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Evaluating Radio Interference and Audible Noise For 400 KV EHVAC And 500 KV HVDC Hybrid Horizontal Single Circuit Transmission Line Using FACE Software and Semi-Empirical Formulae

***Abstract*—**In order to ensure efficient, bulk-power transmission over a long distance, need of increasing transmission infrastruc- ture is being thought for the past many years. Many countries like China, South Afrika, Italy, Japan, USA, USSR, Brazil, China are developing technology for EHVAC-HVDC Hybrid transmission systems. Operating at 400 kV for EHVAC and 500 kV for HVDC demands careful design of transmission infrastructure, switchgear, and other equipment design. This paper analyses the RI and AN electromagnetic environment of a hybrid transmission line comprising 400 kV EHVAC and 500 kV HVDC. The study uses FACE software including EPRI, IREQ. EdF, BPA etc equations to evaluate the audible noise and radio interference. The results provide insights into the combined effects and interactions within the hybrid system, highlighting the advantages and challenges of integrating both AC and DC transmission technologies. The results of the study of static field and magnetic field of the hybrid line are also found to be within prescribed limits suggested by International Commission on Non- Ionizing Radiation Protection (ICNIRP) guidelines.

***Index Terms*—**component, formatting, style, styling, insert

I. INTRODUCTION

The need for efficient power transmission systems has never been more critical. As the demand for electricity continues to rise globally, driven by population growth, urbanization, and the increasing penetration of renewable energy sources, the limitations of traditional power transmission methods are becoming more apparent. To meet these challenges, innovative approaches such as hybrid transmission lines, which com- bine Extra High Voltage Alternating Current (EHVAC) and High Voltage Direct Current (HVDC) technologies, are being explored. This paper investigates the Radio Interference and Audible Noise for 400 kV EHVAC and 500 kV HVDC Hybrid Horizontal Single Circuit Transmission Line. 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.

TABLE I THE COMPARISON OF ROW, SIL AND MW INTENSITY PER METER 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

This paper is structured as follows: The Background section provides a comprehensive overview of EHVAC and HVDC technologies, highlighting their historical development and key applications. The Methodology section details the analytical methods and FACE as a simulation tool used to evaluate the electromagnetic environment of the hybrid transmission line. The Simulation Parameters and Set-Up section describes the specific parameters and configurations used in the analysis. The Electromagnetic Environment Analysis section presents a detailed examination of the electric and magnetic fields, corona effects, audible noise, and radio interference generated by the hybrid system. The Results section provides the findings of the simulations, comparing the performance of the hybrid system to standalone EHVAC and HVDC lines. The Discussion sec- tion interprets the results, addressing the technical challenges and potential benefits of hybrid transmission lines. Finally, the Conclusion summarizes the key insights of the study and suggests areas for future research. By investigating the electromagnetic environment of a hybrid 400 kV EHVAC and 500 kV HVDC transmission line, this paper aims to contribute to the development of efficient and reliable power transmission systems that can meet the growing demands of modern power grids.

II. ANALYSIS OF RI AND AN FOR DIFFERENT HYBRID TRANSMISSION LINE (INDIA)

The electromagnetic environment of 400 kV EHVAC and 500 kV HVDC line is evaluated with the help of standard edition of FACE 2.0.1 software a Windows application that predicts the field and corona effects of high voltage trans- mission lines [19]. It evaluates the audible noise level; radio interference level of AC/DC hybrid transmission lines. While predicting the performance, this also includes the effects for transmission lines operating in heavy rain (HR), wet

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conditions (rain), and in fair weather (FW). In order to analyse hybrid dc/ac transmission lines, an understanding of the engineering of the ac and dc lines, and of interactions between the ac and dc circuits is needed. Since both ac and dc power transmission are complex electro-magnetic systems, the range of possible interactions is vast. Therefore, the analysis framework has been limited to those interactions which have the largest effect on the environmental and technical performance of the lines, and which will have the most significant impact on engineering design of the hybrid dc/ac line.

A. Engineering of ac lines

Typical ac transmission lines are shown in figure 3.1. The design of ac transmission lines consists of electrical, mechanical, structural, and civil engineering of many sub- systems and components. From the perspective of this thesis, the main interest is the electrical engineering, and specifically the electrical performance characteristics of an ac overhead transmission line.

- Power transfer capability.
- Insulation performance for operating voltages, switching over voltages, and lightning over voltages.
- Corona performance, which affects audible noise, radio interference, and corona power losses.
- Electric and magnetic fields at ground level.
- Coupling and interactions during fault conditions.

