Eiffel Effect on Towers of UHV AC Transmission Lines

Chunlei Zhang [1], Junke Han [2]

[1] North China power engineering co., LTD. Of China power engineering consulting group, Beijing 100120, China
[2] China electric power research institute, Beijing 100055, China

Abstract. The principle of Eiffel Effect on transmission towers was analyzed, and the necessity of considering Eiffel Effect on transmission towers, especially multi-loop transmission towers, was proposed. A comparative analysis on calculation methods for Eiffel Effect on tower mast structures both at home and abroad was conducted and the applicability of various calculation methods to transmission towers and their advantages/disadvantages are proposed. On this basis, the analysis method for Eiffel Effect on transmission towers is proposed. The Eiffel Effect was calculated by taking four tower types of EHV/UHV AC multi-circuit transmission lines on the same tower as examples, during which the stress state of member bar of each tower type after considering the Eiffel Effect, the influence of the intersection angle between the main members of the tower on the Eiffel Effect, and the minimum bearing capacity requirement of diagonal members etc. were analyzed. The analysis shows that: It is simple, reasonable and convenient to consider the Eiffel Effect on the tower with the rigidity-reduction method for engineering application; both the diagonal member and the diaphragm member of the tower are influenced by Eiffel Effect, where its influence on the latter is higher; it may be unsafe if designing the minimum bearing capacity requirement for the diagonal member with the internal force not less than 5% of the main members to satisfy the Eiffel Effect on the tower for the UHV transmission towers, and especially for the transmission towers with EHV/UHV AC multi-circuit transmission lines on the same tower.

Keywords: Transmission towers; Eiffel Effect; Transmission towers with EHV/UHV multi-circuit transmission lines on the same tower; Rigidity-reduction method; Minimum bearing capacity of diagonal member.

1. Introduction

Transmission towers are structures with large heights and small cross-sections, where the wind loads are the main controlling loads. A large number of wind measurements show that the time travel curve of wind contains both average wind and fluctuating wind components. The fluctuating wind loads are stochastic in nature, with wind speeds varying not only with height, but also with time. Due to the limited scale of the wind and fluctuating changes, the maximum wind speed is often not reached at the same time at different heights in the same location. Since the influence of this characteristic of the wind on the stressing of the member bar of a single gradient tower is very small, it may not be considered in the design. For the UHV transmission towers, and especially for the transmission towers with multi-circuit transmission lines on the same tower, the tower consists of two or three gradient sections, the contour of the tower is curved, and the internal force of member bars (especially the diagonal member of tower body) is very sensitive to the wind load. Given the similarity in shape between the curved tower and the Eiffel Tower, such effect is known as the Eiffel Effect on the tower.

With the continuous improvement of urban modernization level in China, the land resource is becoming more and more precious, and has received increasingly higher attention in development and utilization as a non-renewable resource. The erection technology of multi-circuit transmission lines on the same tower containing UHV lines will be the preferred solution to the access problem in the locally difficult areas of the currently planned UHV power grid project, which can effectively save line corridors and engineering investment and increase its transmission capacity [1]-[3]. For the multi-circuit transmission lines on the same tower containing UHV lines, the towers with average height of over 100m are more sensitive to the influence of Eiffel Effect. In the past, the studies on the loads of transmission towers and high-rising structures mainly focused on icing loads [4]-[5] and wind loads, while the studies on the wind loads focused on the wind-induced vibration coefficient and wind-induced vibration control [6], and there were few studies on Eiffel Effect [7], so it is necessary to conduct in-depth study on them to ensure the safe and stable operation of UHV transmission lines, and also to provide reference and basis for the design of UHV transmission lines.

