type, a kind of double loop T-connection tower in 110kV with high generality was proposed, then carry out tower head planning and structural internal force analysis. Finally, the electric field finite element simulation is carried out to demonstrate the safety and reliability of the T-connection tower of cross arm arrangement. The tower can cover the T-connection conditions of 110kV double-circuit line in most areas of the country, and draw the tower diagram, which can be included in the general design of state grid transmission tower for reference of line designers. The cross arm of tower head is arranged in a crisscross way, which greatly simplifies the the double-loop T-connection scheme. One tower can replace the traditional multi-tower to complete the T-connection of the line, which reduces the cost and occupation of land, also achieves good economic and environmental benefits.

1.Introduction
At present, the T-connection of 110kV transmission line is to use strain tower as the T-connection point, use 2-3 base tower to drill through the original line and merge with the T-connection line on the other side to form a double circuit. This traditional T-connection mode leads to waste of land resources and high project cost[1][2].

In order to solve the above problems, taking the general design module of State Grid Corporation of China as the basic tower type, a 110 kV double-circuit T-connected tower with high versatility is proposed. The cross arm of the tower head is arranged in a crisscross manner to realize the T-connection of the main line with one tower. This kind of T connection tower effectively reduces the project investment, reduces the project area, shortens the construction period, and can bring huge social and economic benefits.

2.Tower design condition planning
According to a number of engineering design conditions involved in the investigation, the model of grounding wire of 110kV transmission line is as shown in Table 1-1. The model of conductor is mainly 1×JL/G1A-240/30 and 1×JL/G1A-300/40. The model of ground wire is mainly GJ-80, as shown in table 1 below.

| Wire type   | Proportion | Grounding wire type | Proportion |
|-------------|------------|---------------------|------------|
| 1×JL/G1A-240/30 | 43.64%     | 1×7-8.7-1270-B      | 2.22%      |
According to the survey and general design, 1×JL/G1A-300/40 is selected for the conductor and JLB20A-100 is selected for the ground wire (the performance of JLB20A-100 can cover GJ-80).

The icing thickness and wind speed of 110 kV line design conditions are shown in table 2 and table 3.

### Table 2. Icing thickness statistics

| Ice thickness of 110kV transmission line | Proportion |
|----------------------------------------|------------|
| 5mm                                    | 22%        |
| 10mm                                   | 65.5%      |
| 15mm                                   | 12.5%      |

### Table 3. Wind speed statistics

| Wind speed value of 110kV transmission line | Proportion |
|--------------------------------------------|------------|
| 23.5m/s                                    | 14.55%     |
| 25m/s                                      | 12.7%      |
| 27m/s                                      | 54.6%      |
| 28.2m/s                                    | 3.6%       |
| 29m/s                                      | 14.55%     |

According to the investigation, the icing thickness of 110kV line is 10 mm, and the wind speed is 29 m/s, which can cover the T-connection conditions of the wire in most parts of the country.

According to table 1-3 and combined with the state grid general design, the design conditions planning of double-circuit T-connection tower in 110kV is as shown in table 4.

### Table 4. Design conditions planning of Double-circuit T-Connection tower in 110kV

| Module number | nominal height | Wire type | Grounding wire type | Design wind speed | conductor icing | Land form |
|---------------|----------------|-----------|---------------------|-------------------|-----------------|-----------|
| 1ST1          | 15m、18m、21m、24m | 1×JL/G1A-300/40 | JLB20A-100          | 29 m/s           | 10mm           | plain     |

Main line span: 350/500, Considered strain as 0° tension;
Side span of T-connection: 300/450, Considered strain as 20° tension;
Safety factor of conductor: 2.5; Safety factor of ground wire: 4.0

### 3. Study on the type of T connection tower

#### 3.1. Tower head planning

Taking the general design[3] module of State Grid Corporation as the basic tower type, the cross arm of the tower head of 110kV double circuit T-connection tower is arranged in a crisscross way. The tower head planning is shown in figure 1.
3.2. Jumper wire analysis

The Sketch of jumper wire of 110kV double circuit T connection tower is shown in figure 2.