B. Engineering of dc lines

The majority of the electric power transmission and distri- bution in the world is done using ac transmission lines and cables. Largely, this is due to the invention of the power transformer in the late 19th century, which allowed the voltage at which the power is transported to be changed easily, and thereby allowed the losses incurred to be reduced without increasing the cost and complexity of electrical machinery in factories and homes [34]. Nevertheless, there are circum- stances when it is economically or technically preferable to use dc transmission lines and cables for transmission and distribution of electric power.

III.MATHEMATICAL MODELLING FOR AUDIBLE NOISE

Study of audible noise (AN) is one of the important aspects of Hybrid transmission line performance. Corona is the partial break- down (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 lie in the range of 3500–4000 Hz [29]. The A-weighted level is widely used for noise measurement because it accounts for 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].

A. Audible Noise calculations

To allow for a wider range of studies, multiple calculation standards are available to choose from when calculating AN. AC AN can be calculated using Bonneville Power Administra- tion (BPA), IREQ or Electric Power Research Institute (EPRI) models, while DC AN can be calculated using BPA or IREQ models.

B. Audible Noise in AC Transmission Lines

AN in-AC lines can be calculated using BPA, IREQ or EPRI models. The following describes how each standard approaches the equation. It should be noted that for all instances, the variables remain defined the same that is to say:

$AN_x x$ Generated acoustic power in xx (dB above $1\mu W/m$) xx may be: HR(Heavy Rain) or FW(Fair Weather)
n Number of subconductors in a bundle
d Subconductor diameter in cm
d_0 Smallest subconductor diameter in cm
D Bundle diameter in cm
R Distance from conductor to an observer point in m
E Maximum positive peak surface electric field in kV/cm
E_0 Initial surface electric field in kV/cm

1) *BPA Model:* The BPA model for AC circuits has three separate formulas based on the precipitation levels in an area: rain (DC, $L_5 0$), heavy rain (HR, L_5) and fair weather (FW, $L_5 0$). HR and FW formulae are based on the BPA rain formula with correction factors added.

AN in Rain: Light rain resulting in a wet conductor is taken at, and is given by

$$\mathrm{AN}_{\mathrm{rain}}(L_{50}) = 81.7 + 120 \cdot \log \frac{E_{\max}}{E_0} + 55 \cdot \log \frac{d_{\mathrm{eq}}}{d_0} - 11.4 \log D - 5.8$$

$$E_0 = 16.84, \quad d_0 = 63.5 \text{ mm}$$

$$d_{\mathrm{eq}} = \begin{cases} d, & \text{for } n \leq 2 \\ 0.58 d n^{0.48}, & \text{for } n > 3 \end{cases}$$

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

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

AN in Fair Weather (FW): Fair weather is taken at $L_5$0 ,

$$AN_{FW}(L_{50}) = AN_{rain}(L_{50}) - 25$$

AN in Fair Weather (FW): As noted in AN in Fair Weather Conditions, AN for FW conditions is calculated differently with the EPRI model than with the BPA or IREQ models. As such, fair weather is taken at $L_5$0, and is given by:

***2) IREQ model**:* 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].

- AN in light rain resulting in a wet conductor is taken at L50, and is given by Eq. (8).

$$AN_{rain}(L_{50}) = 72 log E_{max} + 22.7 log(n)$$
$$+45.8 log(d) - 57.6 - 11.4 log(D)$$

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

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

AN in Fair Weather (FW): Fair weather is taken at $L_5$0, and is given by:

$$AN_{FW}(L_{50}) = AN_{HR}(L_5) - 25$$

3) EPRI model: The EPRI model for AC circuits has three separate formulas based on the precipitation levels in an area: heavy rain (HR, 4L_5), wet conductor (WC, L_{50}), and fair weather (FW, L_{50}). Rain and FW formulae are based on the EPRI HR formula with correction factors added. AN in Heavy Rain (HR): Heavy rain (HR) is taken at L_5, and is given by

$$\mathrm{AN}_{\mathrm{HR}} = 20 \log(n) + 44 \log(d) - \frac{665}{E} + k_n - 10 \log(R) - 0.02 \log(R)$$

$$k_n = \begin{cases} 82.5, & n = 1 \\ 77.8, & n = 2 \\ 67.9 + 22.9(n-1)\frac{d}{D}, & n \geq 3 \end{cases}$$

AN in Rain (Wet Conductor): Light rain resulting in a wet conductor is taken at L_{50}, and is given by

$$\Delta_{\mathrm{rain}} = k_{\mathrm{rain}} - \frac{14.2 E_c}{E}$$

$$k_{\mathrm{rain}} = \begin{cases} 8.2, & n < 3 \\ 10.4, & n \geq 3 \end{cases}$$

