IET Science, Measurement & Technology

Research Article

Influence of altitude on radio interference level of AC power lines based on corona cage

ISSN 1751-8822
Received on 19th August 2014
Revised on 29th January 2015
Accepted on 10th April 2015
doi: 10.1049/iet-smt.2014.0255
www.ietdl.org

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Abstract: To investigate the effect of altitude on radio interference (RI) of AC power lines, a corona cage test system was used to measure the RI excitation function values of different bundle conductors in different altitude locations, such as Wuhan 23 m, Jingyuan 1408 m, Xining 2261 m, Gonghe 2943 m and Yangbajain 4300 m. Then, the RI curves with different altitudes, bundle numbers and subconductor diameters were obtained. The analysis and comparison show that the actual RI altitude correction values fall in between the range of 1 dB/300 m and $40(1-\sigma/\sigma_0)$ when the altitude below 3200 m, which is widely used as Italian correction term and Westinghouse correction term, respectively. Above this altitude, they are not applicable to predict the correction values. In this study, an RI correction term is proposed from the test results, which are fitted well for different altitude regions <4300 m.

1 Introduction

The ultra-high voltage AC transmission lines are indispensable for the development of electric power transmission in China nowadays. Owing to the imbalance distribution of energy resources, more and more power energy should be transported from western to eastern region in China, so some transmission lines should be built in high-altitude areas inevitably, such as Qinghai-Tibet plateau [1–3]. As we know, the corona phenomenon in high altitude areas becomes more serious, which is mainly caused by the decrease of air density, and the increase of mean free path [4, 5]. Radio interference (RI) is an important factor in corona effect. Therefore it is necessary to investigate the influence of altitude on RI level.

In the early days, there are some studies on RI level with different altitudes. In 1958, the Italian researcher Barntenstein and his partners proposed the term $q/300$ m as the altitude correction factor, in which q is the altitude in metres [6]. In 1960s, The Public Service Company of Colorado and the Westinghouse Electric Corporation carried out the tests together with a full-scale test line at 3200 m near Leadville, then the similar test was done at sea level (195 m) at the Tidd Project. By comparing the Leadville with Tidd data, the term $40(1-\sigma/\sigma_0)$ was proposed by Westinghouse as an additional term for the effect of altitude in 1973, where σ is the relative air density [7–9]. Then, Charier *et al.* [10] summarised the RI test results from a test station located at an altitude of 1953 m near a double-circuit 500 kV line. By comparing with the test results from another station at an altitude of 277 m which is near to a 500 kV line with similar design, they found that the correction factor of 1 dB/300 m was still valid and could also be used for audible noise (AN), television interference and, possibly, corona losses. In 1987, the Eskom built a corona cage in Johannesburg at an altitude of 1584 m, and the identical one of this cage was also built in Italy at sea level in order to obtain relationships between RI, AN and air density. By comparing the two test results under the heavy rain condition, the RI level in Johannesburg was 5–6 dB higher than that in Italy, which is in consistency with the correction factor 1 dB/300 m [11].

In sum, these studies mainly focus on single type of conductor bundles and the valid data of RI level measured above 2000 m altitude were very rare. To investigate the terms 1 dB/300 and $40(1-\sigma/\sigma_0)$ whether or not can be applicable in higher altitude areas, such as 3000 and 4000 m or more, this paper made a summary of cage measurements of RI for six types of conductor bundles in different altitude regions by using a mobile corona cage, and then the excitation function values of different bundle conductors and different altitude areas were calculated and analysed.

2 Experimental method

2.1 Introduction of test conductors and test locations

In this paper, a mobile corona cage is designed into wire-mesh enclosures, with a cross-section of 5 × 5 m and an effective length of 10 m. Six types of bundle conductors are used to measure the excitation function values under the heavy rain condition in the cage. The types of bundle conductors are given as follows: 4 × LGJ400, 6 × LGJ400, 6 × LGJ500, 6 × LGJ630, 8 × LGJ400 and 8 × LGJ630. These bundle conductors have different sizes: the subconductor diameter varies from 26.8 to 33.6 mm, whereas the bundle number alters from 4 to 8 (Table 1). The conductor spacing is set to a constant of 400 mm in this paper. The measuring frequency is 0.5 MHz, and the rate of artificial heavy rain is ~18 mm/h. The conducted RI voltage is measured by RI receiver, model FCKL 1528 m, from Schwarzbeck Mess Company in Germany.

