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Evaluation of Corona Loss in 750 kV Four-Circuit Transmission Lines on the Same Tower Considering Complex Meteorological Conditions

YUNPENG LIU[1,2], SIJIA CHEN[1], AND SHILONG HUANG[1,2]
[1]Hebei Provincial Key Laboratory of Power Equipment Security Defense, North China Electric Power University, Baoding 071003, China
[2]State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources, North China Electric Power University, Beijing 102206, China

Corresponding author: Shilong Huang (simonhuang@ncepu.edu.cn)

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ABSTRACT As an important index for measuring the operational economy of EHV AC transmission lines, corona loss (CL) is one of important factors worth considering during the operation and design of transmission lines. The 750-kV transmission lines are mainly distributed in high-altitude areas in northwestern China, where sand storm occurs frequently in spring and autumn. At present, a few researches are available on the evaluation of CL in multi-circuit transmission lines on the same tower in sandy and dusty area at high altitudes. Based on a transmission project with four-circuit transmission lines on the same tower in the north of Xi'an, Shaanxi Province, China, the electric field distributions of bundle conductors under two types of arrangement structure, including six and four cross-arms tower, were investigated. Then, by using the CL equivalent theory, the CL under meteorological conditions of fair, rainy, snowy, foggy, and dusty weather were evaluated. Finally, the optimal phase-sequence arrangement under the optimal tower modes was proposed, and the CL and resistance loss under the selected arrangements were compared.

INDEX TERMS orona loss, sand and dust weather, corona loss equivalent theory, 750 kV four-circuit transmission lines on the same tower, high – altitude area.

I. INTRODUCTION

With the growing lack of land availability, transmission corridors are increasingly scarce, and therefore the multi-circuit transmission lines on the same tower which can save land occupation with restricted corridors have become the trend for power grids. The corona effect induced by multi-circuit transmission lines on the same tower is more complex due to mutual coupling of lines, diversified phase-sequence arrangements, and construction of taller transmission towers [1]–[5]. As an important part of the corona effect, CL is an important factor for measuring the operation economy and reliability of transmission lines. The CL evaluation of 750 kV AC four-circuit transmission lines on the same tower in dusty and sandy northwestern areas at high altitudes is an important link in the transmission design, lending significance to this research.

The Bonneville Power Administration (BPA) in the USA carried out many tests on bundle conductors, and subsequently proposed a formula for predicting the CL of the bundle conductors in the 1960s. Anderson and Zaffanella [6], Anderson [7] investigated the variation in bundle conductor radius and CL data during the fair, foggy, and rainy weather. Clade *et al.*[8], Clade and Gary [9], [10] analysed a calculating method of bundle conductors in the cylindrical corona cage and subsequently defined the concept of reduced CL. Kolcio *et al.* [11] measured the CL data of bundle conductors in a 765 kV test line with different bundle spacings and sub-conductor radii in foggy and fair weather, which provided a good basis for the selection of conductors. Chartier *et al.* [12] investigated the respective influences of cross-sectional area of conductors and rainfall intensity on CL. Liu *et al.* [13] designed a CL real-time monitoring system and investigated the UHV CL data of a single-circuit test line with bundle conductors (8×LGJ–500/35) under heavy rainy conditions, and the coefficients of surface roughness at various rainfall rates were estimated. Liu *et al.* [14] also developed a sand storm simulation system and measured the corona resistive currents of bundle conductors in a 750-kV transmission project at three specific altitudes by using a movable corona cage. This made it convenient to obtain the experimental CL data in various sand particle concentrations and sizes, as well as the roughness factors in a sand-dust environment. Nigol and Cassan [30] proposed a CL equivalent method and the correctness of the method is verified by comparing the calculated results with the measured data, You *et al.* [15] utilised this method and calculated equivalent CL of actual transmission lines based on the experimental CL data obtained from corona cages. Liu *et al.* [16] proposed a three-dimensional (3-D) calculation model for CL and calculated the CL of four-bundle conductors with sag in the UHV corona cage. Huang *et al.* [17] experimentally explored and acquired the corona onset gradient of common bundle conductors of UHV transmission lines in high-altitude areas. Sollerkvist *et al.* [18] evaluated the average and maximum CL of actual 400-kV transmission lines. By evaluating the CL of UHV AC single- and double-circuit transmission lines in plain areas, Liu *et al.* [19], You *et al.* [20] separately obtained the annual average, and maximum, CL under normal operating voltages considering various weather conditions.