AN in Fair Weather (FW): As noted in AN in Fair Weather Conditions, AN for FW conditions is calculated differently with the EPRI model than with the BPA or IREQ models. As such, fair weather is taken at $L_5$0, and is given by:

$$\mathrm{AN_{FW}} = \mathrm{AN_{HR}} + \Delta_{\mathrm{FW}}$$

$$\Delta_{\mathrm{FW}} = 8.2 - 14.2(E_c + 10)$$

$$E_c = \begin{cases} \frac{24.4}{d^{0.24}}, & n \le 8 \\ \frac{24.4}{d^{0.24}} - 0.25(n-8), & n > 8 \end{cases}$$

Figs. 8–10 are useful for a 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 three methods is also plotted. It is observed that the AN level in fair weather conditions is much lower than that in the rain.

C. Audible Noise in DC Lines

As per the literature, AN in-DC lines can be calculated using BPA or IREQ models. The following describes how each standard approaches the equation. It should be noted that for all instances, the variables remain defined the same. That is to say:

AN_{xx} Generated acoustic power in xx (dB above 1$\mu W/m$) xx may be: HR (Heavy Rain) or FW (Fair Weather)

n Number of subconductors in a bundle d Subconductor diameter in cm d_0 reference subconductor diameter in cm

D Bundle diameter in cm E Maximum positive peak surface electric field in kV/cm k Constant dependent on n

1) BPA Model: For each positive pole above 20/μPa, AN is given by:

$$\mathrm{AN} = 86\log E + k_1\log(n) + 40\log(d) - 11.4\log(D) + k_0 + k_2$$

$$k_0 = \begin{cases} -100.6, & n \ge 3 \\ -93.4, & n < 3 \end{cases}$$

$$k_1 = \begin{cases} 25.6, & n \ge 3 \\ 0, & n < 3 \end{cases}$$

$$k_2 = \begin{cases} -6, & L_{50} \text{ rain} \\ -2.0, & L_{50} \text{ winter fair weather} \\ 2.0, & L_{50} \text{ summer fair weather} \end{cases}$$

*Note: The correction factors for varying weather conditions are included in the BPA model via k_2 .

2) IREQ Model: • For each positive pole, AN generated by each positive line is given by

$A = k_1 + k_2(g - g_0) + k_3 log(d/d_0) + k_4 log(n/n_0) g_0 = 25$

$d_0 = 1.6, n_0 = 6$

TABLE II EMPIRICAL COEFFICIENTS FOR DC AN GENERATION FUNCTION (IREQ MODEL)

Season	Weather Cond.	k1	k2	k3	k4	Max. Error (dB)
Summer	Fair	4.30	1.54	40	10	3.0
	Foul	1.48	1.52	40	10	-3.2
Fall/Spring	Fair	4.43	0.84	40	10	-7.2
	Foul	4.06	0.84	40	10	-1.2
Winter	Fair	1.84	0.51	40	10	-8.7
	Foul	5.65	1.04	40	10	-2.7

IV. MATHEMATICAL MODELLING FOR RADIO INTERFERENCE

Energized HV transmission lines produce electromagnetic emissions over a wide range of frequencies. In the electric utility industry, interference to the AM broadcast frequency band (535 1605 kHz) has been regarded as ”radio interference” (RI). Corona discharges are the primary source of electromagnetic interference, which act as current sources, in- jecting random current pulses into the transmission conductors.

A. Radio Interference Calculations

For DC lines, the negative corona discharges (Trichel pulses) tend to be uniformly distributed over the conductor surfaces, and, thus, are a relatively minor contributor to RI. Conversely, the positive corona are of three types: (1) Hermstein’s glow, (2) plume discharge, and (3) streamers. Plumes and streamers are randomly distributed and usually associated with highly stressed points created by surface imperfections. Therefore, plumes and streamers are considered the primary source of RI. For AC lines, RI is usually about 5 dB worse than that of DC cases. These can be classified in two categories: (1) empirical formulas developed through long-term experiments, and (2) the semi-analytical method where the frequency domain modal analysis is conducted for the transmission line geometry, and corona-induced random current pulses are determined using the generation functions derived experimentally.

Radio Interference in AC Transmission Lines

Several generation functions for RI, determined experimen- tally, have been proposed [1][2][18]. It should be noted that the generation function developed by BPA [41] is the one reported first, it is meant that the experimental data in a corona cage is used for its derivation and for actual electromagnetic (EMI) computations. To allow for a wider range of studies, multiple calculation standards are available to choose from when calculating AC RI: EdF (E´ lectricite´ de France), IREQ and EPRI.

