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Analysis of Electromagnetic Environment in 1200 kV Single Circuit UHVAC Transmission Line by using FACE Software and Semi-empirical Formulae

Satyadharma Bharti [a], Satya Prakash Dubey [b], Kapil Kumar Nagwanshi [c,*], Rania A. Turky [d], Ramesh C. Bansal [e,f], Bodhi Dharma Choubey [g]

[a] Department of Electrical Engineering, Rungta College of Engineering and Technology Bhilai, CSVTU Bhilai, India
[b] The ICFAI University Raipur, India
[c] Department of Computer Science and Engineering, ASET-Amity University Rajasthan, Jaipur, India
[d] Electrical Engineering Department, Faculty of Engineering and Technology, Future University in Egypt, Cairo, Egypt
[e] Electrical Engineering Department, University of Sharjah, Sharjah, United Arab Emirates
[f] Electrical Engineering Department, University of Pretoria, South Africa
[g] Accenture Services Pvt. Ltd., Bangalore, India

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ABSTRACT

In order to ensure efficient, bulk-power transmission over a long distance, need of increasing transmission-level voltage is being thought for the past many years. As a result, Ultra High Voltage AC (UHVAC) Transmission has appeared as a feasible solution. Many countries like Italy, Japan, USA, USSR, Brazil, China, India are developing technology for UHVAC transmission systems. Operating at 1000 kV (and above voltage level) demands careful design of transmission structure, switchgear, and equipment design. This paper presents a review of several studies carried out to analyze the electro-magnetic environment in UHVAC lines. The electromagnetic environment (Field, Audible Noise, Corona Loss, Radio Interference) of 1200 kV, Wardha-Aurangabad single-circuit transmission line, India is also evaluated using FACE (Field and Corona Effect) software. The results of the study of static AC field and magnetic field of the line are found to be within prescribed limits suggested by International Commission on Non-Ionizing Radiation Protection (ICNIRP) guidelines.

1. Introduction

Power Grid Corporation of India Ltd. (PGCIL) has developed a National Test Station (NTS) at Bina, which is operating at 1200 kV Ultra-High Voltage (50 Hz AC). This Indian project is commissioned under the supervision of PGCIL in association with Indian manufacturers, who indigenously made the equipment switchgear and accessories. This test station is equipped with the set up for one single-circuit and one double-circuit transmission line [1–4]. Power-grid has successfully commissioned a substation at Seoni (Madhya Pradesh), operating at 800 kV and the substation design of NTS Bina is generally based on the experience gained in Seoni substation [5]. The purpose of the test station is to verify the dielectric design of the ultra-high voltage equipment. Countries like Italy, USSR, US also commissioned UHV test stations [6]. At present, in China, 1000 kV UHV AC demonstration project is operative at commercial level [7]. The electromagnetic environment at this level is tested and found within prescribed limits. Right from the initial researches in the field of EHV and UHV transmission system, it has always been a point of interest to the design engineers to observe the electromagnetic environment (Field, Audible Noise, Corona Loss, Radio Interference) of the system [8–13]. Power transmission at 1200 kV level results in reduced Right of Way (ROW) in terms of MW power transmitted per metre (MW/m) of ROW,

* Corresponding author.
E-mail addresses: s.bharti@rungta.ac.in (S. Bharti), spdubeyfee@gmail.com (S.P. Dubey), dr.kapil@ieee.org (K.K. Nagwanshi), rania.turky@fue.edu.eg (R.A. Turky), rcbansal@ieee.org (R.C. Bansal), bdchoubey@gmail.com (B.D. Choubey).

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which is a major environmental issue. A comparative study of surge impedance loading (SIL), ROW and MW intensity per metre of ROW for 400 kV, 765 kV and 1200 kV and HVDC Transmission Lines is given in Table 1. Thus, reduced loss and reduced corridor width are the immediate advantages of UHV AC transmission.

Initially, when 500 kV and 750 kV extra high voltage (EHV) transmission lines were being erected in the 1960's, great interest was shown by many countries in enhancing the transmission voltage level further higher in the UHV range i.e. 1000 kV to 1500 kV AC [7]. In this context, many countries developed their UHV lines and research stations with an objective to gain technical knowledge and expertise of operating the transmission line above 1000 kV. This trend continued for next four decades. UHV transmission lines and stations were developed for experiments and study in Russia (the former Union of Soviet Socialist Republics), Japan, USA, Italy, and other countries like Canada, Brazil, China, etc. [8]. Research to develop various transmission systems above 700 kV, followed by 1000 kV are described as follows [14].

1.1. Russia (The Former USSR)

The initial study was carried out on a three-phase test transmission line with a length of 1.17 km located at the Bely Rast Substation, operated at 1150 kV. Corona performance of conductor bundles was studied. Other major studies were related with the electromagnetic environment namely audible noise (AN) level, radio interference (RI) level, electric fields in a substation. Tests of the air insulation were conducted. Experiments to determine the insulation of equipment, switching over-voltage were performed and hands-on working experience were obtained on the installation, maintenance and operation of UHV equipment [7].

1.2. Japan

Japan started UHV system study in the year 1973. The initial study included corona behavior of 8-conductor, 10-conductor, and 12-conductor bundles along with AN, RI and television interference (TVI) as well as studies of the effects of electric fields were studied. Based on the special requirement of the country, towers under storm and earthquake were examined. Construction and maintenance techniques were developed [7,15].

1.3. The USA

In USA, three separate research and test facilities were developed to assess the technical viability of transmission lines operating above 1000 kV. UHV studies were conducted at:

i. General Electric Company (GE),
ii. Bonneville Power Administration (BPA),
iii. American Electric Power Company (AEP), and
iv. Electric Power Research Institute (EPRI)

Study to estimate the long-term corona performance of an 8-conductor bundle, electromagnetic field analysis, dielectric behavior for different air-clearances was studied and the tests for pollution performance of transmission line and station insulators were carried out [7,16].

1.4. Italy

Italy also began the study on UHV transmission system in mid-1970's. A one km long 1000 kV test line was installed at Suverto for air insulation, corona studies, switching impulse behavior of air clearances and field study. Interference levels of UHV system were also examined [7,16].

1.5. Canada

At Hydro-Que'bec Institute of Research (IREQ), UHV transmission system related studies at system voltages up to 1500 kV were carried out, which includes corona and electromagnetic environment studies [7].

1.6. Brazil

A test line and a test cage were installed to analyze 1500 kV UHVAC at the research institute CEPEL in Adrianopolis, Brazil [7].

1.7. China

China began study on the UHV transmission system in 1986. A 1000 kV, 200 m long test line was constructed in 1994. At present, the system is working satisfactorily [7].

1.8. India

At NTS Bina, tests like corona measurement, radio interference and audible noise measurement, inrush current measurement, lightning impulse withstand voltage, sweep frequency response analysis (SFRA), frequency domain spectroscopy (FDS), thermovision scanning etc. are carried out for 1200 kV system [1,2]. Commissioning tests were carried out to ensure proper performance of the system and the integrity of equipment and system in grid was confirmed [2].

From the above review of UHV AC system of many countries, the conclusion can be drawn that, although the technical feasibility is approved, but further research is required in this area to make UHV transmission a global success. The power transmission at 1200 kV is a feasible and viable option. The research carried out in several countries shows that compared to power transmission at EHV level, UHV transmission supports environmental protection. The concept of smart grids is also being introduced to get reliable and efficient supply of electrical energy from generating station to the end user [17]. In recent past, many changes have been witnessed by Indian power sector to ensure its reliability [18].

2. Analysis of Electromagnetic Environment of Wardha-Aurangabad Single Circuit UHVAC Line (India)

The electromagnetic environment of 1200 kV UHVAC line is evaluated with the help of standard edition of FACE 2.0.1,

Table 1
The comparison of ROW, SIL and MW intensity per metre of ROW [3].