Regarding the Eiffel Effect on steel towers, shear-ratio method and rigidity-reduction method are generally used at home and abroad to consider the influence on the mechanical properties of steel towers. In the Code for Design of High-rising Structures [8] of China and Lattice Towers and Masts - Part 1: Code of Practice for Loading [9] of UK, Eiffel Effect was calculated mainly with shear-ratio method. In the Code for Design of High-rising Structures [8] which was implemented since 2007, corresponding calculation method was proposed for the Eiffel Effect on steel towers, stipulating that the internal force of diagonal member should be adjusted when the ratio of shear on the diagonal members to the shear on the pillars of the same level is less than 0.4. In the Lattice Towers and Masts - Part 1: Code of Practice for Loading [9], the influence of Eiffel Effect was considered on the basis of different gust response coefficients for main members and diagonal members of the tower, where the gust response coefficients are relevant to the ratio of the shear on the diagonal members to the total horizontal load of the structure above this section. In the Eurocode 3: Design of Steel structures - Part 3-1: Towers, Masts and Chimneys - Towers and Masts [10] and Structural Standard for Antenna Supporting Structures and Antennas [11], Eiffel Effect was calculated with rigidity-reduction method. Both codes put forward the concept of patching load and list the calculation conditions of patching load considering Eiffel Effect.

2. Analysis Method for Eiffel Effect

The overall influence of Eiffel Effect on the tower is relatively obvious at the diagonal members, and the reason for this phenomenon is that the main members of the tower has a variable gradient so that the outer contour of the tower is curved, the intersection between the main members in the lower section is located at a middle position below the tower top, and two bending moments on the opposite directions are generated at the intersection between the main members in the lower section; when the difference between the fluctuating wind speeds above and below the intersection changes, the value and direction of the bending moments at the intersection will change accordingly, which will produce internal forces in the diagonal member under serious circumstances, leading to significant changes in tension and pressure. Therefore, it is necessary to determine the most unfavourable combination of internal forces of diagonal member, obtain the maximum internal force of diagonal member that can be generated and ensure the design safety of tower in light of this characteristic of the curved tower.

Since the curved tower and especially the towers of UHV transmission lines are relatively high, the influence of Eiffel Effect should be considered. In the Code for Design of High-rising Structures [8] and Lattice Towers and Masts - Part 1: Code of Practice for Loading [9], the design internal force of diagonal member should be obtained through conversion, and the calculation method is too cumbersome; since the UHV tower consists of a large number of sections, the work load would be very high and the calculation efficiency would be low if the diagonal members in each section are calculated with this method. Besides, the Code for Design of High-rising Structures was proposed for the high-rising structures with evenly varying mass with the height such as TV towers and communication towers, while the mass of transmission towers varies unevenly with the height due to the pole arm of the conductor/grounding wire; thus, the applicability of the calculation method for the high-rising structures to the transmission towers needs to be further investigated. Eurocode 3: Design of Steel structures - Part 3-1: Towers, Masts and Chimneys - Towers and Masts [10] and Structural Standard for Antenna Supporting Structures and Antennas [11] provide a relatively simple calculation method which is close to the principle of Eiffel Effect; the design control internal force of diagonal member can be obtained directly via the finite element calculation procedure of the tower.

According to the characteristics of fluctuating wind, the wind speed at the peak is about 1.35 times of the average wind speed, and the wind speed at the valley is about 0.75 times of the average wind speed, so the ratio of valley wind speed to peak wind speed is about 0.555, and thus the ratio of valley wind pressure to peak wind pressure is about 0.3. In this paper, the rigidity-reduction method is used to analyze the Eiffel Effect on the towers of UHV transmission lines, and the wind pressure reduction factor is taken as 0.3. Firstly, determine the position of the intersection between the main members in each section with varying gradient of the UHV tower; secondly, divide the tower into upper and lower sections with the intersection between main members as the boundary; thirdly, apply the design wind load and reduced wind load respectively on each section so as to establish several different wind load conditions; finally, obtain the maximum internal force of the diagonal member under the influence of Eiffel Effect via finite element analysis.