EdF Generation Functions: The EdF model for AC circuits has three separate formulas based on the precipitation levels in an area: rain (DC, L_{50}), heavy rain (HR, L_1) and fair weather (FW, L_{50}). Rain and FW formula are based on the EdF HR formula with correction factors added. RI in Heavy Rain (HR): Heavy rain (HR) is taken at L_1, and is given by:

$$\Gamma_{\mathbf{HR}} = 155 \log\left(\frac{g}{11.1}\right) + (11.5 + 2\log(n))\,r - B(n)$$

$$B(n) = \begin{cases} 0, & n = 1 \\ 5, & n = 2 \\ 7, & n = 3 \\ 8, & n = 4 \\ 9, & n = 6 \\ 9.5, & n = 8 \end{cases}$$

Where g is the surface gradient in kV/cm, r is the radius of the conductor in cm, and n is the number of sub conductors. RI in Rain: Light rain resulting in a wet conductor is taken atL_{50}, and is given by

$\tau rain = \tau HR - 14$

RI in Fair Weather (FW): Fair weather is taken at

$L50$

, and is given by:

$tau_{FW} = \tau_{HR} - 20$

1) IREQ Generation Functions: The IREQ model for AC circuits has three separate formulas based on the precipitation levels in an area: rain (DC; dry conductor, L_{50}), heavy rain (HR, L_1) and fair weather (FW, L_{50}). Rain and FW formulae are based on the IREQ HR formula with correction factors added. RI in Heavy Rain (HR): Heavy rain (HR) is taken at L_1, and is given by:

$$\Gamma_{\mathbf{HR}} = -90.25 + 92.42\log(g_{\max}) + 43.02\log(2r) - B(n)$$

$$B(n) = \begin{cases} 0, & n = 1 \\ 3.7, & n = 2 \\ 6, & n \geq 3 \end{cases}$$

Where g_{max} is the maximum surface gradient in kV/cm, r is the radius of the conductor in cm, and n is the number of sub conductors. RI in Rain: Light rain resulting in a wet conductor is taken at L_{50}, and is given by

$\tau rain = \tau HR - 14$

RI in Fair Weather (FW): Fair weather is taken at L_{50}, and is given by

$\tau_{FW} = \tau_{HR} - 20$

2) EPRI Generation Functions: The EdF model for AC circuits has three separate formulas based on the precipitation levels in an area: rain (DC, L_{50}), heavy rain (HR,L_5) and fair weather (FW,L_{50}). Rain and FW formulae are based on the EdF HR formula with correction factors added. RI in Heavy Rain (HR): For one sub conductor bundle, heavy rain (HR) is taken at , and is given by:

$\tau_{HR} = 81.1 - 580/E_max + 38log(d/3.8)$

where E_{max} is the maximum electric gradient in kV/cm and d is the diameter of the sub conductor in cm .
RI in Rain: Light rain resulting in a wet conductor is taken at L_{50}, and is given by:

$$\Gamma_{\text{rain}} = \Gamma_{\text{HR}} + \Delta_{\text{rain}}$$

$$\Delta_{\text{rain}} = 8.2 - \frac{14.2E_c}{E}$$

$$E_c = \frac{24.4}{d^{0.24}} - K_e$$

$$K_e = \begin{cases} 0, & n \le 8 \\ 0.25(n-8), & n > 8 \end{cases}$$

where E is the electric gradient in kV/cm and d is the diameter of the sub conductor in cm.
RI in Fair Weather (FW): Fair weather is taken at L_{50}, and is given by:

$$\tau FW = \tau rain - 17$$

*B. **Radio Interference in DC Lines***
1) IREQ Generation Function: RI in DC lines is given by IREQ:
$\tau_{hr} = 90.25 + 94.42log(g_max) + 43.02log(2r) - B(n)$
where: g_{max} Maximum bundle surface gradient in kV/cm g_0 Reference value =25kV/cm n_0 Reference value =6 d_0 Reference value =1.6cm

TABLE III EMPIRICAL COEFFICIENTS FOR DC CL BIPOLAR GENERATION FUNCTION (IREQ MODEL)

Season	Weather Cond.	$k1$	$k2$	$k3$	$k4$	Max. Error (dB)
Summer	Fair	4.30	1.54	40	10	3.0
	Foul	1.48	1.52	40	10	-3.2
Fall/Spring	Fair	4.43	0.84	40	10	-7.2
	Foul	4.06	0.84	40	10	-1.2
Winter	Fair	1.84	0.51	40	10	-8.7
	Foul	5.65	1.04	40	10	-2.7
Overall Fair	N/A	11.85	0.89	20	36.4	-5.1
Overall Foul	N/A	16.91	0.73	20	8.0	2.9