3.2.1. Calculation method of sag of direct lead jumper

Calculation formula of inclination angle $\theta$ of strain insulator string:\[2]\]

$$\theta = \tan^{-1} \left[ \frac{G_v + g_1 l}{2T} + \frac{h}{T} \right]$$

(1)

In the formula: $G_v$—Tension insulator string gravity, N; $g_1$—Gravity per unit length of conductor wire, N/m; $l$, $h$—Calculate the side span and height difference, m; $T$—Horizontal tension of conductor under calculation conditions, N

The wind deflection angle $\varphi$ of strain insulator string is calculated as follows:

$$\varphi = \tan^{-1} \left( \frac{G_H + g_1 l}{2T} \right)$$

$G_H = 9.81A \frac{V^2}{16}$

(2)

In the formula: $G_H$—Wind pressure on tension insulator string, N; $A_1$—Wind area of insulator
string, m2; v—wind speed, m/s; ge—Unit wind load under conductor calculation condition wire, N/m;

Calculation formula of wind deflection angle \( \eta \) of jumper string and heavy hammer jumper:

\[
\eta = \tan^{-1} \left( \frac{P}{G} \right)
\]  

(3)

In the formula: \( P, G \)—Wind load and self weight load of conductor, N

The solution method of minimum allowable sag \( f_{\text{min}} \)[4](graphic method): The minimum allowable sag refers to the minimum sag between the upper cross arm components and the tension string grounding components under various clearance inspection conditions after the jumper wire is over tensioned and wind deflection is generated. The minimum sag is the largest of the minimum sag under various inspection conditions, which is generally controlled.

Maximum allowable sag \( f_{\text{max}} \) solution method[5]: when calculating the maximum allowable sag, it is necessary to calculate the average horizontal offset \( e_{cp} \) and average vertical displacement \( d_{cp} \) of suspension points on both sides of jumper wire under lightning overvoltage, switching overvoltage and power frequency voltage. The maximum allowable sag \( f_{cp} \) of jumper wire is calculated, and the minimum sag is taken as the maximum allowable sag \( f_{\text{max}} \) of jumper wire.

\[
d_{cp} = \frac{1}{2} (\lambda_1 \sin \theta_1 + \lambda_2 \sin \theta_2)
\]  

(4)

\[
e_{cp} = \frac{1}{2} (\lambda_1 \cos \theta_1 \sin (\psi \pm \phi_1) + \lambda_2 \cos \theta_2 \sin (\psi \pm \phi_2))
\]  

(5)

In the formula: \( \psi \)—Half of the line rotation angle; \( H \)—Cross arm length; \( \beta \)—The angle between the main material of the tower body and the horizontal line in the front view shall be added with suspension insulator string.

Determine construction sag \( f_{po} \) of the jumper wire:

When \( f_{\text{max}} < f_{\text{min}} + 0.3 \) (lower voltage can be 0.2), overhanging insulator string shall be added instead of construction sag.

When \( (f_{\text{min}} + 1) \geq f_{\text{max}} \geq (f_{\text{min}} + 0.3), f_{po} = \frac{f_{\text{max}} + f_{\text{min}}}{2} \).

When \( f_{\text{max}} > (f_{\text{min}} + 1), f_{po} = f_{\text{min}} + 0.5 \) (lower voltage can be reduced to 0.3).