Parameter	400 kV AC	765 kV AC	±500 kV HVDC	1200 kV AC	±800 kV HVDC
ROW (m)	46	64	52	92	70
Capacity MW	1000	2300–2900	2000–2500	6000–8000	6000–6400
MW/m	22	45	48	87	90

a Windows™ application that predicts the field and corona effects of high voltage transmission lines [19]. It evaluates the audible noise level; radio interference level; corona loss; electric and magnetic fields of high voltage AC, DC, or AC/DC hybrid transmission lines. While predicting the performance, this also includes the effects for transmission lines operating in heavy rain (HR), wet conditions (rain), and in fair weather (FW).

Audible noise and corona losses are evaluated by using user-selectable empirical formulae developed by BPA, EPRI or IREQ. Radio interference is evaluated by the semi-analytical method. As such, the generating functions obtained experimentally by IREQ, EPRI, BPA, EdF and CIGRE are used. The frequency domain modal analysis is employed to analyze the transmission line geometries as they pertain to radio interference. Static fields are computed by the method of successive images in AC, DC, and AC/DC hybrid transmission lines. Fig. 1 gives schematic arrangement for single circuit tower (horizontal configuration) [3], where, phase spacing and conductor height above ground at tower are 24 m and 37 m, respectively [20–22]. Fig. 2 gives the snapshot showing the windows of the FACE GUI (Graphical User Interface) set for the study of single circuit line.

Table 2 gives the circuit model parameters of single circuit line, which is set for line voltage of 1150 kV, with a loading of 3800 A, corresponding to 8000 MW. The spacing between the bundled conductors of R, Y and B phases is kept 24 m. The sub conductors of 46.3 mm diameter, Bersimis ACSR conductor, having DC resistance of 0.0419Ω/km are kept 46.0 cm apart. Table 2 appears on the screen of FACE GUI showing circuit model of single circuit line in which first three line corresponds to R, Y and B phases whereas last two rows are for the ground wire, located at the top of the tower.

The technical specifications of UHV projects include their nominal operating voltage as well as highest voltage for which the equipments are designed. It is customary to name the UHV projects by their highest voltage. As such, the Indian UHVAC project is known as 1200 kV transmission system, whereas its rated (nominal) operating voltage is 1150 kV. The technical parameters being considered for 1200 kV Transmission Lines are summarized in Table 1 of their article [3]. The standard voltage and maximum voltage of the UHV Transmission system in China are described as 1000 kV and 1100 kV respectively [23].

Table 3 shows the values for conductor surface gradients (kV/cm) for single circuit line, which are found to be within the permissible limit for the conductor surface gradients 10 kV/cm for 50 Hz frequency. The static AC field distribution at the height of 1.5 m above ground level is evaluated for ROW of 92 m. The result shown in Fig. 3a clearly indicates the maximum field intensity to be less than 5 kV/m. The field strength at the extreme end of ROW is found to be 3.77 kV/m. The maximum field intensity was found to be 4.67 kV/m on either side at 31.5 m from the centre, whereas the field at the centre is found to be 2.38 kV/m. This is well below the limiting value (10 kV/m for 50 Hz) suggested as per guideline published by ICNIRP (International Commission on Non-Ionizing Radiation Protection) [20].

The value of magnetic field at the centre is found to be 184.69 mG (where, 1 milli Gauss $= 1.0 \times 10^{-7}$ Tesla). At the edge of ROW, i.e. at 46 metre from centre, its value is 99.08 mG, whereas at 54.5 metre from the centre the field intensity is reduced to 80.11 mG as shown in Fig. 3b. As per ICNIRP (International Commission on Non - Ionizing Radiation Protection), the safety limits for general public exposure for the time-varying magnetic fields, in the range of 25 Hz to 50 Hz, is 200 μ T, whereas the maximum value of magnetic field under the transmission line is obtained as 18.469 μT only (corresponds to 184.69 mG); which is well within the safe limit [24].

IEEE Std. 539™ –2005 (Revision of IEEE Std 539–1990) describes corona as a luminous discharge, which takes place due to ionization process around an electrode in the surrounding air. When the voltage gradient exceeds a particular critical value, this phenomenon takes place. Some power loss is associated with this phenomenon which is termed as corona loss. This work is based on IEEE Std 539–2005 which is active at the time of submission of the manuscript; however, for the future work IEEE approved draft P539/D6 [25] Sept 2020 version, must be referred. In overhead transmission lines, the corona loss is expressed in watts per metre (W/m) or kilowatts per kilometre (kW/km) [26].

The evaluation of corona loss, using BPA formula, as shown in Fig. 4, indicates the foul weather corona loss for rain rate of 4, 5, 10 and 15 mm/hr is found to be 138.49, 149.74, 190.85 and 219.95 W/m, respectively. Bonneville Power Administration

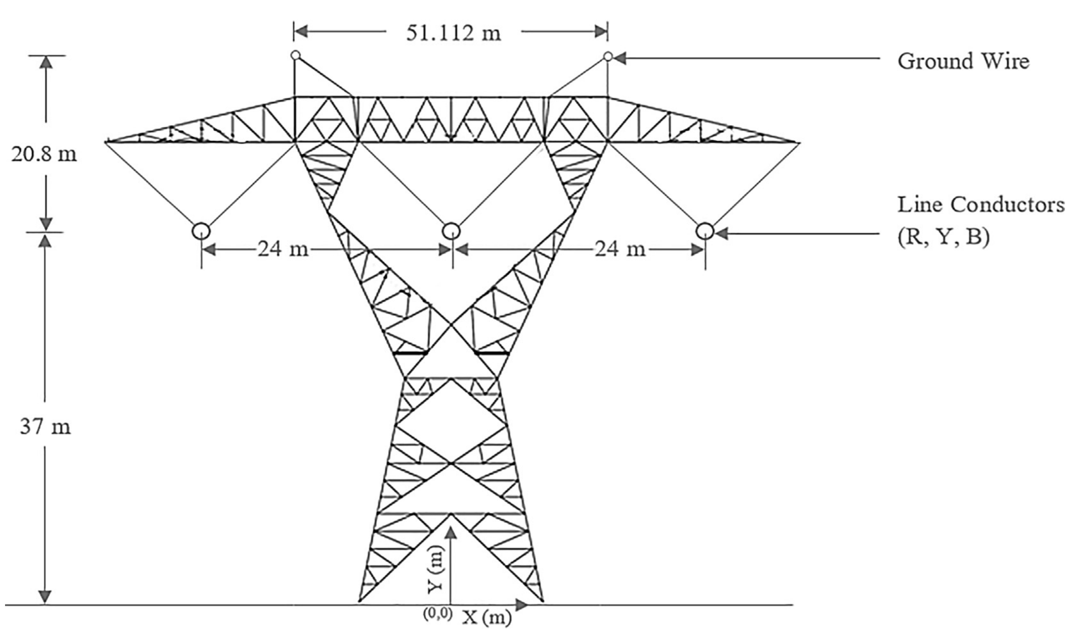


Fig. 1. Single Circuit Tower (horizontal configuration).