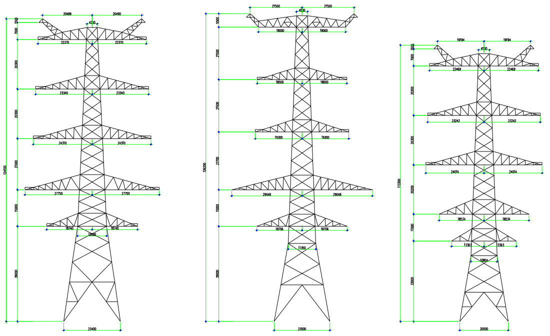
3. Parameters of UHV Lines

The EHV/UHV AC/DC multi-circuit transmission lines on the same tower are planned for the EHV grid project to solve the access problem in light of the characteristics of local area. The EHV/UHV AC/DC multi-circuit transmission lines on the same tower mainly include the multi-circuit transmission lines on the same tower composed of AC double-circuit 1,000kV line and AC double-circuit 500kV or 220kV line, as well as the multi-circuit transmission lines on the same tower composed of the DC single-circuit ±800kV and AC double-circuit 500kV or 220kV lines. The design meteorological conditions for the lines are given in Table 1, where the maximum wind speed of 32m/s refers to the reference wind speed at the height of 10m.

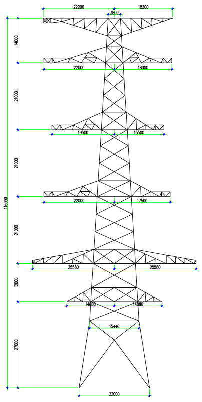
Table 1 Design Meteorological Conditions

Parameters	Air Temperature T (℃)	Wind speed, V(m/s)	Ice Thickness, C(mm)
Design icing	-5	10	Conductor 10, grounding wire 15
Verified icing	-5	10	Conductor 20, grounding wire 25
Maximum wind speed	-5	32	0
Maximum air temperature	40	0	0
Minimum air temperature	-15	0	0
Average air temperature	15	0	0
Mounting condition	0	10	0
Lightning overvoltage	15	15	0
Switching overvoltage	15	20	0
Hot-line work	15	10	0

The Eiffel Effect was analysed for the four tower types of the EHV/UHV AC/DC multi-circuit transmission line on the same tower, where SSZT2V is tangent tower of four-circuit transmission lines on the same tower composed of AC double-circuit 1,000kV lines and AC double-circuit 500kV lines (with V-type insulator chain), SSZT2I is tangent tower of four-circuit transmission lines on the same tower composed of AC double-circuit 1,000kV lines and AC double-circuit 500kV lines (with I-type insulator chain), SSJT3 is strain tower of four-circuit transmission lines on the same tower composed of AC double-circuit 1,000kV lines and AC double-circuit 500kV lines, and SSZT22V is tangent tower of four-circuit transmission lines on the same tower composed of AC double-circuit 1,000kV lines and AC double-circuit 220kV lines. The schematic diagrams of the four tower types are shown in Figure 1, where the HV conductors are on the upper part of the tower, and the LV conductors are on the lower part of the tower.



(a)SSZT2V (b)SSZT2I (c)SSZT22V



(d)SSJT3

Figure 1 Schematic Diagram of Towers

4. Calculation Results

As shown in Figure 1 Schematic Diagram of Towers, the tower body consists of 2 gradient sections. Therefore, each tower type will be calculated under 3 conditions: Condition 1, where the design wind speed is adopted for the full height of the tower; Condition 2, where the design wind speed is adopted for the part above the intersection between main members in the lower section, and the reduced wind speed is adopted for the part below the intersection; Condition 3, where the reduced wind speed is adopted for the part above the intersection between main members in the lower section, and the design wind speed is adopted for the part below the intersection. The Condition 1 is the design condition of conventional high wind, while the Condition 2 and Condition 3 are conditions considering the Eiffel Effect.

1) SSZT2V

The analysis on Eiffel Effect shows that only the diagonal member on the side of the tower at the pole arm below 1,000kV conductor is controlled by the Eiffel Effect. The calculation results are given in Table 2, in which the stress ratio refers to the ratio of the calculated stress of the member bar to the design stress. The calculation results given in Table 2 show that the influence of Eiffel Effect on SSZT2V tower is low.

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Table 2 Calculation Results of Eiffel Effect on SSZT2V Tower

Member Bar Type	Condition 1		Condition 2		Condition 3	
	Axial Force (kN)	Stress Ratio (%)	Axial Force (kN)	Stress Ratio (%)	Axial Force (kN)	Stress Ratio (%)
Tower body diagonal member	-309.71	71.7	-309.84	71.7	-115.90	26.8

2) SSZT2I

SSZT2I tower is obviously influenced by Eiffel Effect, where the calculation results are given in Table 3, and the member bar number is shown in Figure 2.