However, little research is available on the CL of the multi-circuit transmission lines on the same tower in high-altitude areas where sandy-dusty weather occurs frequently. Based on the transmission project of four-circuit transmission lines on the same tower in the north of Xi'an in Shaanxi Province, China, two types of tower modes (six and four cross-arm towers) were investigated to calculate the average maximum electric fields of bundle conductors at various phases under the two types of structural arrangement. Only the reverse phase sequence was taken into account in the six cross-arm tower, while the four cross-arm towers considered four kinds of typical phase sequences. Afterwards, by employing the CL equivalent theory, on the premise of considering the sandy and dusty weather condition as well as rainy, snowy and foggy weather conditions, the CL of transmission lines was evaluated. Finally, the research proposed the optimal phase-sequence arrangement under the optimal tower mode and further compared CL and resistance loss under the selected optimal and worst arrangements, respectively.

II. DESIGN PARAMETERS OF TRANSMISSION PROJECT

A. DESIGN INDICES of 750 kV FOUR-CIRCUIT TRANSMISSION LINES ON THE SAME TOWER

As provided by Northwest Electric Power Design Institute CO., LTD. Of China Power Engineering Consulting Group, the design parameters of 750 kV four-circuit transmission lines on the same tower are listed in Table 1. Owing to the altitude of practical transmission lines being a continuous value, the transmission line was divided into three segments for the convenience of calculation, and the calculated altitude of each segment was used for analysis. The specific parameters of each segment are listed in Table 2.

TABLE 1. Design parameters of transmission lines.

Description	Value
Design capacity (MW)	2300
Total line length (km)	20
Foundation number	46
Conductor type	LGJ-500/45
Conductor resistance (Ω/km)	0.05912
Types of ground wire	JLB20A-150
Average foundation distance (m)	450
Altitude(m)	168~1500

TABLE 2. Calculated parameters of each segment.

	Length/km	Calculated altitude/m	Number of tower foundations
1st	5	340	12
2nd	7.5	750	17
3rd	7.5	1250	17

B. METEOROLOGICAL CONDITIONS ALONG TRANSMISSION LINE

The annual average hours of typical meteorologic conditions along transmission line are listed in Table 3.

TABLE 3. Meteorological conditions along transmission line.

	Fair weather	Rain	Snow	Fog	Sand and dust	Sum
Annual average hours/h	5123	2328	418	840	51	8760

C. PRELIMINARILY SELECTED TOWER MODES AND PHASE SEQUENCE ARRANGEMENT

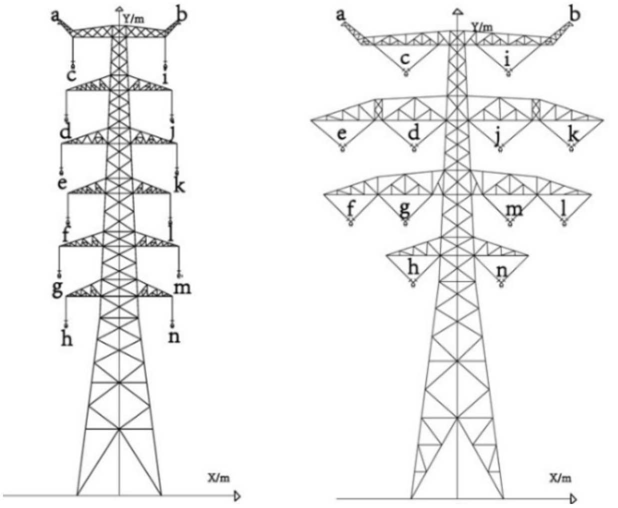
The six- and four-cross-arm tower modes were planned to be applied in the transmission project of the 750 kV four-circuit transmission line on the same tower. The six-cross-arm tower was arranged by the reverse phase sequence in which the insulator strings were suspended in an I-shape [29]. For the four-cross-arm tower, four typical phase sequences were analyzed in which the insulator strings were suspended in a V-shape.