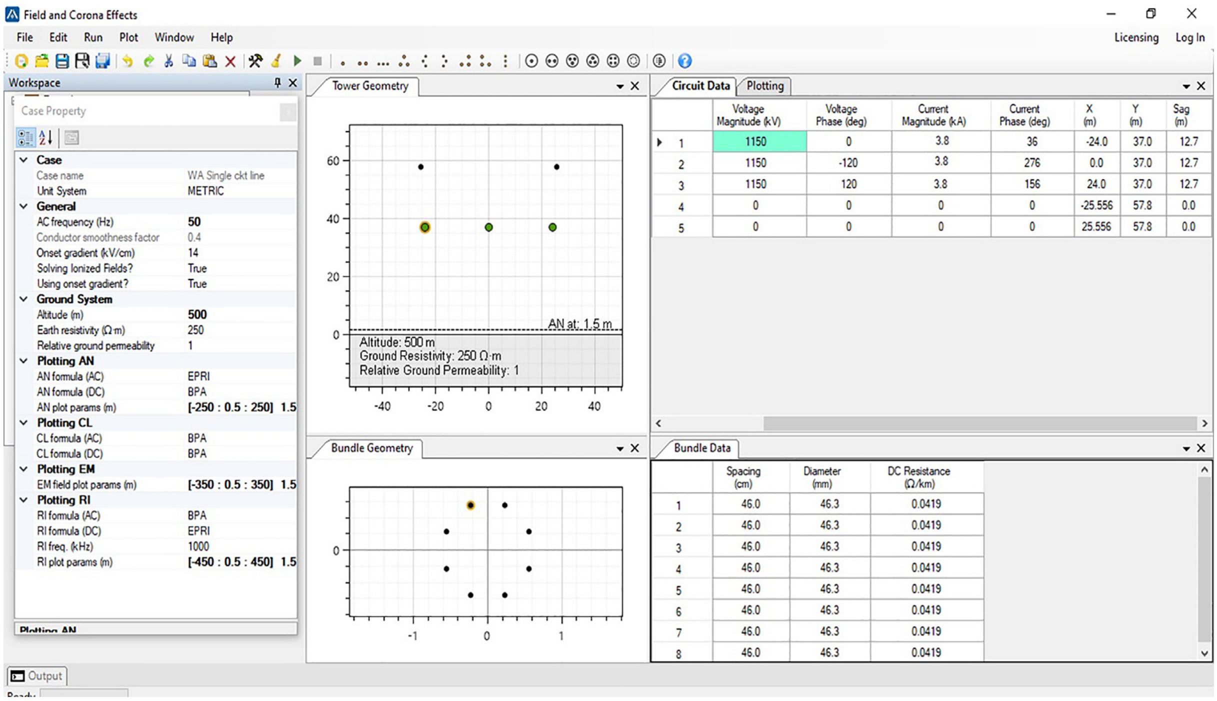


Fig. 2. Snapshot of FACE GUI, for the study of Single Circuit Line.

Table 2
Circuit model parameters of single circuit line.

Voltage Magnitude (kV)	Voltage Phase (deg)	Current Magnitude (kA)	Current Phase (deg)	X (m)	Y (m)
1150	0	3.8	36	–24	37.0
1150	–120	3.8	276	0	37.0
1150	120	3.8	156	24	37.0
0000	0	0	0	25.556	57.8
0000	0	0	0	25.556	57.8

Table 3
Average Conductor Surface Gradients (ACSG) (kV/cm) for Single circuit line.

Bundle No.	Position (x,y) (m)	ACSG (kV/cm)
1	(-24.00, 37.00)	9.00
2	(00.00, 37.00)	9.71
3	(24.00, 37.00)	9.00

(BPA) has developed the empirical formula to calculate AC corona, given below as Eq. (1) [27].

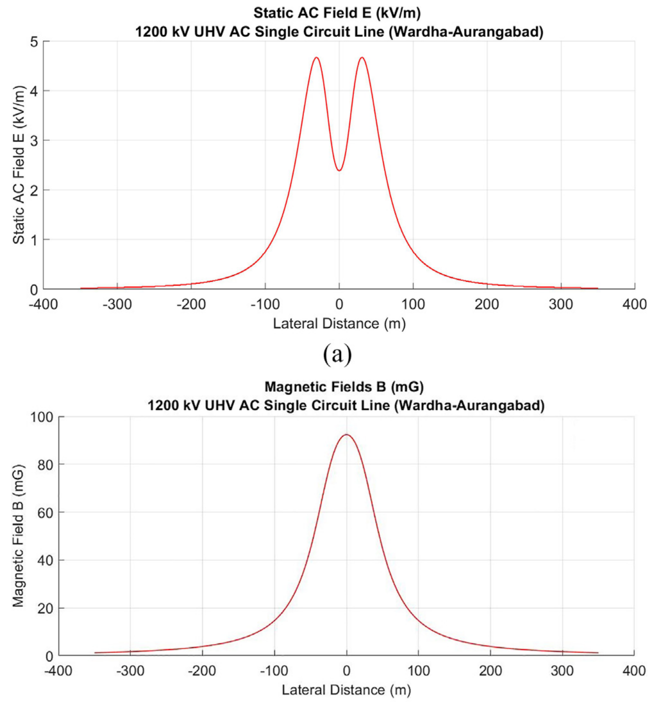
$$\begin{cases} CL_{AC} = 14.2 + 65log\left(\frac{E}{18.8\sqrt{2}}\right) + \\ 40log\left(\frac{d}{3.512}\right) + K_1 log\left(\frac{n}{4}\right) + K_2 \\ K_1 = \begin{cases} 13 & n \leqslant 3 \\ 19 & n > 4 \end{cases} \\ K_2 = \begin{cases} -17 & R = 0 \\ 10log(R/1.676) & R \leqslant 3.6 \\ 3.3 + 3.5log(R/3.6) & R > 3.6 \end{cases} \end{cases} \tag{1}$$

where, CL_{AC} represents AC corona loss in dB above 1.0 W/m, R is the Rain rate in mm/hr, n represents number of sub-conductors in a bundle, d represents sub-conductor diameter in cm, K_1, and K_2 are constants dependent on n and R, respectively, and E denotes maximum positive peak surface electric field in kV/cm.

Study of audible noise (AN) is one of the important aspects of UHV transmission line performance. Corona is the partial breakdown (ionization) of air surrounding the conductor, which takes place at high electrically stressed points on the conductor surface. These discharges produce compressions of air and acoustic waves are propagated in the free space. The portion of the acoustic energy spectrum that falls in the sonic range is called audible noise (AN). This is one of the important design factors for UHV AC transmission line.

In the FACE program, empirical formulas are employed to predict the AN of transmission lines. The term dB(A) means that the noise level is A-weighted. A normal human ear in general, responds to frequencies ranging from 10 to 3500 Hz. In air, the wavelengths of audio frequencies lie in the range of about 17 m to 17 mm corresponding to the frequency range of 20 Hz to 20 kHz [28]. Human ear can hear the highest frequency of about 20 kHz which is a very low frequency, when the entire electromagnetic spectrum is considered. Frequencies for peak sensitivity of human hearing lies in the range of 3500–4000 Hz [29]. The A-weighted level is a widely used for the noise measurement because it accounts the entire frequency spectrum of the noise but at the same time gives more weightage to the mid-frequencies (500–3000 Hz) for which a human ear is most sensitive [30]. The A-weighted curve gives more weight to those frequencies and peaks around 1080 Hz [26].

Bonneville Power Administration (BPA) has developed the empirical formula to calculate Audible Noise (AN), given in Eqs. 4



(b)

Fig. 3. (a) Static AC Field and (b) Magnetic Field evaluated for Single circuit UHVAC line.

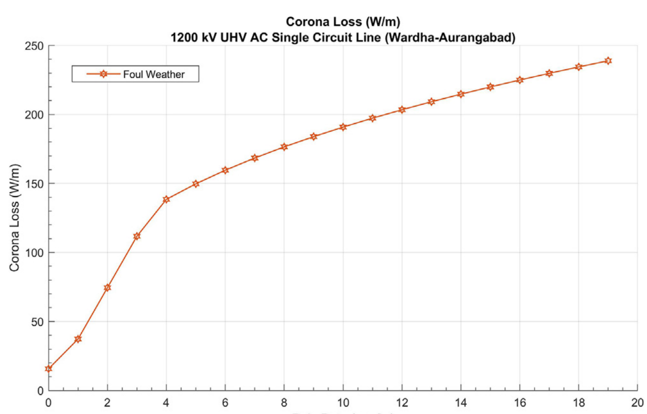


Fig. 4. Foul weather corona loss for single circuit line.

and 3 [26], Fig. 5 shows the audible noise (BPA Model) for single circuit line. The equation for calculating the AN during light rain, which results in a wet conductor and denoted as L_{50}, is as follows.