The atmospheric pressure of different altitude may be approximated by the empirical equation [12]

$$P = P_0\left(1 - \frac{H}{k}\right) \quad (1)$$

where H is the altitude in kilometres, P_0 is the standard atmospheric pressure 101.325 kPa and k is a constant 10.7.

Besides, the relative air density is a function of temperature t (°C) and pressure P (kPa) of the air surrounding the conductor surface [12]

$$\delta = \frac{273+25}{273+t}\cdot\frac{P}{101.325} \quad (2)$$

Table 1 Relationship between conductor type and subconductor diameter unit: millimetres

Conductor type	LGJ400	LGJ500	LGJ630
subconductor diameter, mm	26.8	30	33.6

Therefore the air pressures in Wuhan (23 m), Jingyuan (1408 m), Xining (2261 m), Gonghe (2943 m) and Yangbajain (4300 m) were calculated as 101.1, 88.0, 79.9, 73.4 and 60.6 kPa, respectively. The temperatures were about 10°C, and variation range was <±6°C. Then, the relative air densities of these five locations were 1.05, 0.91, 0.83, 0.76 and 0.63, respectively. The influence of humidity can be ignored because the test was done in heavy rain condition, and the influence of temperature was much smaller when compared with the air pressure/altitude. Therefore the altitude was the major influence factor on RI level in these measurements.

The five different altitude areas are shown in Fig. 1.

2.2 Introduction of measuring method

In this paper, the conducted RI voltage was measured by a test circuit connected between the ground and the bundle, which includes a high-voltage coupling capacitor. The schematic diagram of this method is indicated in Fig. 2.

The high-voltage coupling capacitor should be chosen to meet the requirement of $C \geq 5C_{cage}$ [13], where C_{cage} indicates the capacitance between bundle conductors and the cage. In these experiments, the high-voltage coupling capacitor is assembled by using three capacitors of 10 000 pF in series to supply both the large capacitance and high withstanding voltage. The resistor R_2 is selected as 50 Ω, and the filter has an impedance of not <20 000 Ω at 0.5 MHz.

Owing to the independence from actual conductor or line configuration, the excitation function is widely used in the propagation analysis and RI level prediction for practical transmission line configurations. Therefore the RI excitation function correction factors of different altitudes were discussed in this paper. The calculation method of excitation function values is shown in [13, 14].

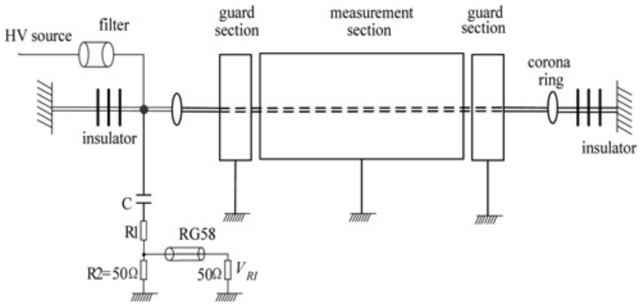

Fig. 2 *Schematic diagram of a corona cage and RI measurement system*

3 Test results and discussion

3.1 Corona inception field calculation

In the beginning, the corona inception fields of different conductors were calculated by Peek's formula [12–14], and the results are given in Table 2

$$E_{\text{onset}} = 21.9m\delta\left(1 + \frac{0.308}{\sqrt{\delta r}}\right)\ (\text{kV/cm}) \quad (3)$$