The specific structures of these two tower modes are displayed in Figure 1 and there are 40 sheets in each insulator string. The coordinates and phase sequences of each location are listed in Table 4.

III. DESIGN OPTIMISATION

A. CALCULATION OF THE AVERAGE MAXIMUM FIELD STRENGTH OF BUNDLE CONDUCTORS UNDER VARIOUS PHASE-SEQUENCE ARRANGEMENTS OF PRELIMINARILY SELECTED TOWER MODES

By using the FEM method, the field strength on the surface of bundle conductors was calculated. By taking A-phase peak voltage in II phase-sequence arrangement of the four-cross-arm tower mode, the distributions of field strengths around the bundle conductors and sub-conductor of A2 are as displayed in Figure 2.

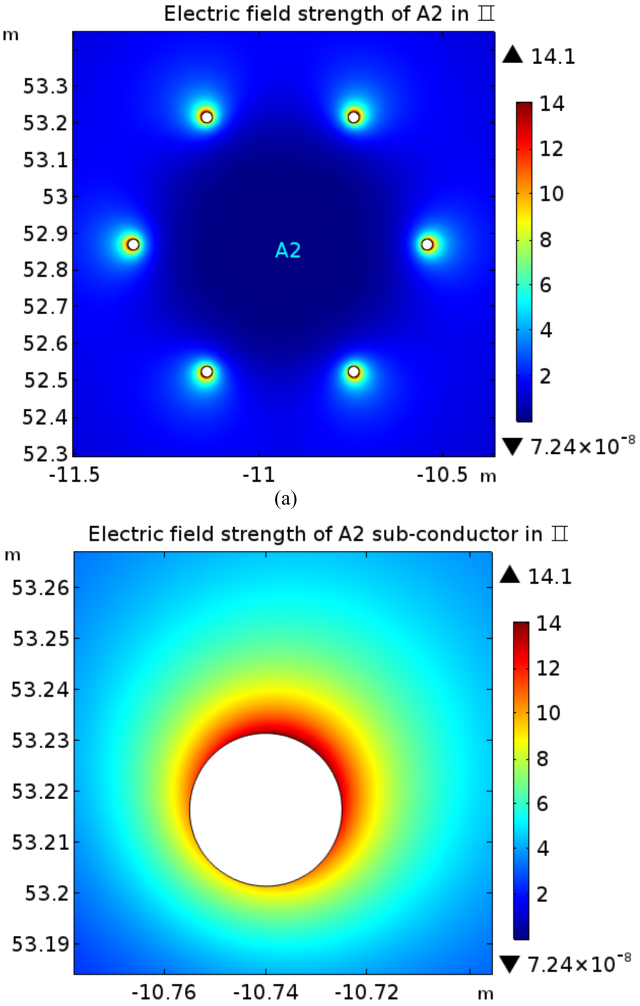


(a) (b)

FIGURE 1. The phase-sequence arrangement of the two tower modes; (a) Six-cross-arm arrangement; (b) Four-cross-arm arrangement.

TABLE 4. Coordinates of arranged insulator strings on the preliminarily tower modes.