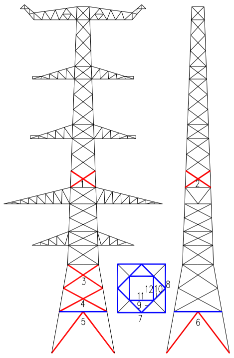

Figure 2 Member Bar Number of SSZT2I Tower

Table 3 Calculation Results of Eiffel Effect on SSZT2I Tower

Member Bar Type	Member Bar Number	Condition 1		Condition 2		Condition 3	
		Axial Force (kN)	Stress Ratio (%)	Axial Force (kN)	Stress Ratio (%)	Axial Force (kN)	Stress Ratio (%)
Diagonal member of tower body	1	-489.22	96.9	-490.85	97.3	-388.14	76.9
	2	-326.3	90.9	-331.04	92.2	-167.74	46.7
	3	-587.34	77.8	-629.85	83.5	-433.6	57.5
	4	-407.45	87.5	-451.17	96.9	-290.08	62.3
Diagonal member of tower leg	5	-513.25	89.5	-592.27	103.3	-358.94	62.6
	6	-347.09	60.5	-438.58	76.5	-86.84	15.1
Diaphragm member	7	-278.45	77.9	-322.11	90.1	-197.29	55.2
	8	-199.41	77.6	-242.82	94.5	-86.72	33.8
	9	-60.79	44.7	-66.71	49.1	-44.53	32.8
	10	-42.30	31.1	-49.65	36.5	-14.01	10.3
	11	-90.54	78.3	-99.01	85.6	-67.64	58.5
	12	-65.25	80.8	-75.75	93.8	-25.35	31.4

The calculation result given in Table 3 shows that the influence of Eiffel Effect on the stressing of SSZT2I tower increases from top to bottom. It thus can be considered that the Calculation Condition 3 with reduced wind load in upper section has no influence on the material selection of member bar, and Calculation Condition 2 with reduced wind load in lower section has high influence on the material selection of member bar. The Eiffel Effect not only influences the stressing of the diagonal member of the tower body, but also on the stressing of the diaphragm member, especially on the stressing of the pole arms of the diaphragm.

The influence of Eiffel Effect on the axial force of diagonal member of the tower body above the location with varying gradient is low, and the increase ratio of the axial force is within 1.5%. The influence of Eiffel Effect on the axial force of diagonal member of the tower body below the location with varying gradient is high, and the increase ratio of the axial force is about 10%. The influence of Eiffel Effect on the diagonal member of tower leg is most obvious, and the increase ratio of axial force in the diagonal member of tower leg on the side of tower body is up to 26%. The influence of Eiffel Effect on the pole arms of the diaphragm at the tower leg is higher than that of the diagonal member of the diaphragm, the increase ratio of axial force of the pole arms of the diaphragm is up to 22% and the increase ratio of axial force of the diagonal member of the diaphragm is up to 17%.

3) SSZT22V

The influence of Eiffel Effect on SSZT22V is obvious. The calculation results are given in Table 4 and the member bar number is shown in Figure 3.

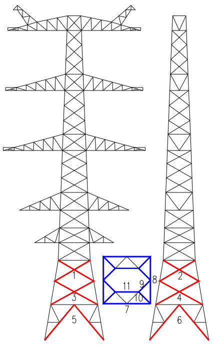

Figure 3 Member Bar Number of SSZT22V Tower

Table 4 Calculation Results of Eiffel Effect on SSZT22V Tower

Member Bar Type	Member Bar Number	Condition 1		Condition 2		Condition 3	
		Axial Force (kN)	Stress Ratio (%)	Axial Force (kN)	Stress Ratio (%)	Axial Force (kN)	Stress Ratio (%)
Diagonal member of tower body	1	-422.50	95.90	-456.88	103.70	-292.67	66.40
	2	-377.98	85.80	-403.01	91.40	-94.19	39.60
	3	-321.02	95.50	-358.41	106.70	-215.65	64.20
	4	-262.37	78.10	-306.77	91.30	-63.42	36.80
Diagonal member of tower leg	5	-377.03	74.40	-439.91	86.80	-245.59	48.40
	6	-307.96	60.70	-379.59	74.90	-79.72	15.70
Diaphragm member	7	-249.69	88.50	-289.61	102.70	-166.26	58.90
	8	-209.91	74.40	-229.17	81.20	-64.2	22.80
	9	-31.08	35.70	-36.56	42.00	-9.53	10.90
	10	-31.08	64.40	-36.56	75.80	-9.53	19.80
	11	-43.95	45.90	-51.7	54.00	-13.48	14.10