*2) **BPA Generation Functions:*** An RI generation function for DC lines in corona has been developed during the Project HVTRC by GE. For a positive conductor in fair weather, the generation function is given by [33]

$\tau = 31 + 86log(g/g_0) + 40log(d/d_0) + 10log(n/n_0)$
Where: g DC surface gradient in kV/cm g_0 Reference value
=25kV/cm n Number of subconductors in a bundle n_0 Ref- erence value =3 d Bundle diameter in cm d_0 Reference value
=1.799cm

V. FACE SIMULATION RESULTS FOR RADIO INTERFERENCE (RI) AND AUDIBLE NOISE (AN) IN HYBRID TRANSMISSION LINES

A. Simulation Criteria

All the simulations are carried out in an PSCAD based FACE software. Model validation is done by simulating EHVAC and HVDC lines combinedly for Audible Noise and Radio Interference. A hybrid transmission line with 10 different configurations is considered. Boundary conditions and excitations of simulation model is validated first with test cases of available literature. Same model set up is then used for further analysis of main design configuration of hybrid transmission line under simulation.

TABLE IV SIMULATION CIRCUIT MODEL PARAMETERS

Sr. No.	Parameter	EHVAC	HVDC	Remarks
1	Voltage (kV)	400	±500	Delta Connection
2	Current (kA)	2	4	RMS Value
3	Power (MW)	800	2000	Power Transfer Capacity
4	Sub conductor Diameter (mm)	40.69	40.69	(Value is in mm)
5	Sag (Meter)	0	0	(Value is in Meter)

6	Splitting Distance (mm)	457.2	457.2	(Value is in mm)
7	Splitting number	4	4	NA
8	D (Horizontal Distance, Meter)	15	11	(Value is in Meter)
9	H (Vertical Distance, Meter)	28	18	(Value is in Meter)
10	DC to AC Phase Clearance (m)	10		(Value is in Meter)
11	AC to AC Phase Clearance (m)	15		(Value is in Meter)

B. Simulation Conditions and Sensitivity Analysis parameters

Delta connected transmission line is considered. To get the accurate RI and AN results, Simulation model is extended beyond the RoW. RoW for the configuration is Optimized to be 46 m (Recommended as per MoP and CBIP guideline) Simulations are performed at center of span length since that condition provides the minimum ground clearance.
Sensitivity analysis determines how the target parameters are affected based on the changes in input variables. Total more than 500 design variations are considered for the simulation. 3 Major parameters are considered with minimum to maximum limit of dimensions to perform the sensitivity analysis:
DC Height = 18 m to 52 m, 1 m step. DC AC Clearance = 10 m
AC AC Clearance = 15 m

C. Hybrid Horizontal Transmission Line Model

Fig. 1 gives schematic arrangement for single circuit hy- brid horizontal transmission line model [3], where, all the simulation parameters are shown in table 2. Fig. 2 gives the snapshot showing the windows of the FACE GUI (Graphical User Interface) set for the study of single circuit line.

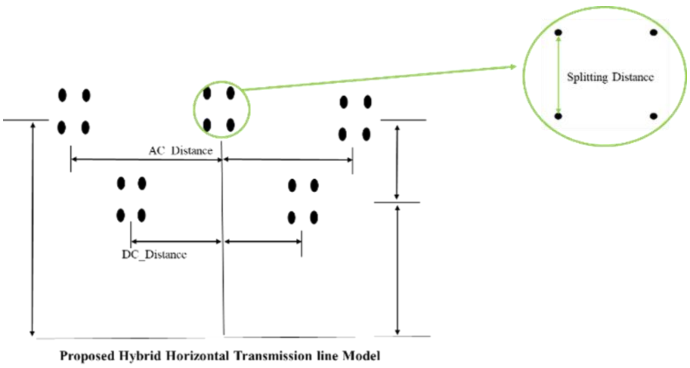

Fig. 1. Single Circuit Hybrid Horizontal Transmission Line Model

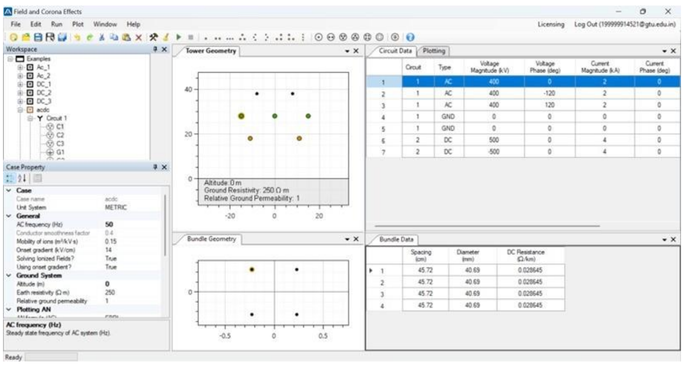

Fig. 2. Snapshot of FACE GUI, for the study of Single Circuit Hybrid Horizontal Transmission Line