where E_{onset} is the root-mean-square (RMS) value of the corona inception field; δ is the relative density of the air; r is the subconductor radius in centimetres; m is the roughness coefficient of the conductor surface, because of the presence of water drops in the heavy rain condition, the value of m is in the range of 0.3–0.6 [12]. Before the experiments, an ultraviolet imager model CoroCAM 504 was used to detect the photon production of electric discharges on the conductor surface in heavy rain condition, which can also deduce the corona inception field of bundle conductors. By comparing the measured corona inception field values and calculated values from Peek's formula, it is found that m-value of 0.4 is more suitable for different bundle conductors to meet the actual situation better when the rain rate is ~18 mm/h. Therefore in this paper, the m-value is selected as 0.4 to calculate the corona inception field.

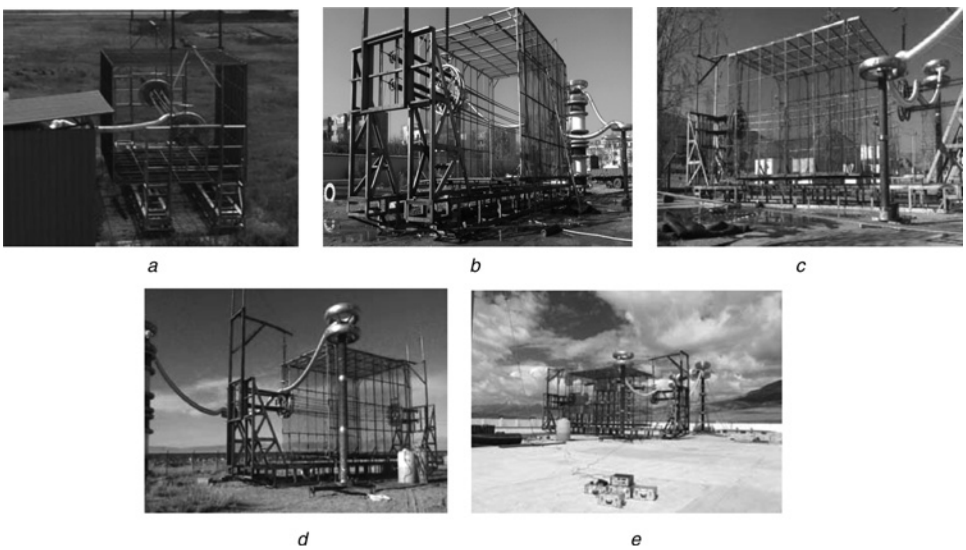

Fig. 1 *Tests at different altitude locations*

a Wuhan (23 m)
b Jingyuan (1408 m)
c Xining (2261 m)
d Gonghe (2943 m)
e Yangbajain (4300 m)

Table 2 Corona inception field of each conductor in five different locations unit: kVrms/cm

Test locations conductor types	Wuhan, 23 m	Jingyuan, 1408 m	Xining, 2261 m	Gonghe, 2943 m	Yangbajain, 4300 m
LGJ400	11.58	10.19	9.39	8.69	7.37
LGJ500	11.45	10.07	9.28	8.58	7.26
LGJ630	11.33	9.96	9.17	8.47	7.17