AN in heavy rain is taken at (L_5), and is given by Eq. (2).

$$AN_{HR}(L_5) = AN_{Rain}(L_{50}) + 3.5 \tag{2}$$

AN in fair weather is taken at (L_{50}), and is given by Eq. (3).

$$AN_{FW}(L_{50}) = AN_{Rain}(L_{50}) - 25 \tag{3}$$

$$\begin{cases} AN_{Rain}(L_{50}) = 81.7 + 120log\left(\frac{E_{max}}{E_0}\right) + \\ 55log\left(\frac{d_{eq}}{d_0}\right) - 11.4logD - 5.8 \\ E_0 = 16.84 \\ d_0 = 63.5mm \\ d_{eq} = \begin{cases} d & \forall n \leqslant 2 \\ 0.58dn^{0.48} & \forall n > 3 \end{cases} \end{cases} \tag{4}$$

where, AN_{xx} represents generated acoustic power in xx (dB above 1.0 μW/m, xx can be HR (Heavy Rain) or FW (Fair Weather), n depicts number of sub-conductors in a bundle, d is the sub-conductor diameter in cm, d_0 is the smallest sub-conductor diameter in cm, D denotes the bundle diameter in cm, R represents the distance from conductor to an observer point in m, while E be the maximum positive peak surface electric field in kV/cm, and E_0 is the initial surface electric field in kV/cm.

EPRI has developed the empirical formula to calculate Audible Noise (AN), as given in Eqs. (5)–(7) [31]. AN in heavy rain is taken at (L_5) and is given by Eq. (5).

$$\begin{cases} AN_{HR} = 20log(n) + 44log(d) - \\ 665/E + K_n - 10log(R) - 0.02log(R) \\ K_n = \begin{cases} 82.5 & n = 1 \\ 77.8 & n = 2 \\ 67.9 + 22.9(n-1)d/D) & n \geqslant 3 \end{cases} \end{cases} \tag{5}$$

AN in rain (wet conductor): light rain resulting in a wet conductor is taken at L_{50}, and is given by Eq. (6).

$$\begin{cases} AN_{rain} = AN_{HR} + \Delta_{rain} \\ \Delta_{rain} = k_{rain} - 14.2\frac{E_c}{E} \\ k_rain = \begin{cases} 8.2 & n < 3 \\ 10.4 & n \geqslant 3 \end{cases} \end{cases} \tag{6}$$

AN in fair weather is taken at L_{50}, and is given by Eq. (7).

$$\begin{cases} AN_{FW} = AN_{HR} + \Delta_{FW} \\ \Delta_{FW} = 8.2 - 14.2(E_c + 10) \\ E_c = \begin{cases} \frac{22.4}{d^{0.24}} & n \leqslant 8 \\ \frac{22.4}{d^{0.24}} - 0.25(n-8) & n > 8 \end{cases} \end{cases} \tag{7}$$

Fig. 6 shows the audible noise (EPRI Model) for single circuit line. The IREQ model for AC circuits has three separate formulas based on the precipitation levels in an area. The empirical formulae to calculate Audible Noise (AN), based on IREQ rain formula with correction factors added, are given in Eqs. (8)–(10) [31]. Fig. 7 shows the audible noise (IREQ Model) for single circuit line. AN in light rain resulting in a wet conductor is taken at L_{50}, and is given by Eq. (8).

$$\begin{aligned} AN_{rain}(L_{50}) &= 72logE_{max} + 22.7log(n) \\ &+45.8log(d) - 57.6 - 11.4log(D) \end{aligned} \tag{8}$$

AN in Heavy Rain: Heavy Rain (HR) is taken at L_5, and is given by Eq. (9).

$$AN_{HR}(L_5) = AN_{rain}(L_{50}) + 3.5 \tag{9}$$

AN in Fair Weather: Fair weather is taken at L_{50}, and is given by Eq. (10).

$$AN_{FW}(L_{50}) = AN_{HR}(L_5) + 25 \tag{10}$$

Figs. 8–10, are useful for comparative study of Audible Noise for three different rain conditions, as the AN level evaluated by BPA, EPRI and IREQ models are plotted on a single graph. The fourth curve showing the mean value of the results obtained by all the three methods is also plotted. It is observed that the AN level in fair weather conditions is much lower than that in the rain.

Table 4 is an outcome of evaluation of audible noise is an outcome calculated by various formulae developed by Bonneville Power Administration (BPA), Quebec Electricity Research Institute (IREQ) and Electric Power Research Institute (EPRI) projects. On comparative study of the results of Table 4 audible noise, obtained from different formulae used for BPA, IREQ or EPRI projects, variation is observed in the obtained values of AN for same values of the input variables. Table 5 gives a comparison of the results obtained

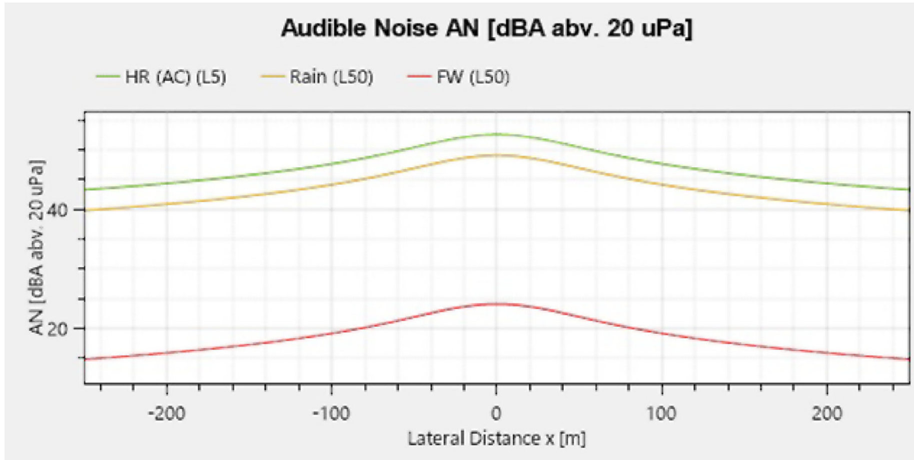


Fig. 5. Audible noise (BPA Model) for single circuit line.

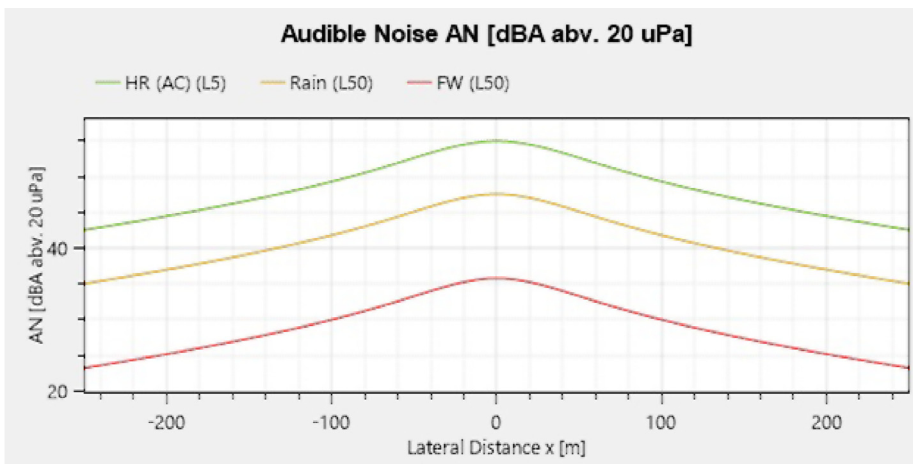


Fig. 6. Audible noise (BPA Model) for single circuit line.