Table 3 gives the circuit model parameters of single circuit line, which is set for line voltage of 400 kV, with a loading of 2000 A, corresponding to 800 MW for EHVAC and 500 kV, with a loading of 4000 A, corresponding to 2000 MW for HVDC. The spacing between the bundled conductors are kept 15 m for EHVAC and 11 m for HVDC. The sub conductors of 40.69 mm diameter, Bersimis ACSR conductor, having DC resistance of 0.028645 X/km are kept 46.0 cm apart. Table 3 appears on the screen of FACE GUI showing circuit model of single circuit hybrid 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 equipment is designed. The technical parameters being considered for separate 400 kV EHVAC and 500 kV HVDC Transmission Lines are summarized in Table 1 of their article [3].
Figure bellow shows the results for audible noise for all three models for single circuit line. The equation for calculating the AN during light rain, which results in a wet conductor and denoted as L50, AN in heavy rain is taken at (L5) and AN in fair weather is taken at L50, are as follows.

TABLE V CIRCUIT MODEL PARAMETERS FOR SINGLE CIRCUIT LINE

Sr No	Circuit	Type	Volt. Magnitude (kV)	Volt. Phase (deg)	Current Magnitude (kA)	Current Phase (deg)	X (m)	Y (m)	Sag (m)
1	1	AC	765	0	2	0	-11.0	35.0	0.0
2	1	AC	765	-120	2	0	0.0	35.0	0.0
3	1	AC	765	120	2	0	11.0	35.0	0.0
4	1	GND	0	0	0	0	-5.0	48.0	0.0
5	1	GND	0	0	0	0	5.0	48.0	0.0

TABLE VI BUNDLE DATA

Bundle Number	Spacing (cm)	Diameter (mm)	DC Resistance (/km)
1	45.72	32.0	0.0028645
2	45.72	32.0	0.0028645
3	45.72	32.0	0.0028645
4	45.72	32.0	0.0028645
5	45.72	32.0	0.0028645
6	45.72	32.0	0.0028645

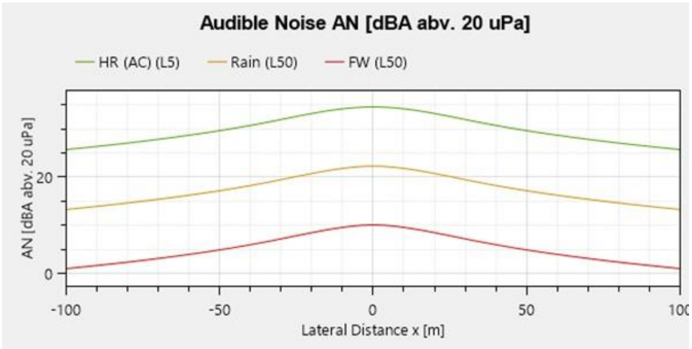

Fig. 3. Audible noise (BPA Model) for Single Circuit Hybrid Horizontal Transmission Line

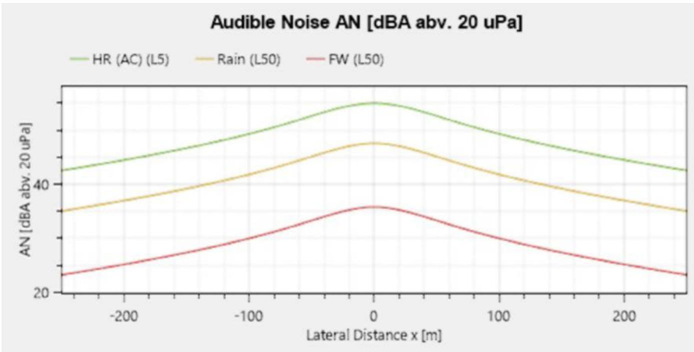

Fig. 4. Audible noise (BPA Model) for Single Circuit Hybrid Horizontal Transmission Line

Figure bellow is 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.