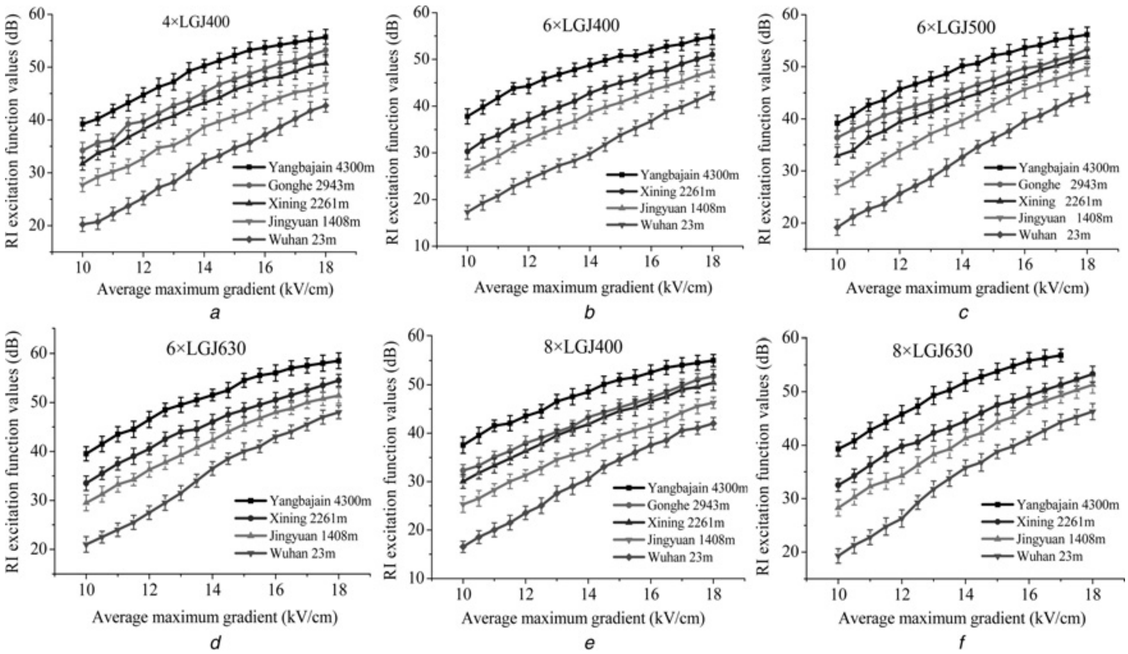

Fig. 3 *RI excitation function values with different bundle numbers and different subconductor diameters in different altitude areas*

a 4 × LGJ400
b 6 × LGJ400
c 6 × LGJ500
d 6 × LGJ630
e 8 × LGJ400
f 8 × LGJ630

3.2 Measured excitation function values of different bundle conductors and altitudes

All the measurements were carried out in heavy rain condition with different bundle conductors in different altitude areas. The results are shown in Fig. 3, where the average maximum gradient is the RMS value.

From Fig. 3, it can be seen that the altitude has a great influence on RI performance. As the altitude increases, the RI levels of all bundle conductors also increases. Besides, the RI difference in various regions displays a decreasing trend with an increasing gradient of conductor surface, which is similar with the test results in [15]. This is mainly because the corona discharge of bundle conductors is not obvious in low-altitude regions with low-potential gradient because of a higher corona inception field. However, the corona inception field is reduced in high-altitude areas [5], so the corona phenomenon is obvious in these areas in low-potential gradient. With the increase of gradient, the corona discharge becomes more severe and adequate in low-altitude areas, and the differences between high-altitude locations and low-altitude locations become smaller.

In this paper, the average maximum gradients of bundle conductors is selected from 16 to 18 kV/cm to discuss the RI performance, which is because that the gradient of transmission lines is usually designed in this range [16]. Then, the average RI excitation function values of this range with different subconductor diameters and different bundle numbers are discussed. Owing to the test conductors in Gonghe location are incomplete, the discussion of this section are just using the test data in other four locations.

The RI excitation function mean values of six-bundle conductors with different subconductor diameters and LGJ400 with different bundle numbers are depicted in Figs. 4 and 5.

In Fig. 4, the subconductor diameter is from 26.8 to 33.6 mm, and the RI level increases as the subconductor diameter increases. In Fig. 5, the influence of bundle number on RI performance is much smaller when compared with the subconductor diameter.