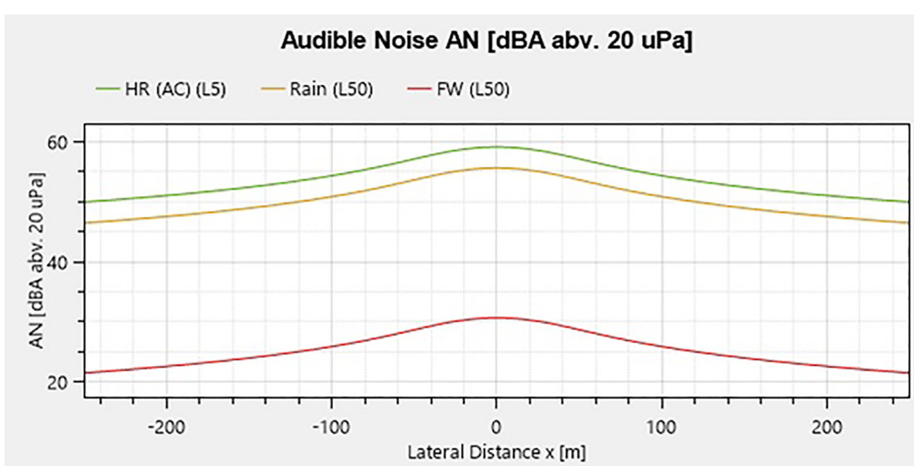


Fig. 7. Audible noise (IREQ model) for single circuit line.

under different weather conditions. The last column of the table indicates the average value of variation in audible noise between higher and lower values.

It is not the intention of the paper to recommend the use of a particular method over the other. This comparison indicates that a variation exists in results using different formulae which consider many variables namely weather condition, number of sub-conductors in a bundle, sub-conductor diameter, bundle diameter, distance from conductor to an observer point. Apart from this, sight difference in the value of conductor surface gradient in differ-

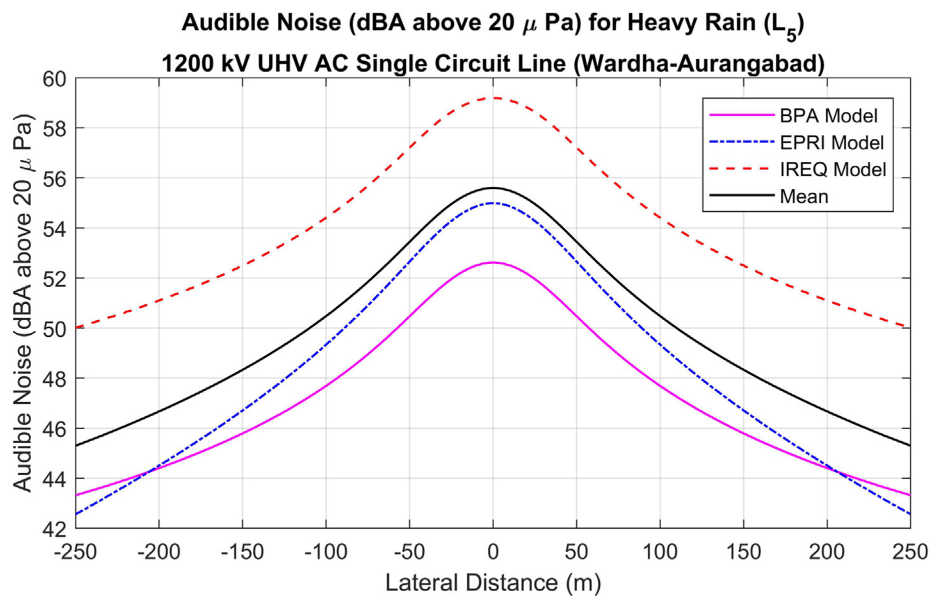


Fig. 8. Audible Noise for Heavy Rain (L_5) Condition.

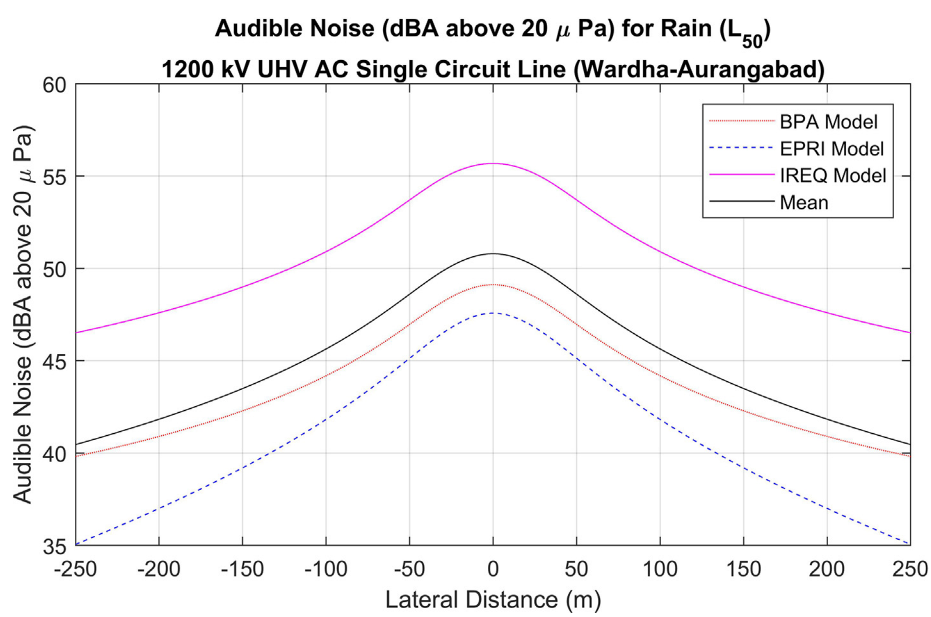


Fig. 9. Audible noise for rain (L_{50}) condition.

ent methods may also lead to variation in the calculated results. Similar study is carried out by a Task Force of the Corona and Field Effects Subcommittee, in which nine methods were applied to a variety of eighteen different line configuration for operating voltage in the range of 525 kV- 1450 kV. These nine methods include American Electric Power (AEP), Ontario Hydro, Bonneville Power Administration (BPA), Central Research Institute of Electric Power Industry Japan (CRIEPI), Electricite de France (EdF), Ente Nazionale per L'Energia Elettrica Italy (ENEL), FGH Germany, General Electric Company (Project UHV), and Hydro Quebec-Institute of Research (IREQ). The deviation between calculated and measured noise levels for different methods is tabulated in literature [32]. The possible reason for the deviation are also discussed.

A comparative study of the corona performance of conductor bundles for 1200 kV transmission lines at IREQ [33] highlights that the primary constraint will most likely be the audible noise at this voltage level (1200 kV). An acceptable criterion at Hydro-Quebec for audible noise is about 60 dB above 2^{-5} N/m^2 at 100 feet from the outside phase. Accordingly, the last set of the evaluation of Audible noise is made at 30.5 m (100 feet) away from the outer phase conductor and all the values are found to be within the limit [34].