Location	Six-cross-arm tower		Four-cross-arm tower				
	Coordinate (x, y)/m	Phase sequence	Coordinates (x, y)/m	□	□	□	□
a	(-18.2, 142)	G1	(-28.8, 116.6)	G1	G1	G1	G1
b	(18.2, 142)	G2	(28.8, 116.6)	G2	G2	G2	G2
c	(-14, 129)	A1	(-12.7, 104.7)	A1	A1	A1	A1
d	(-16, 113)	B1	(-10.6, 86.2)	B1	B1	B1	B1
e	(-18, 97)	C1	(-28.4, 86.2)	C1	C1	C1	C1
f	(-15.6, 82)	A2	(-26.4, 67.9)	A2	C2	A2	B2
g	(-18.2, 66)	B2	(-12.9, 67.9)	B2	B2	B2	C2
h	(-16.2, 51)	C2	(-10.9, 52.9)	C2	A2	C2	A2
i	(14, 129)	C3	(12.7, 104.7)	A3	A3	C3	C3
j	(16, 113)	B3	(10.6, 86.2)	B3	B3	B3	B3
k	(18, 97)	A3	(28.4, 86.2)	C3	C3	A3	A3
l	(15.6, 82)	C4	(26.4, 67.9)	A4	C4	C4	A4
m	(18.2, 66)	B4	(12.9, 67.9)	B4	B4	B4	B4
n	(16.2, 51)	A4	(10.9, 52.9)	C4	A4	A4	C4



(a)

(b)

FIGURE 2. The distributions of field strengths of A2 phase in II phase-sequence arrangement of the four-cross-arm tower under A-phase voltage peak; (a) distribution of field strengths of A2-phase bundle conductor; (b) the distribution of field strength of A2 sub-conductor.

TABLE 5. Average maximum field strengths of conductors under various phase sequences of preliminarily selected tower modes.

Arrangement		Average maximum field strength (kV/cm)											
		A1	B1	C1	A2	B2	C2	A3	B3	C3	A4	B4	C4
Six-cross arm		14.68	15.29	15.60	15.70	15.49	14.33	15.60	15.29	14.68	14.33	15.49	15.70
Four -cross arm	□	12.62	12.54	15.19	15.90	13.81	13.02	12.62	12.54	15.19	15.90	13.81	13.02
	□	13.08	12.54	12.72	13.53	13.81	13.39	13.08	12.54	12.72	13.53	13.81	13.39
	□	14.48	12.54	14.97	15.63	13.81	15.12	14.96	12.54	14.49	15.12	13.81	15.63
	□	14.84	13.55	13.93	15.48	14.60	15.58	12.29	13.17	14.71	12.95	14.79	14.78

Due to the skin effect of bundle conductors and imbalanced distribution of actual transmission lines, the average maximum field strength is generally calculated for analysis. The average maximum field strength is equal to the arithmetic mean of maximum field strengths of the individual sub- [22]. The average maximum field strengths of bundle conductors under various phase sequences of the two preliminarily selected tower modes were calculated, as listed in Table 5.

B. CALCULATION OF CL EQUIVALENT FACTOR

For AC transmission lines, the space charges induced by corona discharge are restricted in the space around the conductors. Therefore, for different geometric arrangements, the corona effects caused by conductors can be ensured to be the same if the field strengths on the surface of bundle conductors are the same. This equivalency is easy to establish and therefore the CL of conductors is generally calculated by using the measured CL in a corona cage.

By applying the CL equivalent theory, the effective CL factor K was introduced [10]–[12]. Then, the CL of actual transmission lines P_{eq} can be obtained based on Formula (1):

$$P_{eq} = P_{cage} \times \frac{K_{line}}{K_{cage}} \qquad (1)$$

Where:

K_{line} and K_{cage} = effective CL equivalent coefficients of practical transmission lines and in a corona cage;
P_{cage} = measured CL in a corona cage;
P_{eq} = CL of actual transmission lines.

The calculated values of K_{line}/K_{cage} under various phase sequences of the preliminarily selected tower modes are listed in Table 6.