3.2.2 Calculation results of direct lead jump wire

According to the tower head planning and the above formula, the wind deviation angle and construction sag of jumper about each crossbar is shown in the table below:

| Project                  | Construction sag/m | Wind deflection angle of power frequency high wind jump wire | Wind deflection angle of Operating voltage jump wire | Wind deflection angle of lightning overvoltage jump wire | Wind deflection angle of live working jump wire |
|--------------------------|-------------------|------------------------------------------------------------|---------------------------------------------------|--------------------------------------------------------|-----------------------------------------------|
| Main superior phase      | 1.795             | 66.23°                                                     | 21.42°                                            | 9.89°                                                  | 9.89°                                         |
| Main middle phase        | 1.848             | 64.73°                                                     | 21.42°                                            | 9.89°                                                  | 9.89°                                         |
| Main lower phases        | 1.899             | 62.73°                                                     | 21.42°                                            | 9.89°                                                  | 9.89°                                         |
| T-Connect superior phase | 1.821             | 65.53°                                                     | 21.42°                                            | 9.89°                                                  | 9.89°                                         |
| T-Connect middle phase   | 1.874             | 63.82°                                                     | 21.42°                                            | 9.89°                                                  | 9.89°                                         |
| T-Connect lower phase    | 1.920             | 61.43°                                                     | 21.42°                                            | 9.89°                                                  | 9.89°                                         |

3.3 Drawing of tower head clearance circle

In the layout of the tower, the structural margin corresponds to the selection of angle steel alignment, and the structural margin of 110kV tower is taken as 150 mm[6]. Draw the tower head clearance circle[7] of T-connected tower through the wind deflection angle and construction sag under the maximum wind speed, operating over-voltage, lightning over-voltage and live working conditions obtained.
above, as shown in the figure 3 and figure 4 below.

Figure 3. Circular diagram of interphase gap in main line about upper, middle and lower Phases

Figure 4. Circular diagram of interphase gap in T-connection about upper, middle and lower Phases

3.4. Dimension design of ground wire support and cross arm

3.4.1. Height selection of ground wire support

For double circuit, the protection angle of opposite side conductor of ground wire on 110kV line tower should not be greater than 10° and the protection angle of ground wire of T-type tower of 110kV double circuit is less than 10°, which meets the requirements.

The distance between the conductor and the ground wire on the tower shall be calculated according to the following formula:

$$S \geq 0.012L + 1$$  \hspace{1cm} (6)

In the formula: $S$—Distance between conductor and ground wire(m); $L$—Span(m).

According to the tower head plan, the distance between the conductor and the ground wire is $S = 7.74m > 0.012 \times 300 + 1 = 4.6m$, meeting the requirements.

3.4.2. Cross arm size verification

1）The equivalent distance between horizontal lines of triangular arrangement of traverse \(^8\) is calculated according to the following formula:

$$D_x = \sqrt{D_p^2 + (4/3D_z)^2}$$  \hspace{1cm} (7)

In the formula: $D_x$—Equivalent distance between horizontal lines of triangular arrangement of conductors(m); $D_p$—Horizontal projection distance between conductors(m); $D_z$—Vertical projection distance between wires(m);

2）For T-connected tower, the distance between horizontal lines is calculated according to the following formula:

$$D = \frac{U}{110} + 0.65\sqrt{f_c}$$  \hspace{1cm} (8)

According to the specification requirements, $D_x > D$.

According to the tower head plan, the 110kV double circuit T connection tower can meet the
requirements of \( D_x > D \).

4. Structural optimization design of T-connected tower

4.1. Design conditions of T-connected tower

The design conditions of T-connected tower in 110kV are shown in table 6.

| Conditions     | Temperatures \(^{\circ}\)C | Designed wind speed /m | Ice thickness /mm |
|----------------|---------------------------|-------------------------|------------------|
| Strong wind    | -5                        | 29                      | 0                |
| Microtherm     | -20                       | 0                       | 0                |
| Icing          | -5                        | 10                      | 10               |
| Installation   | -10                       | 10                      | 0                |
| Annual average | 15                        | 0                       | 0                |
| Temperature    |                           |                         |                  |
| Disconnection  | -5                        | 0                       | 10               |
| Uneven icing   | -5                        | 10                      | 10               |
| Long-term      | 15                        | 5                       | 0                |
| Megatemperature| 40                        | 0                       | 0                |

4.2. The most unfavorable load combination of double-circuit T-connected tower

The load combination of normal operation, disconnection, uneven icing and installation of T-connection tower shall be calculated \[9\]-\[10\]. For T-connection tower, the most unfavorable load is combined with the overhead view, as shown in table 7.