Radio Interference : While designing a transmission line operating at UHV level of 1200 kV, factors like conductor, number of sub conductor, bundle diameter, tower configuration, clearances, sag span, weather condition are considered to keep the corona loss, audible noise, radio interference within the permissible limits. Table 6 shows the evaluation of Radio Interference (Above 1.0μ V/m), observed at 1.5 m

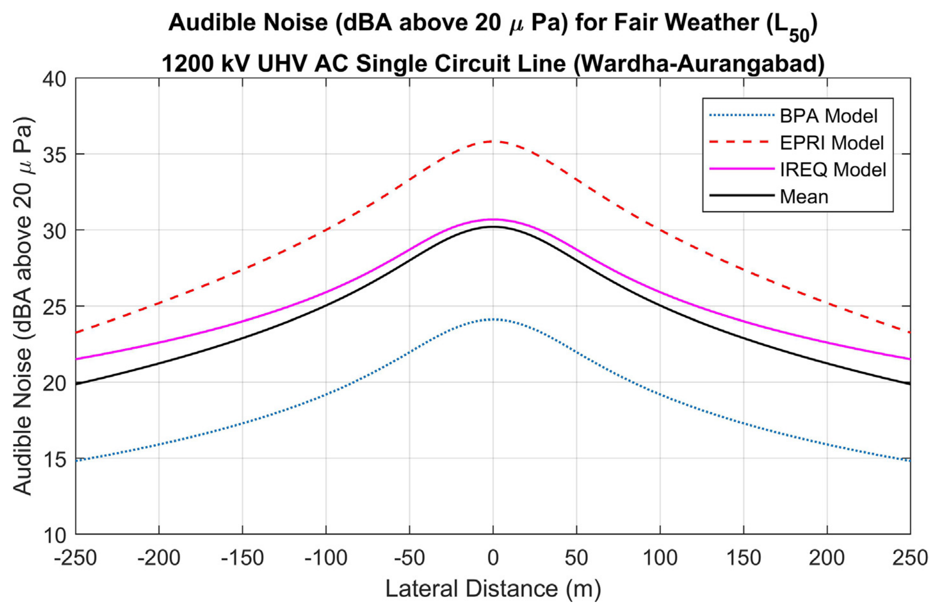


Fig. 10. Audible noise for fair weather (L_{50}) condition.

Table 4
Evaluation of Audible Noise (dBA above 20 μPa).

Point of measurement	Rain type	BPA Model	EPRI Model	IREQ Model
At the tower base centre	HR L_5	52.62	54.99	59.18
At the tower base centre	RainL_{50}	49.12	47.58	55.68
At the tower base centre	FWL_{50}	24.12	35.81	30.68
At the edge of ROW	HR L_5	50.73	52.94	57.46
At the edge of ROW	RainL_{50}	47.23	45.42	53.96
At the edge of ROW	FWL_{50}	22.23	33.60	28.96
At 30.5 m from outer phase	HR L_5	50.18	52.33	56.92
At 30.5 m from outer phase	RainL_{50}	46.68	44.81	53.42
At 30.5 m from outer phase	FWL_{50}	21.68	32.99	28.42

Table 5
Comparison of the Audible Noise with BPA, IREQ, and EPRI formulae.

Weather Condition	BPA Model	IREQ Model	EPRI Model	Variation
Fair Weather (L_{50})	Lower	Moderate	Higher	10.33 dB
Rain (L_{50})	Moderate	Higher	Lower	9.55 dB
Heavy Rain (L_5)	Lower	Higher	Moderate	6.69 dB

height from ground level. The RI level for Wardha-Aurangabad UHV line is evaluated using GUI based application software FACE, using five different models namely BPA, EPRI, IREQ, EdF and CIGRE. RI computations are conducted by an advanced semi-analytical method, where generating functions obtained experimentally are utilized and the frequency domain model analysis is implemented. The study is performed for three different weather conditions defined by IEEE. These conditions are: heavy rain (L_1), rain (L_{50}), and fair weather (L_{50}) (FACE Online Help [27]).

Fair weather : The weather condition when the precipitation intensity is zero and the transmission line conductors are dry.

Rain : Precipitation in the form of liquid water drops with diameters greater than 0.5 mm or, if widely scattered, smaller diameters. The rainfall is categorized as follows:

- Very light rain - When the rain drops are scattered and do not result in achieving completely wet condition of the conductor surface, irrespective of the duration of exposure.
- Light rain - the rainfall rate up to 2.5 mm/h is considered as light rain.
- Moderate rain- from 2.6 mm/h to 7.6 mm/h, and
- Heavy-over 7.6 mm/h [35].

Figs. 11–13, show the graphical display of radio interference for heavy rain (L_1), rain (L_{50}), and fair weather (L_{50}) respectively; which

Table 6
Evaluation of radio interference (above $1.0\mu V/m$), at 1.5 m height.

Rain Type	Model	At centre	At edge of ROW(46 m)	At 30.5 m from outer phase
HR (L_1)	BPA	80.40	71.98	70.51
HR (L_1)	EPRI	88.39	79.98	78.50
HR (L_1)	IREQ	84.29	75.87	74.40
HR (L_1)	EdF	80.47	72.05	70.58
HR (L_1)	CIGRE	81.32	72.90	71.43
Rain (L_{50})	BPA	72.40	63.98	62.51
Rain (L_{50})	EPRI	79.45	71.03	69.56
Rain (L_{50})	IREQ	76.29	67.87	66.40
Rain (L_{50})	EdF	72.47	64.05	62.58
Rain (L_{50})	CIGRE	73.32	64.90	63.43
FW (L_{50})	BPA	55.40	46.98	45.51
FW (L_{50})	EPRI	62.45	54.03	52.56
FW (L_{50})	IREQ	59.29	50.87	49.40
FW (L_{50})	EdF	55.47	47.05	45.58
FW (L_{50})	CIGRE	56.32	47.9	46.43

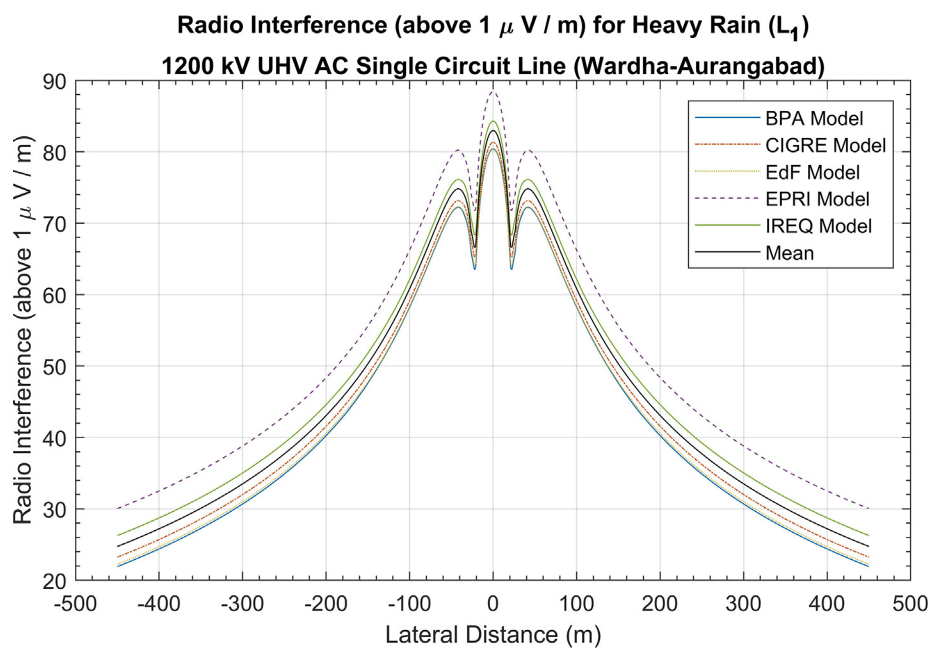


Fig. 11. Radio interference for heavy rain (L_1) condition.

are evaluated at 1.5 m above ground level, by using five models namely BPA, EPRI, IREQ, EdF, and CIGRE. Radio interference for heavy rain is found to be 25–26 dB more than that for fair weather radio interference value. The radio interference for fair weather is found to be 16–17 dB less than that in light rain condition. The similar results were found on actual field measurements of radio interference, made on China UHVAC line, where the difference of 16–19 dB was observed for fair weather and foul weather (light rain) condition [27,36].