The calculation result given in Table 4 shows that the influence of Eiffel Effect on the stressing of SSZT22V tower also follows the law of gradual increase from top to bottom. It thus can be considered that the Calculation Condition 3 with reduced wind load in upper section has no influence on the material selection of member bar, and Calculation Condition 2 with reduced wind load in lower section has high influence on the material selection of member bar. Eiffel effect also has influence on the stressing of diaphragm member.

The diagonal member of tower body above the location with varying gradient is not influenced by the Eiffel Effect. The diagonal member of tower body below the location with varying gradient is not influenced by the Eiffel Effect, and the increase ratio of axial force is 6.62%-16.92%. The influence of Eiffel Effect on the diagonal member of tower leg is most obvious, and the increase ratio of axial force is up to 23%. With consideration to the influence of Eiffel Effect on the pole arms of the diaphragm at the tower leg, the increase ratio of axial force is about 16%; for the diagonal member of the diaphragm, the increase ratio of axial force is about 18%.

4) SSJT3

The Eiffel Effect analysis shows that only the diagonal member on the front of the second tower section below the middle pole arm of 1,000kV conductor is controlled by the Eiffel Effect, and the calculation results are given in Table 5.

Table 5 Calculation Results of Eiffel Effect on SSJT3 Tower

Member Bar Type	Condition 1		Condition 2		Condition 3	
	Axial Force (kN)	Stress Ratio (%)	Axial Force (kN)	Axial Force (kN)	Stress Ratio (%)	Axial Force (kN)
Diagonal member of tower body	-1039.14	89.0	-1039.24	89.1	-952.04	81.6

The calculation results given in Table 5 shows that the calculation condition with reduce wind load on upper section has no influence on the material selection of member bar of SSJT3 tower. It thus can be considered that the calculation condition with reduced wind load on the lower section has certain influence on the diagonal member of the tower, but the influence is relatively low. With consideration to the Eiffel Effect, the axial force of the diagonal member on the front of the second tower section below the middle pole arm of 1,000kV conductor increases by 0.01%.

5. Minimum Bearing Capacity Requirement of Diagonal Member

The Eiffel Effect analysis on 3 tangent towers and 1 strain tower of UHV transmission lines show that the influence of Eiffel Effect on the tower is relevant to the gradient of the main members. When the tower body is composed of 2 or more gradient sections, the influence of Eiffel Effect on the stressing of member bar depends on the intersection angle between the two bottom gradient sections, i.e. the intersection angle (acute angle) between the main members in the bottom tower sections, which is known as the intersection angle between the main members. The statistics of the intersection angle between the main members of 4 UHV tower and the influence of Eiffel Effect on member bars of different locations are given in Table 6.

Table 6 Results Statistics of Eiffel Effect

Tower Type	SSZT2V	SSZT2I	SSZT22V	SSJT3
Intersection angle (acute angle) between the main members	5.58	8.22	7.48	5.36
Number of controlling diagonal member of tower body	1	6	4	1
Number of controlling diagonal member above location with varying gradient	2	2	0	2
Number of controlling diagonal member below location with varying gradient	0	4	4	0
Number of controlling diaphragm members	0	5	5	0

For the four types of towers analyzed, when the intersection angle between the main members is less than 5 degrees, the Eiffel Effect on the tower is low and may not be considered in the design; when the intersection angle is about 5 degrees, the individual diagonal member above the location with varying gradient is influenced by the Eiffel Effect, and the calculation results show that the influence is low; when the intersection angle is more than 7 degrees, the influence of Eiffel Effect on the diagonal member above the location with varying gradient is low, and the influence of Eiffel Effect on the diagonal member above the location with varying gradient and the diaphragm member at the tower leg is high.