| Conditions          | Cause                                          |
|---------------------|------------------------------------------------|
| Normal operating conditions | Under strong wind condition, the wind direction is 90° to the main line direction Maximum wind load on main line |
|                      | Under strong wind condition, the wind direction is 0° to the main line direction Large unbalanced tension is received on the T-connection side |
|                      | Under strong wind condition, the wind direction is 90° to the direction of T-connection side Maximum wind load on main line |
|                      | Under strong wind condition, the wind direction is 0° to the direction of T-connection side Large unbalanced tension is received on the T-connection side |
| Uneven icing        | uneven icing Under the condition of uneven icing, the unbalanced tension is large |
| Disconnection       | The main line breaks A side: the main line wire opposite to the T-connection side breaks two phases of the conducting wire The tower is subjected to large bending moment and torque |
| Installation        | Under the installation condition, the main line is tight to the lower phase of A side conductor, and the conductor has not been hung in adjacent span The main line is subject to the combined force under various installation conditions, and the unbalanced tension is large |

4.3. Slope optimization and root span determination

The slope of 110kV double-circuit tower (below the head of tower) is generally 9% ~ 15%. When the root opening increases, the stress of the main members decreases, and the member specification decreases. But when the root span is too large, the geometric dimensions of the diagonal and auxiliary members increase, and the member structure layout becomes complex, so that the tower weight increases correspondingly \[11\]-\[12\]. The optimal tower slope of 110kV double-circuit T-connection tower is determined by Dao Heng's function about optimization slope. As is shown in table 8 for the tower's calculated weight corresponding to the tower slope.
### Table 8. Calculated tower weight

| Tower model          | Slope  | Calculated tower weight | Slope  | Calculated tower weight |
|----------------------|--------|--------------------------|--------|--------------------------|
| 110kV double-circuit T-connection tower | 9.40%  | 25.495 t                 | 11.80% | 24.867 t                 |
|                      | 9.80%  | 25.389 t                 | 12.20% | 24.346 t                 |
|                      | 10.20% | 25.319 t                 | 12.60% | 24.412 t                 |
|                      | 10.60% | 25.312 t                 | 13.00% | 24.447 t                 |
|                      | 11.00% | 25.349 t                 | 13.40% | 24.527 t                 |
|                      | 11.40% | 24.976 t                 | 13.80% | 24.598 t                 |

It can be concluded that the optimal slope of 110kV double circuit T-connection tower is 12.2%. According to the variable groove width through the string center calculation, the tower root span size corresponding to each nominal height can be obtained, as shown in the table 9.

### Table 9. Root span of Double-circuit T-Connection tower in 110kV

| Nominal height | Optimum tower slope | Tower's root span | Foundation's root span |
|----------------|---------------------|-------------------|------------------------|
| 15.0m          | 12.20%              | 5443 mm           | 5493 mm                |
| 18.0m          |                     | 6175 mm           | 6225 mm                |
| 21.0m          |                     | 6908 mm           | 6958 mm                |
| 24.0m          |                     | 7640 mm           | 7690 mm                |

### 4.4. Electric field analysis

#### 4.4.1. Electric field and potential distribution near T-connected tower

The distribution of electric potential and electric field is calculated by the method of finite element simulation when the initial phase of conductor voltage is zero\(^{[13]}\), as shown in the figure 5-8.

![Figure 5. Potential line distribution along the direction of main circuit](image)

![Figure 6. Electric field line distribution along the direction of main circuit](image)
As can be seen from the above figure, the electric potential line and electric field line in the direction of main circuit and T-connection circuit are roughly distributed symmetrically along the center of the tower, and the maximum electric field values of the main circuit and T-connection circuit appear on outside the conductor, reaching 958 kV/m and 502 kV/m respectively, without reaching the air breakdown strength (3000 kV/m).