3. Environmental Considerations of Other Projects (Outside India)

3.1. Corona performance

Environmental considerations have always been the main focus of studies of UHV AC transmission. As per reference [37], which is significant literature describing the 6-Years experience of a 1200 kV Transmission Line Test and Development Program at the Bonneville Power Administration, an extensive test and evaluation program was launched to study the performance of 1200 kV system, equipment, and accessories. Electric field effect and environmental impact were carefully observed in accordance with CIGRE guidelines.

Electromagnetic environment study deals with corona loss, RI and AN, Table 7 presents conductor corona performance for Lyons test line and typical BPA 550 kV line. Foul weather L_{50} levels for AN, RI TVI and CL are shown together with fair weather RI. The investigation for AN and RI was made at 15 m from the outer conductor and TVI at 40 m [37].

The test result indicates that a reduction from 8 to 7 subconductors in the bundle will increase AN by 3 dBA and RI by 12 dB. The TVI is found relatively unaffected by the conductor configuration as it caused by insulator and hardware corona. Extra High and Ultra High voltage substations use three different types of switchgear namely, (i) Air Insulated Switchgear; (ii) Gas Insulated Switchgear; and (iii) Hybrid Gas Insulated Switchgear. Radio interference due to corona discharge of conductor and fittings is much severe in air insulated switchgear [8].

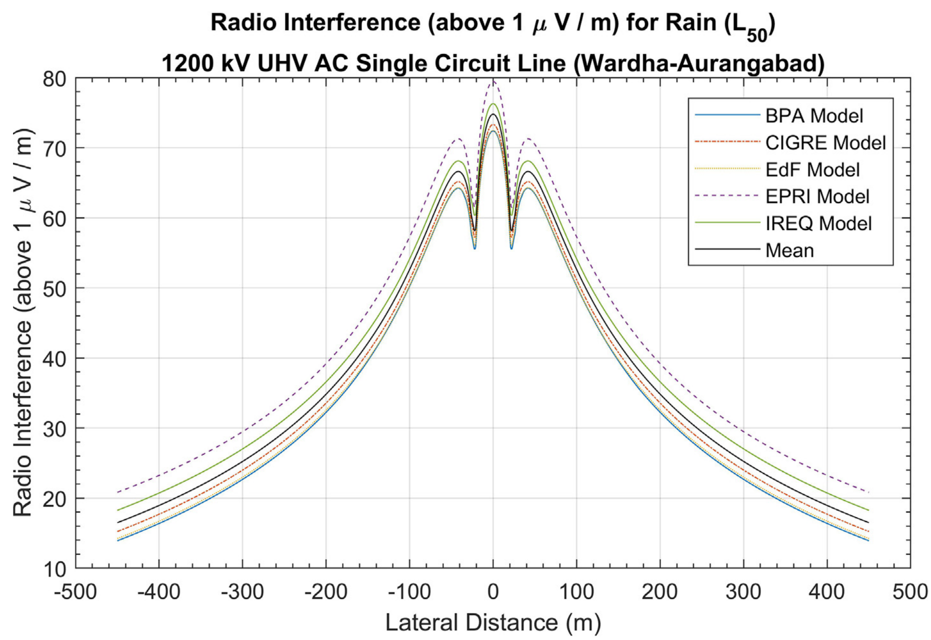


Fig. 12. Radio interference for rain (L_{50}) condition.

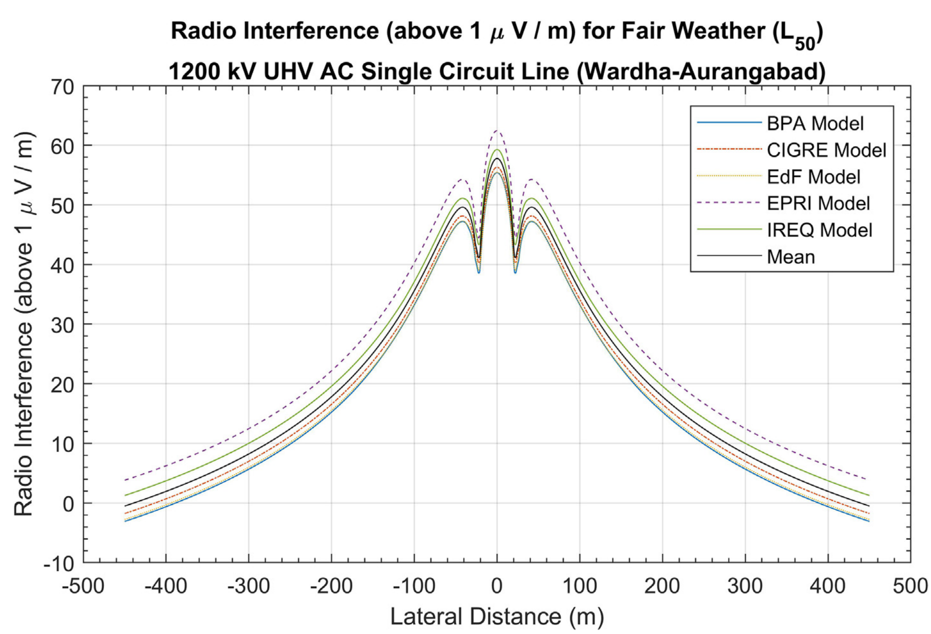


Fig. 13. Radio interference for fair weather (L_{50}) condition.

Table 7
Corona Performance of conductor for Lyons test line (1150 kV) and BPA (550 kV) line.

Parameter	8 × 41 mm bundle of Lyons UHV line	7 × 41 mm bundle of Lyons UHV line	2 × 41 mm bundle of BPA single circuit line	3 × 33 mm bundle of BPA single circuit line
Operating Voltage (kV)	1150	1150	550	550
AN: dBA	53	56	56	46
RI: QP 0.5 MHz (dB/μV/m) Fair/ Foul	46/65	58/77	52/70	46/68
TVI: QP 75 MHz (dB/μV/m)	13	12	27	24

Corona cage studies were performed at UHV test lab at Central Power Research Institute Hyderabad, India through a corona cage having size of 6.1 m (H) × 6.1 m (W) × 21 m (L). A 18 m long insulated section with two end sections of 1.5 m having corona shield and end fittings connected at both ends was used to carry out the study. Bundle of Eight-Bersimis ACSR conductors were used and the study was carried out with sub- conductor spacing of 350 mm, 450 mm and 550 mm for two precipitation rates of 57 mm/hr and 85 mm/hr. During the study, Corona Inception Voltage, Corona loss, AN & RIV were measured and based on that conductor surface voltage gradients (Ec), conductor surface factor (m) were determined. The results of field test are tabulated in Table 6 of article written by Nayak et al. [3].

The Chinese National Standard suggests the limit of radio interference arising due to an AC high voltage overhead transmission lines (GB15707-1995). According to the standard, the value of radio interference (RI) should be exceeded above 55 dB (dB/μV/m) when measured at a point located 20 m away from the outer phase of the UHV AC line, under fair weather condition [36]. Tables 8–10, indicate the RI of 1000 kV China Project measured in the vicinity of UHVAC substations namely Jing Dongnan GIS substation, Nay Yang HGIS substation and Jing Men HGIS substation. These RI levels are within the safe limit. All the measurements are carried out at a distance of 20 m from the point of measurement shown in Tables 8–10, at a frequency of 0.5 MHz.

3.2. Study of UHV AC system on Environment

Prior to energizing 1200 kV line at BPA (US), series of studies involving trees, shrubs, crops, wildlife, cattle, honey-bee, plants, animals, birds, etc. were performed. Apart from this, biological effects of electric field as well as magnetic field in the vicinity of line corridor were investigated in many countries, time to time; however, no substantial evidence of ill effect on plants, animals and humans was established [37,38].