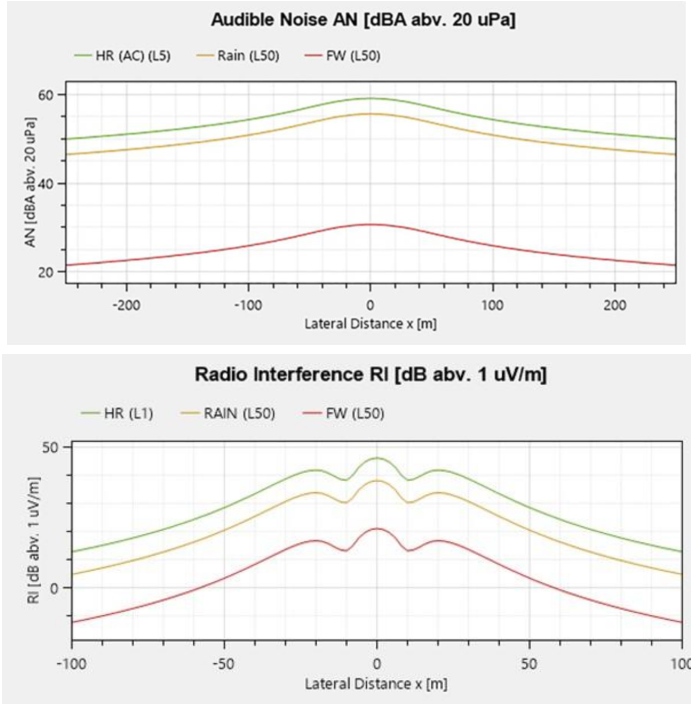

Fig. 5. Audible noise (IREQ model) for Single Circuit Hybrid Horizontal Transmission Line

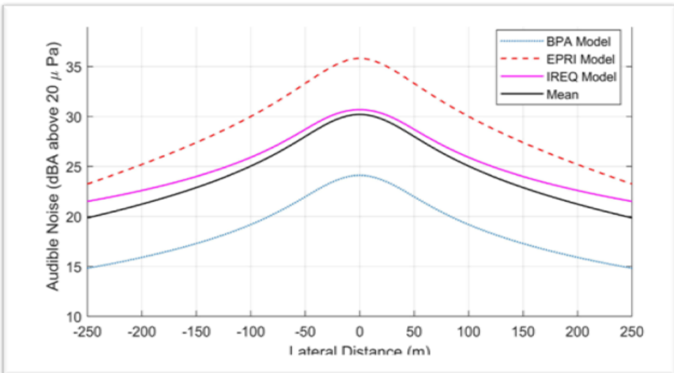

Fig. 6. Audible noise (IREQ model) for Single Circuit Hybrid Horizontal Transmission Line

Table below 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 Insti- tute (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 VII MEASUREMENT DATA FOR DIFFERENT MODELS

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	Rainlse	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 Ls	50.73	52.94	57.46
At the edge of ROW	Rainlso	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	50.18	52.33	56.92
At 30.5 m from outer phase	Rainlse	46.68	44.81	53.42
At 30.5 m from outer phase		21.68	32.99	28.42

Figure below shows the results for radio Interference (BPA Model) for single circuit line. The equation for calculating the AN during light rain, which results in a wet conductor and denoted as L50, AN in heavy rain is taken at (L1) and AN in fair weather is taken at L50, are as follows.
show the graphical display of radio interference for heavy rain (L1), rain (L50), and fair weather (L50) respectively;

which 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].

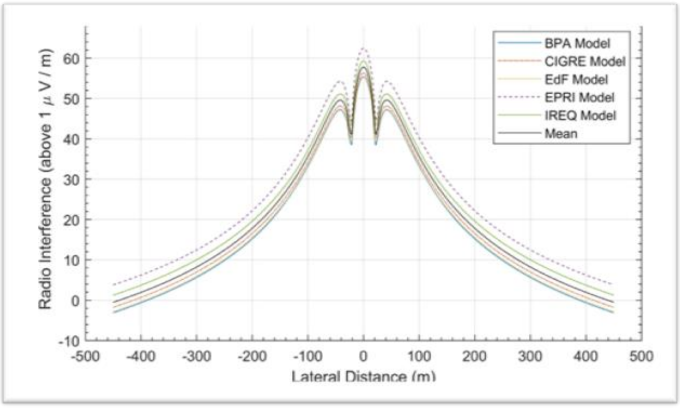

Fig. 8. Radio Interference (BPA Model) for Single Circuit Hybrid Horizontal Transmission Line

Table 6 shows the evaluation of Radio Interference above 1.0 uV/m, at 1.5 m height height from ground level. The RI level for proposed Hybrid 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. (FACE Online Help [27]).