TABLE 6. **Calculated values of CL equivalent coefficients under various phase sequences of preliminarily selected tower modes.**

Arrangement		CL equivalent factor K_{line}/K_{cage}											
		A1	B1	C1	A2	B2	C2	A3	B3	C3	A4	B4	C4
Six-cross-arm		0.812	0.815	0.816	0.817	0.815	0.809	0.816	0.815	0.812	0.809	0.815	0.817
Four -cross -arm	☐	0.810	0.821	0.812	0.817	0.825	0.815	0.810	0.821	0.812	0.817	0.825	0.815
	☐	0.810	0.821	0.812	0.815	0.825	0.817	0.810	0.821	0.812	0.815	0.825	0.817
	☐	0.810	0.821	0.812	0.817	0.825	0.815	0.812	0.821	0.810	0.815	0.825	0.817
	☐	0.810	0.821	0.812	0.815	0.817	0.825	0.812	0.821	0.810	0.817	0.825	0.815

C. THE SUM OF CL OF ALL PHASES IN HEAVY RAIN AND SANDY-DUSTY WEATHER CONDITIONS

The CL test results of 6×LGJ-500/45/s400 conductors in heavy rain (rainfall rate, 7.6 mm/h) and sandy-dusty weather (concentration and particle size were 460 mg/m^3 and 0.125 to 0.25 mm, respectively) are shown in Figure 3 in which measured CL in a corona cage P$_{cage}$ were obtained [13], [14], and the calculated altitude for each segment is listed in Table 2.

According to the calculation results of the average maximum field strengths in Table 5 and the CL equivalent coefficients in Table 6, the CL from practical transmission lines under various phase sequences of the two preliminarily selected tower modes in heavy rain and sandy-dusty weather can be obtained based on the data shown in Figure 3. The results of the total-phase CL under various phase sequences of the two tower modes are displayed in Table 7.

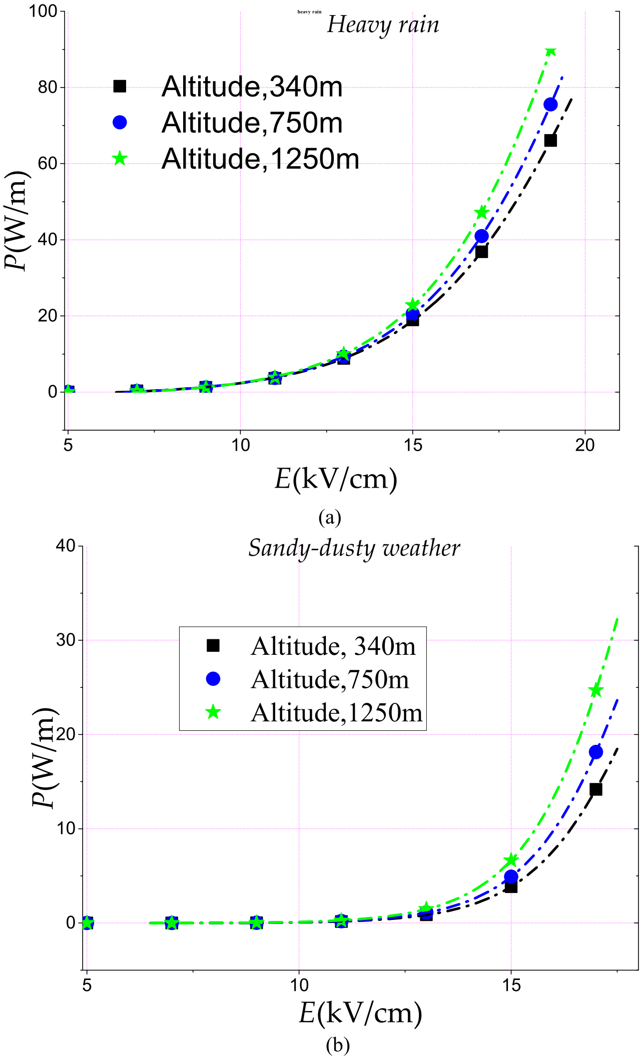


FIGURE 3. **Test results of CL for 6×LGJ-500/45/s400 in corona cage after altitude correction; (a) CL in heavy rain (precipitation intensity, 7.6 mm/h) after altitude correction; (b) CL in sandy-dusty weather (concentration and particle size, 460 mg/m^3 and 0.125 to 0.25 mm, respectively) after altitude correction.**