3.2.1. Vegetation studies

For study of the effect of 1200 kV on trees, shrubs, etc., they were intentionally left growing in the vicinity of the UHV line. The comparisons were made with the other plants of the same variety located away from the line. Damage was observed in the branches of trees having sharp needles. A slight burning effect at the tip was noted but no tree was severely damaged by electric field. The effect of damage at the sharp points was due to concentration of electric field at those points. Trees and plants with long sharp leaves up to 20 m away from the conductor have shown slight damage. The test studies on trees and plants found that the damage in the form of burning of leaf tip is appreciable when the associated field is stronger than 15–20 kV/m. It was also found that no effect was detected on the shrubs growing in 8–10 kV/m electric field.

3.2.2. Wildlife studies

Small mammals and birds inhabiting the 1200 kV corridor of BPA project were studied for five years. No specific pattern was indicated in birds and small animals. Study of biological and behavior effects were found to be within normal limits and no noticeable change was observed.

3.2.3. Honeybee studies

This was also the part of BPA project to study the behavior of honey-bee. Clear indications were reflected that the honey-bee colony can be adversely affected if located near 1200 kV UHV transmission line. Effects include increased propolization, increased irritability of the bees, reduced honey production and increased colony mortality. Induced current inside the hive seems to be responsible for this effect.

Table 8
RI measurement Jing Dongnan GIS substation [8].

Point of Measurement at 20 m away from:	RI (dB/ μV/m)
North fence of the substation	48.3
East fence of the substation	42.0
West fence of the substation	43.1
South fence of the substation	37.8

Table 9
RI measurement Nay Yang HGIS substation [8].

Point of Measurement at 20 m away from:	RI (dB/ μV/m)
North fence of the substation	32.2
East fence of the substation	37.6
South fence of the substation	47.7
West fence of the substation	35.4

Table 10
RI measurement Jing Men HGIS substation [8].

Point of Measurement at 20 m away from:	RI (dB/ μV/m)
North fence of the substation	38.8
West fence of the substation	34.6
South fence of the substation	38.4
East fence of the substation	33.1

3.2.4. Cattle studies

This was designed to investigate the change in grazing or drinking behavior if the electric field is 12 kV/m or AN of the order of 55 dB. It was observed that the cattle spent less time near the line when it is charged, compared to when it is de-energised. Considering very limited or no noticeable effect on the environment, Secondary Utilization of Facilities and Properties Program came under consideration. proposals are being worked out, to make use of corridor for natural sites, bicycle paths, sports arenas, community gardens, mini-golf courses, and parking lots [37].

4. Conclusion

At the outset, the paper presents a review of the study for an electromagnetic environment of major UHV projects. Research and development is going on, on the advancement in 1200 kV UHV-AC transmission Line. The electromagnetic environment of 1200 kV, Wardha-Aurangabad single-circuit transmission line, India is evaluated using FACE (Field and Corona Effect) software; which is useful to evaluate static AC field, magnetic field, conductor surface gradient, corona loss (using BPA Formula) of the line. It is also useful to evaluate to study audible noise (using EPRI, IREQ, BPA Formulae) and radio interference (using EPRI, IREQ, BPA, EdF, CIGRE Formulae) for different rain conditions. The results of the study of average static AC field and magnetic field of the line are found to be within prescribed limits suggested by International Commission on Non-Ionizing Radiation Protection (ICNIRP) guidelines. The values for conductor surface gradients for single circuit line are found to be 9.0 kV, 9.71 kV, and 9.0 kV for R, Y, B Phases. The maximum field intensity is found to be less than 5 kV/m. The field strength at the extreme end of ROW is found to be 3.77 kV/m. The maximum value of magnetic field under the transmission line is obtained as 18.469 μT. Corona loss of the line is also evaluated for different rain rate. The audible Noise and radio interference results of the study are in line with the values suggested by CIGRE working group B3.22 guidelines for technical requirements for substation exceeding 800 kV and other existing UHV projects.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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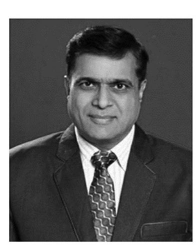
Satyadharma Bharti is presently working as an Associate Professor in Department of Electrical Engineering at faculty of Rungta College of Engineering and Technology, Bhilai. He received degree of B.E. (Electrical Engineering) in 1990 from Rani Durgawati Vishwavidylaya Jabalpur, and Master of Technology in 2007 from Pt. Ravishankar Shukla University Raipur. He has obtained Ph.D. from Chhattisgarh Swami Vivekananda Technical University, Bhilai, India in 2020. His research interests include High Voltage Engineering, Electrical Machines and Power system. He has 26 + years of teaching experience in Electrical Engineering courses in both undergraduate and postgraduate. He supervised 20 ME scholar theses, published over 36 articles in peer-reviewed journals and conferences.



Satya Prakash Dubey has received his Bachelor of Electrical Engineering from Government Engineering College (now National Institute of Technology) Raipur, India, in 1995. He completed his Master in Engineering (Power Apparatus & Electrical Drives) from Indian Institute of Technology, Roorkee, India in 2000. He obtained Ph.D. Degree from Birla Institute of Technology and Science, Pilani, India in 2006. Currently, he is serving as a Vice-Chancellor at The ICFAI University Raipur, India. His current Research include Power Converters, active filtering, power conditioning, AC and DC drives, neural network and fuzzy logic-based controller design for electrical Drives, High Voltage, Genetic Algorithm technique for inductor capacitor filter design.

Kapil Kumar Nagwanshi received the B.E.. degree (Hons.) from Guru Ghasidas Central University, Bilaspur, in 2001, and the M.E.. degree in computer technology and application and the Ph.D. degree from Chhattisgarh Swami Vivekanand Technical University (CSVTU) Bhilai, in 2008 and 2019, respectively. He is currently an Associate Professor with ASET Amity University Rajasthan, Jaipur, India. His primary domain of teaching and research includes the Internet of Things, digital image processing, cyber forensics, data science and engineering, AI, and computer networking.

Rania A. Turky received the B.Sc. and M.Sc. degrees in electrical power engineering from the Faculty of Engineering, Ain Shams University, Cairo, Egypt, in 2004 and 2010, respectively, where she is currently pursuing the Ph.D. degree. Her research interests include modern control techniques, power systems dynamics and control, energy storage systems, renewable energy systems, and smart grid.

Ramesh C. Bansal is currently a Professor with the Department of Electrical Engineering, University of Sharjah, and an Extraordinary Professor at the University of Pretoria (UP), South Africa. Previously, he was a Professor and the Group Head (Power) with the ECE Department, UP. Prior to his appointment at UP, he was employed by the University of Queensland, Australia; The University of the South Pacific, Fiji; BITS Pilani, India; and Civil Construction Wing, All India Radio. He has more than 25 years of diversified experience of research, scholarship of teaching and learning, accreditation, industrial, and academic leadership in several countries. He has significant experience of collaborating with industry and government organizations. These utilities include NTPC (a 60 GW Indian power generation company), Powerlink, and ESKOM. He has made significant contribution to the development and delivery of B.S. and M.E. program for utilities. He has extensive experience in the design and delivery of CPD program for professional engineers. He has carried out research and consultancy and attracted significant funding from industry and government organizations. He has published over 350 journal articles, presented papers at conferences, books, and chapters in books. He has Google citations of over 12000 and H-index of 50. He has supervised 25 Ph.D. and four postdoctoral students. His diversified research interests include renewable energy (wind, PV, DG, and micro grid) and smart grid., Prof. Bansal is a fellow and a Chartered Engineer of IET, U.K., and a fellow of the Institution of Engineers, India. He is an Editor of several highly regarded journals, such as IET-RPG and IEEE Systems Journals.

Bodhi Dharma Choubey has obtained B.E. Electrical Engineering Degree from Chhattisgarh Swami Vivekananda Technical University, Bhilai, India in 2017. Currently he is working in Accenture Solutions Pvt. Ltd. as a Senior Software Analyst (Telecommunication Projects & Maintenance Coordinator & FTTX, Fiber Roll Out Planning & Projects, O&M, Rectification in Telecommunication Sector).