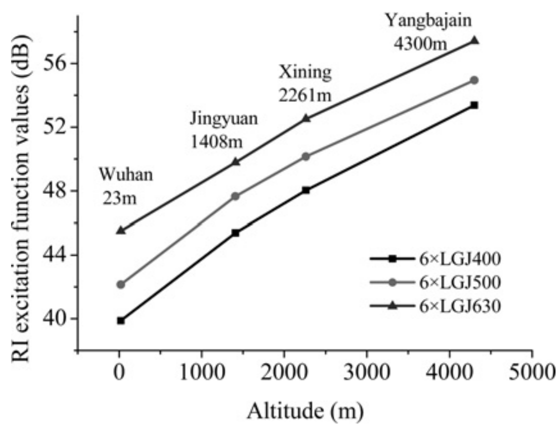

Fig. 4 *RI levels of different subconductor diameters and the same bundle number 6*

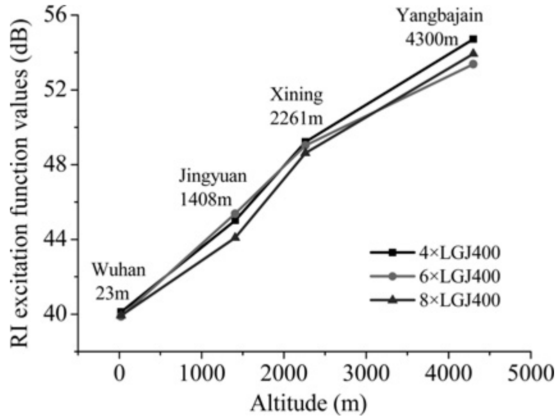

Fig. 5 *RI levels of different bundle numbers and the same subconductor diameter LGJ400*

3.3 Discussion of measured RI correction factor

The measured average RI correction values of different bundle conductors between 16 and 18 kV/cm are shown in Fig. 6. Besides, the correction factors of Italian term and Westinghouse term are also described in this figure to make a contrast with test results.

From Fig. 6, the measured average correction values fall in between Italian term and Westinghouse term when the altitude is below about 3200 m. Above 3200 m, the correction factor is less than both terms. It can also be seen that this factor is increased non-linearly, and actually, it increases more slowly when the altitude exceeds a certain extent. The phenomenon is discussed as follows.

The RI is mainly caused by the high-frequency corona current, which is mainly affected by two factors, the ion mobility K and the strength of collision ionisation near bundle conductors [12]. Therefore the influences of altitude on these two factors are analysed.

First, about the corona discharge ion mobility, it was discussed at reduced pressures in [17, 18], where the mobility value at low pressure was corrected to standard conditions (273 K and 101.325 kPa) as

$$K_0 = K \times \frac{P}{101.325} \times \frac{273}{T} \tag{4}$$

From (4), the ion mobility K increases with the decrease of atmospheric pressure P when the K_0 and temperature T keep constant. Therefore the ion mobility is increased with the increase in altitude.

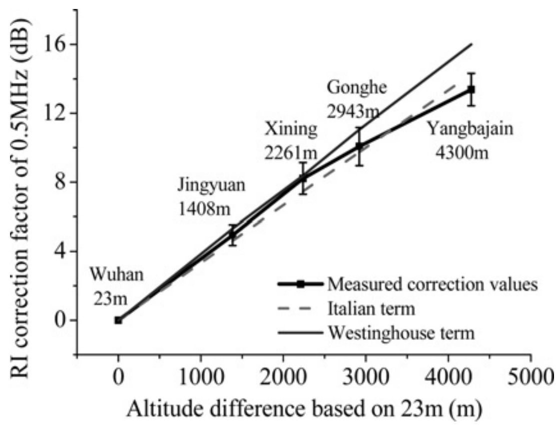

Fig. 6 *RI correction factors of different altitudes*

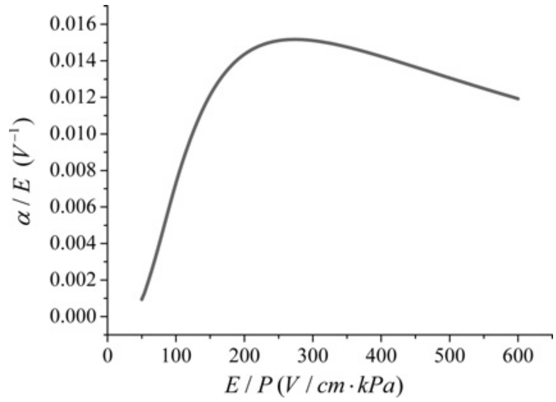

Fig. 7 *Ionisation efficiency as function of E/P*

Second, about the strength of collision ionisation, it can be represented by the collision ionisation coefficient α, which is calculated by formula (5) [19]

$$\alpha = AP\mathrm{e}^{-B(E/P)} \tag{5}$$

where $A = 11.3$ cm·kPa and $B = 274$ V/(cm·kPa).