D. EVALUATION OF CL CONSIDERING SANDY-DUSTY WEATHER AND OTHER METEOROLOGICAL CONDITIONS

Generally, corona discharge does not happen in transmission lines in fair weather, and the CL from transmission lines is mainly attributed to the leakage loss of insulator strings. The research related to the leakage loss of insulators on EHV and UHV transmission lines found that the loss from each insulator sheet was found to be 4.68 W [7]. According to the number of tower foundations for the whole transmission line, the type of insulator strings, and the number of hours of sunshine annually are summarized in Table 3, subsequently the annual sum CL in fair weather W_1 is listed in Table8.

Heavy, moderate, and light rainy conditions are classified according to their respective precipitation intensity [22] (7.6 mm/h, 2.6 mm/h to 7.6 mm/h, and less than 2.5 mm/h, respectively). The logarithms of different precipitation intensity indicate an approximately linear relationship with that of the CL [20], and the calculation factors for heavy, moderate, and light rain are 1.35, 1, and 0.65, respectively. In terms of estimation on snowy days, the equivalent precipitation intensity is used for an equivalent analysis. It is supposed that the corresponding precipitation intensity of heavy, moderate, and light snow are 2.54, 0.635, and 0.127 mm/h and therefore the calculation factors for heavy, moderate, and light snow are 1, 0.68, and 0.34, respectively [7]. On this basis, a doubled CL of those results is taken as the CL value on a snowy day. The CL on foggy days is lower, and therefore it is estimated to be 80% of the CL on a light snow day.

The heavy, moderate, and light intensity account for one third of the annual average hours on rainy and snowy days, respectively. Based on Tables 3 and 7, as well as the calculation factors used for heavy, moderate, and light intensity of rain and snow, the annual sum CL of the transmission lines on rainy, snowy and foggy days W_2can be acquired:

$$W_2 = \sum P_{ij} T_j L_i \tag{2}$$

Where:

P_{ij} = The total-phase CL of the *i*th segment of line on the weather categories *j,* in which the weather categories *j* includes heavy, moderate, and light intensity of rain, snow as well as fog;

T_j = Annual average hours of different weather categories *j*;

L_i = Length of the *i*th segment of the transmission line.

The calculated values of W_2 under various phase sequences of the two preliminarily selected tower modes in rainy, snowy, and foggy conditions are listed in Table 9.

When the particle size and concentration of sand and dust are low, the CL of conductors is consistent with that in fair weather, however, when the particle size and the concentration of sand and dust are increased to a certain extent, the corona onset voltage of conductors decreases, causing the CL to increase significantly. Therefore, the estimation of CL of conductors on sandy-dusty weather is divided into two parts: W_{dust} (dusty weather) and $W_{strongsand}$(strong-sandy weather). For the dusty weather, owing to the corona onset electric field strength of conductors on conditions of small particle size and low concentration of sand and dust remains unchanged [14], it is inferred that corona discharge does not happen on actual transmission lines so that the CL is still attributed to leakage loss from insulator strings. The estimation of CL in dusty weather is equivalent to that in fair weather, which is estimated by using the aforementioned method. The CL in strong-sandy weather can be estimated based on the CL data in a corona cage under sandy-dusty conditions. In order to estimate the strong dust weather, the experimental data with the highest concentration 460 mg/m^3 are selected. Because the 750 kV four-circuit tower is high, the larger particle size sand cannot be blown up so high. And the smaller particle size has less influence on corona loss, therefore the medium particle size 0.125∼0.25mm is selected. The experimental data is shown in Figure 3(b). Dusty and strong-sandy weather conditions separately account for half of the annual hours of sandy-dusty weather. According to Tables 3 and 8, the annual sum CL of transmission lines in sandy-dusty weather conditions W_3 can be calculated thus:

TABLE 7. **The sum of total-phase CL on practical transmission lines in heavy rain and sandy-dusty weather.**

Calculation altitude (m)	Arrangement		Total-phase CL (kW/km)	
			Heavy rain	Sandy-dusty weather
340	Six-cross-arm		201.85	44.91
	Four-cross-arm	I	136.34	24.87
		II	97.04	10.40
		III	161.11	30.66
		IV	149.88	26.70
750	Six-cross-arm		216.68	57.21
	Four-cross-arm	I	143.74	31.66
		II	99.45	13.18
		III	170.94	39.01
		IV	158.32	33.97
1250	Six-cross-arm		239.18	77.52
	Four-cross-arm	I	155.71	42.85
		II	104.34	17.73
		III	186.35	52.79
		IV	171.77	45.94

TABLE 8. **The annual sum CL in fair weather W_1.**

	Six cross-arms tower	Four cross-arms tower
W_1 (kW·h)	0.53×10^6	1.06×10^6

TABLE 9. **The annual sum CL in rainy, snowy, and foggy weather conditions W_2.**

	Six-cross-arm tower	Four-cross-arm tower			
		I	II	III	IV
W_2 (kW·h)	10.98×10^6	7.26×10^6	4.99×10^6	8.64×10^6	8.00×10^6

$$W_3 = W_{dusty} + W_{strong-sand} \tag{3}$$

$$W_{strong-sand} = \sum P_i T L_i \tag{4}$$

Where:

P_i = The total-phase CL of the *i*th segment of transmission lines in the sand-dust weather (the concentration of 460 mg/m^3 and the particle size of 0.125 to 0.25 mm);

T = Annual average hours of strong sandy-dusty weather conditions;

L_i = The length of the *i*th segment of the transmission line.

The W_3 of transmission lines under each phase sequence of the preliminarily selected tower modes in sandy-dusty weather conditions are listed in Table 10.

TABLE 10. **The annual sum CL in dusty-sandy weather conditions W_3.**

	Six-cross-arm tower	Four-cross-arm tower			
		I	II	III	IV
W_3 (kW·h)	0.037×10^6	0.023×10^6	0.013×10^6	0.027×10^6	0.024×10^6

By calculating the sum of the CL under various meteorological conditions, the annual sum CL of the whole transmission line under total meteorological conditions W_{sum} can be obtained:

$$W_{sum} = W_1 + W_2 + W_3 \tag{5}$$

By dividing the W_{sum} from the transmission line by the whole number of hours (8,760 h) in a year and the total length of the transmission line, the annual average CL can be obtained. Based on the weather (heavy snow) on which there is the largest CL from transmission lines, the CL of the total segments of transmission lines can be calculated to acquire the maximum CL, and the results under each phase sequence of the preliminarily selected tower modes are listed in Table 11.

TABLE 11. The annual average and maximum CL under each phase sequence of the preliminarily selected tower modes.

Arrangement		Annual average CL (kW/km)	Maximum CL (kW/km)
Six-cross-arm tower		65.92	299.04
Four-cross-arm tower	□	47.62	216.86
	□	34.63	149.16
	□	55.54	258.17
	□	51.84	238.90

E. COMPARISON OF THE CL AND RESISTANCE LOSS UNDER THE OPTIMAL AND WORST PHASE SEQUENCE ARRANGEMENTS

It can be seen from Table 11 that the CL from transmission lines under four-cross-arm tower mode were superior to those under six-cross-arm tower mode. Moreover, for the former mode, the CL indices of transmission lines under II-phase sequence arrangements were better than those under the other phase sequences. Therefore, the four-cross-arm tower mode under the II-phase sequence was considered to be the optimal arrangement of the CL in the transmission project with four-circuit transmission lines on the same tower. Although the six-cross-arm tower exhibited a large CL, it also showed its advantages such as small land occupation and therefore the phase sequence in practical engineering needs to be arranged according to specific conditions.