4.4.2 Electric field intensity at 1.5m above the ground
In the code for design of electric power industry in China, it is required to control the undistorted electric field no more than 4kV/m at 1.5m above the ground for the crossed non long-term residential buildings and adjacent houses. Select the section of 1.5m above the ground to calculate the electric field strength. The calculation results are shown in Figure 9. The maximum value is 1.32kV/m, which is less than the standard of 4KV/m, meeting the requirements.

4.5 Full stress calculation
Using Dao Heng calculation software to calculate the full stress of the 110kV double-circuit T-connection tower after the load is applied. By controlling the index of slenderness ratio and stress ratio, the member specifications and arrangement forms of the 110kV double-circuit T-connection tower are adjusted repeatedly, and finally the T-connection tower structure with resource conservation and reasonable stress distribution is completed.

The stress ratio and slenderness ratio of the whole pole of 110kV double circuit T-connection tower meet the requirements, as is shown in figure 10 and figure 11. Most of the stress ratio colors of tower main members are in the yellow and green range (stress ratio: 70% - 95%), and the stress ratio is controlled within 0.95. The stress ratio of diagonal and auxiliary members is controlled within 0.98, and most of them are in the green and blue range (70% - 85%). Therefore, it can be concluded that the model is reasonable and the stress of the members can be effectively allocated.
5. Fabrication of tower processing drawing
According to the general design mode, the design conditions, supplementary instructions, root-opening size and foundation force of 110kV double circuit T-connection tower are indicated.
After the command diagram output by the T-connection tower model, the processing diagram of 110kV double circuit T-connection tower is drawn according to the command diagram, which can be used as a direct reference by the design unit according to the use conditions.

6. Engineering application and economic comparative analysis
The pilot application is based on the 110kV transmission line project of An Tuo-Jing Ye No.2 substation T-connected to Ling Shou No.2 substation in Shijiazhuang. The following three T-connected plans are proposed for comparative analysis of the project, as shown in table 10.

Table 10. Three schemes of T-connection

| Plans | Scheme Description | Tower Model | Cardinal number | Full Height / m |
|-------|--------------------|-------------|-----------------|-----------------|
| Plan A (new technology of T-connection tower) | one 110kV double circuit T-connection tower + one 110kV double circuit terminal tower | IST1-18 | 1 | 37.1 |
| Plan B | four 110kV single circuit tension towers + two 110kV double circuit terminal towers | 1A3-J2-15 | 2 | 21.5 |
| | | 1A3-J4-15 | 2 | 21.5 |
| | | 1D5-SDJ-18 | 2 | 29.9 |
| Plan C | two 110kV cable terminal poles + cable duct | SDJG-18 | 2 | 30.3 |

The total investment and floor area of the three plans are compared, as shown in table 11.

Table 11. Cost comparison of three schemes

| Plans | Total investment (million) | Floor Area (mu) |
|-------|---------------------------|-----------------|
| Plan A | 1.12 | 0.30 |
| Plan B | 1.83 | 0.90 |
| Plan C | 2.31 | 0.05 |

The total investment of plan A is 38.8% and 59.4% lower than that of plan B and plan C respectively, and the floor area is 0.6 Mu lower than that of plan C, saving 66.7% of the floor area. As plan C adopts cable duct arrangement, the total investment is high, and it is not easy to form a general
design for popularization and application. Therefore, the project adopts one 110kV double circuit T-connection tower instead of the traditional T-connection scheme, which effectively reduces the project investment and achieves good economic benefits.

7. Conclusion
Through reasonable planning of tower design conditions, the crisscross 110kV double-circuit T-connection tower can meet the T-connection conditions of most of the plain areas in the country, and realize the goal that one tower completes T-connection of main line. The T-connection tower can be used as a direct reference for the design unit according to the use conditions.

The T-connection tower has been successfully applied to transmission project of An Tuo-Jing Ye No.2 substation T-connected to Ling Shou No.2 substation, which has effectively reduced the land occupation, reduced the cost and brought good economic and environmental benefits.

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