Then, the α/E represents the ionisation efficiency, which means that the strength of collision ionisation in per voltage

$$\alpha/E = A\mathrm{e}^{-B(E/P)}/(E/P) \tag{6}$$

From (6), the ionisation efficiency is the function of (E/P), where E in volt per centimetres and P in kilopascals. The curve of this function is described in Fig. 7.

From Fig. 7, with the increase of E/P, the ionisation efficiency α/E increases first and then decreases. Therefore when the electric field E keeps constant, the strength of collision ionisation begins to increase and then decrease with increasing altitude, which is known as Stoletow effect [20].

This phenomenon is caused by two competing effects. On one hand, the energy gathered from the geometrical electrostatic field (which is taken as constant with changing pressure) raises because of the increased mean free path at reduced pressure, on the other hand, the collision number and by that the number of ionising collisions declines at reduced pressure.

Therefore because of the combination of ion mobility and strength of collision ionisation, the corona current rises more and more slowly when the pressure reduces to a certain extent. Then, the RI correction factor rises more slowly when the altitude exceeds a certain extent.

3.4 Reasonable correction term

On the basis of the measured RI correction results, neither Italian term nor Westinghouse term fits very well in more high altitude. In this paper, a correction term of formula (7) is fitted by using least mean squared error method from the test results, which is more suitable for both low altitude and high altitude areas

$$\mathrm{RI}_A = 22.8(1 - \mathrm{e}^{(-(H/5000))}) \tag{7}$$

where RI_A is the correction term in decibels and H is the altitude difference with 23 m in metres.

The comparisons of calculated correction values and tests results are shown in Fig. 8.

From Figs. 6 and 8, the Italian term and Westinghouse term are valid below 3200 m, but above this altitude, these two terms have a more error than formula (7).

IET Sci. Meas. Technol., 2015, Vol. 9, Iss. 7, pp. 861–865

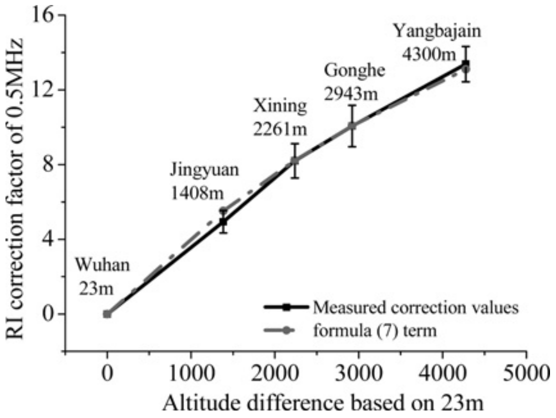

Fig. 8 *Comparison of test results and calculated results*

4 Conclusions

(1) In this paper, the RI excitation function values with different bundle numbers and different subconductor diameters were measured in five different altitude locations by using a mobile corona cage.
(2) The RI correction factor was analysed from the test results. It is found that the RI correction factor is not raised linearly with the increase of altitude, and actually it rises slowly when the altitude exceeds a certain extent, and this phenomenon is discussed qualitatively.
(3) The widely used Italian RI correction term and Westinghouse correction term are valid below 3200 m, but above this altitude, they are not applicable.
(4) An RI correction term is proposed in this paper, which is applicable for different altitude areas <4300 m, and whether or not this term can be applicable for more higher altitude regions than 4300 m should be investigated in the future.