The CL from transmission lines is primarily determined by meteorological conditions while the resistance loss mainly depends on the line load. The CL and resistance loss of 750 kV transmission lines under the optimal and the worst phase sequence arrangements were compared, in which the resistance loss was calculated at the rated operating state. The specific parameters are displayed in Table 1 and the comparison is summarized in Table 12.

TABLE 12. Comparison of CL and resistance loss

Arrangement	Resistance loss (kW/km)	CL (kW/km)	
		Mean Annual	Maximum
Optimal arrangement (Four-cross-arm tower, II sequence)	139	34.63	149.16
Worst arrangement (Six-cross-arm tower)		65.92	299.04

The mean annual CL was 25% of the resistance loss under the optimal phase sequence arrangement while it was 47% under the worst phase sequence arrangement. Due to the corona effect of transmission lines, a considerable energy loss was found along such lines. The annual average loss can be reduced by optimising the tower mode and phase sequences. The maximum CL from transmission lines was 107% of the resistance loss under the optimal arrangement while it was 215% under the worst arrangement. Under maximum load and the worst meteorological conditions, the transmission capacity and reliability of transmission lines is reduced. By optimising the tower mode and phase sequence, the maximum CL can be decreased and the influence of bad meteorological conditions on the reliability of the power grid can be reduced. The maximum CL was still slightly larger than the resistance loss under the optimal arrangement and therefore it is necessary to concentrate on the maximum CL during the selection of reserve capacity.

IV. CONCLUSION

Based on the results presented in this study, the following conclusions may be drawn:

1) Under various phase sequences, the average maximum electric field strengths of transmission lines of six- and four-cross-arm towers in the transmission project of 750 kV four-circuit transmission lines on the same tower were in the range of 14.33 – 15.70 kV/cm, and 12.29 – 15.90 kV/cm, respectively.

2) The CL test data of 6×LGJ-500/45/s400 bundle conductors under various field strengths in heavy rain and sandy-dusty weather (after altitude correction) at altitude of 340, 750, and 1,250 m were acquired.

3) Based on the CL equivalent theory, the CL equivalence coefficients for six- and four-cross-arm tower under various phase sequences were calculated.

4) Considering fair, rainy, snowy, foggy weather, and in particular sandy-dusty weather, the CL from four-circuit transmission lines on the same tower under various phase sequences of the two tower modes were evaluated to thus acquire the mean annual CL and the maximum CL. The optimal arrangement (the four-cross-arm tower mode under II phase sequence) was obtained.

5) By comparing the CL and resistance loss of transmission lines under the optimal and the worst phase sequence arrangements in the project involving 750 kV four-circuit transmission lines on the same tower, it was found that the annual average CL was 25% to 47% of the resistance loss. Moreover, the maximum CL from such transmission lines was 107% to 215% of the resistance loss.

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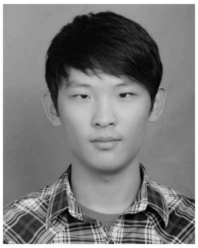
YUNPENG LIU was born in Jinzhai, Anhui, China, in 1976. He received the B.Sc. degree in electrical engineering and the Ph.D. degree in high voltage and insulation technology from North China Electric Power University, Baoding, China, in 1999 and 2005, respectively.

He is currently a Ph.D. Supervisor and a Professor with North China Electric Power University. His research interests are ultra-high voltage transmission, fault detection, and diagnosis of electric equipment.



SIJIA CHEN was born in Hejian, Hebei, China, in 1993. He received the B.Sc. degree from North China Electric Power University, Baoding, China, in 2017,where he is currently pursuing the M.Sc. degree. His research interests are UHV power transmission.

SHILONG HUANG was born in Lintao, Gansu, China, in 1992. He received the B.Sc. degree from North China Electric Power University, Baoding, China, in 2014, where he is currently pursuing the Ph.D. degree with the School of Electrical Engineering. His research interests are UHV power transmission and plasma science technology.

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