At present, when the structure design of pole towers of overhead transmission lines is not considered, it is stipulated that the internal force of its design is not less than 5% of the internal force in the main member at the corresponding position in order to ensure that the diagonal member has sufficient bearing capacity if the influence of Eiffel Effect on the transmission towers is not considered. The correspondence between the internal force in the diagonal member below the location with varying gradient and the internal force in the main member is calculated for SSZT2I and SSZT2VV towers under high influence of Eiffel Effect in Table 7, and the results are given in Table 8 and Table 9. The member bar number in the table are shown in Figure 2 and Figure 3, where the ratio of internal force in the diagonal member to the internal force in the main member refers to the ratio of the internal force in diagonal member to the internal force of main member at the corresponding position.

Table 7 Results Comparison of SSZT2I Tower

Member Bar Type	Member Bar Number	Without Considering Eiffel Effect		With Considering Eiffel Effect	
		Axial force of diagonal member (kN)	Ratio of axial force of diagonal member to main member (%)	Axial force of diagonal member (kN)	Ratio of axial force of diagonal member to main member (%)
Diagonal member of tower body	3	-587.34	5.97	-629.85	6.40
	4	-407.45	4.25	-451.17	4.71
Diagonal member of tower leg	5	-513.25	5.49	-592.27	6.34
	6	-347.09	3.71	-438.58	4.69

Table 8 Results Comparison of SSZT22V Tower

Member Bar Type	Member Bar Number	Without Considering Eiffel Effect		With Considering Eiffel Effect	
		Axial force of diagonal member (kN)	Ratio of axial force of diagonal member to main member (%)	Axial force of diagonal member (kN)	Ratio of axial force of diagonal member to main member (%)
Diagonal member of tower body	1	-422.50	4.85	-456.88	5.24
	2	-377.98	4.34	-403.01	4.63
	3	-321.02	3.79	-358.41	4.23
	4	-262.37	3.10	-306.77	3.62
Diagonal member of tower leg	5	-377.03	4.54	-439.91	5.30
	6	-307.96	3.71	-379.59	4.57

The calculation results show that the ratio of the internal force in the diagonal member of the tower body and diagonal member at the tower leg to the axial force of the main member is more than 6% after considering the Eiffel Effect for SSZT2I tower, and the ratio of the internal force in the diagonal member of the tower body and diagonal member at the tower leg to the axial force of the main member is more than 5% after considering the Eiffel Effect for SSZT22V tower. For UHV transmission towers and especially for UHV transmission towers of EHV/UHV AC transmission lines on the same tower, the minimum bearing capacity requirements of conventional diagonal member could not satisfy the actual needs since the tower are high and obviously curved. It is necessary to calculate and analyze according to the actual structure to ensure the safe and stable operation of the transmission towers.

6. Conclusion

In this paper, the principle of Eiffel Effect on the transmission towers is explained, a comparative analysis on calculation methods for Eiffel Effect on tower mast structures both at home and abroad was conducted, and the analysis methods for the Eiffel Effect on the transmission towers is suggested. On this basis, the Eiffel Effect on 4 UHV transmission towers were analyzed, and the influence of Eiffel Effect on the members bar of the tower and the minimum bearing capacity requirement of diagonal member was analyzed. It is concluded that:

1) For the transmission towers, Eiffel Effect not only has an influence on the stressing of the diagonal member of the tower, but also has a certain influence on the member bars at the tower leg, and the Eiffel Effect will increase the stressing of the diagonal member and the member bar, which shall be considered when designing the tower.

2) The rigidity-reduction method can consider the randomness of the spatio-temporal distribution of fluctuating wind loads, and the calculation method is similar to the principle of Eiffel Effect, which is relatively simple, and easy to apply in engineering.

3) It may be unsafe if designing the minimum bearing capacity requirement for the diagonal member with the internal force not less than 5% of the main members to satisfy the Eiffel Effect on the tower for the HV transmission towers, and especially for the transmission towers with EHV/UHV AC multi-circuit transmission lines on the same tower.

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