5 References

1 Liu, Z.Y.: 'Ultra-high voltage grid. Beijing' (China Economy Press, China, 2006), pp. 2–8
2 Liu, Z.Y.: 'Electric power and energy in China' (China Electric Power Press, Beijing, China, 2012), pp. 161–176
3 Wu, X., Wan, B.Q.: 'The electromagnetic environment of power transmission project' (China Electric Power Press, Beijing, China, 2009), pp. 108–133
4 Bian, X.M., Wang, L.M., Liu, Y.P., Yang, Y.J., Guan, Z.C.: 'High altitude effect on corona inception voltages of DC power transmission conductors based on the mobile corona cage', *IEEE Trans. Power Deliv.*, 2013, **28**, (3), pp. 1971–1973
5 Liu, Y.P., You, S.H., Lu, F.C., Wan, Q.F., Bian, X.M., Wang, L.Y.: '500 kV EHV bundle conductors' corona onset voltage calculation and analysis in corona cage at different altitudes', *IEEE Trans. Power Deliv.*, 2012, **27**, (4), pp. 2090–2097
6 Barntenstein, R., Meyer de Stadelhofen, J.: 'Influence of air density on the level of radio electric interference caused by high voltage lines, report 408'. CIGRE, 1958
7 Robertson, L.M., Pakala, W.E., Taylor, E.R.: 'Leadville high-altitude extra-high-voltage test project part III – radio influence investigations', *IEEE Trans. on Power Appar. Syst.*, 1961, **80**, (3), pp. 732–743
8 Robertson, L.M., Smith, J.C., Pakala, W.E., O'neil, J.E.: 'Leadville high-altitude extra-high-voltage test project – single conductor tests', *IEEE Trans. Power Appar. Syst.* ., 1962, **81**, (3), pp. 939–943
9 IEEE Committee Report: 'A comparison of radio noise prediction methods with CIGRE/IEEE survey results', *IEEE Trans. Power Appar. Syst. Vol. PAS*, 1973, **92**, (3), pp. 1029–1042
10 Chartier, V.L., Lee, L.Y., Dickson, L.D., Martin, K.E.: 'Effect of high altitude on high AC transmission line corona phenomena', *IEEE Trans. Power Deliv.*, 1987, **2**, (1), pp. 225–237
11 Britten, A.C., Konkel, E.C.H.: 'Radio interference, corona losses, audible noise and power frequency electric fields as factors in the design of Eskom's 765 kV lines'. Proc. CIGRE Open Conf. on EHV transmission systems, 1987, pp. 3.5–3.13
12 Maruvada, P.S.: 'Corona performance of high-voltage transmission lines' (Research Studies Press, Baldock, UK, 2000)
13 Radio interference characteristics of overhead power lines and high-voltage equipment (2nd ed.), CISPR Standard 18, June 2010
14 Begamudre, R.D.: 'Extra high voltage AC transmission engineering' (New Age International Press, New Delhi, India, 2008, 3rd edn.), pp. 138–141
15 Gary, C., Moreau, M.: 'L'effet de couronne en tension alternative' (Editions Eyrolles, Paris, 1976)
16 Tang, J., Liu, Y.P., Wu, X., *et al.*: 'Effect of altitude on radio interference based on corona test cage', *High Volt. Eng.*, 2009, **35**, (3), pp. 601–606 (in Chinese)
17 Tabrizchi, M., Rouholahnejad, F.: 'Corona discharge ion mobility spectrometry at reduced pressures', *Rev. Sci. Instrum.*, 2004, **75**, (11), pp. 4656–4611
18 Hill, Jr. H.H., Siems, W.F., St. Louis, R.H.: 'Ion mobility spectrometry', *Anal. Chem.*, 1990, **62**, (23), pp. 1201–1209
19 Essam, N.: 'Fundamentals of gaseous ionization and plasma electronics [M]' (John Wiley and Sons, New York, 1971)
20 Raizer, Y.P., Allen, J.E.: 'Gas discharge physics' (Springer-Verlag, Berlin, 1991)