VI. Comparison of Simulation Results and Hands on Calculation

Audible Noise and Radio Interference are both highly- noticeable corona-related environmental effects of EHV trans-

TABLE VIII Rain Type Model Data

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)	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)	CGRE	81.32	72.90	71.43
Rain (t se)	BPA	72.40	63.98	62.51
Rain (Ise)	EPRI	79.45	71.03	69.56
Rain (S se)	IREQ	76.29	67.87	66.40
Rain (L se)	EdF	72.47	64.05	62.58
Rain (L 50)	CICRE	73.32	64.90	63.43
PW (L 50)	BPA	55.40	46.98	45.51
PW (L 50)	EPRI	62.45	54.03	52.56
FW (L se)	IEEQ	59.29	50.87	49.40
FW (L s0)	EdF	55.47	47.05	45.58
PW (L 50)	CICRE	56.32	47.9	46.43

mission lines. Levels are obviously related to the level of corona, so the inception gradient is a relevant parameter for hybrid lines too. The simulations carried out here presents the Audible Noise and Radio Interference as by product of Corona Effect Calculation at ground level as well as in a space around the different hybrid transmission line model configurations including impact of design parameters changes on output parameters. In case of HVAC condition corona is greatest for rainy weather, but for HVDC condition corona, audible noise, and radio interference are greatest in fair weather. [16]

TABLE IX NOISE AND RADIO INTERFERENCE DATA

Sr. No.	Parameters	FACE Results [dBA]	Hands on Calculations [dBA]	Remarks
1	Audible Noise	52.62	52.33	Rain
		49.12	47.12	Fair
2	Radio Interference	60.47	56.98	Rain
		55.40	55.60	Fair

VII. CONCLUSION

This paper provides a comprehensive review and study of the Audible Noise and Radio Interference of proposed Single Circuit Hybrid Horizontal Transmission Line, focusing on the development of 400 kV EHV-AC and 500 kV HVDC-DC transmission lines. The evaluation is conducted using FACE (Field and Corona Effect) software, which proves useful for assessing coronal losses (using BPA formulas) of the proposed Single Circuit Hybrid Horizontal Transmission Line in India. Additionally, FACE software facilitates the study of audible noise (using EPRI, IREQ, BPA formulas) and radio interfer- ence (using EPRI, IREQ, BPA, EdF, CIGRE formulas) under different rain conditions. The study findings are Audible noise and radio interference results align with hands on calculations values suggested by CIGRE Working Group B3.22 guidelines for technical requirements for existing Hybrid Transmission Line projects.

REFERENCES

1. Agrawal S, Tamoli D, De Bhowmick B, Kumar BS, Rao S, Sundaran A. 1200 kV national test station: taking Indian Power System to next orbit. Water and Energy International 2013; 70(4): 4–6.
2. Bharti S, Dubey SP. No-load performance study of 1200 kV Indian UHVAC transmission system. High voltage 2016; 1(3): 130–7.
3. Nayak R, Bhatnagar M, De Bhowmick B, Tyagi R. 1200 kV transmission system and status of development of substation equipment/transmission line material in India. Water and Energy International 2009; 66(4): 70–7.
4. Bharti S, Dubey SP. Application of smart computing techniques in cost optimization of 1200 kV autotransformer. Journal of Information and Optimization Sciences 2018; 39(1): 249–62.
5. R. Goehler, D. Helbig, L.-R. Jaenicke, E. Kynast, G. Lingner, B. Raeth, J. Schmid, G. Srinivas, and N. Trapp, "1200 kV AC substations: Full-scale products and integrated solutions," in Second International Symposium on Standards for Ultra High Voltage Transmission, pp. 1–11, 2013.
6. Janssen ALJ, Dufournet D, Ito H, Shperling B. Investigations on Requirements for UHV/EHVAC Switchgear by CIGRE Study Committee A3. IEEE Trans. Power Delivery 2015; 30(1): 377–84.
7. Huang D, Shu Y, Ruan J, Hu Y. Ultra High Voltage Transmission in China: Developments, Current Status and Future Prospects. Proc. IEEE 2009; 97(3): 555–83.
8. Bao-Quan Wan, Hui-Chun Xie, Guang-Zhou Zhang, and Xiao-Wu Zhang, "Electromagnetic environment of 1000 kV UHVAC substation," in Asia-Pacific International Symposium on Electromagnetic Compatibility, pp. 1413–1416, 2010.
9. D. Huang, Z. Zheng, Z. Huang, X. Xie, J. Ruan, and F. Huo, "Study on parameters design and corona characteristics test equivalent of grading rings for 1000 kV UHVAC compact transmission line," in Annual Report Conference on Electrical Insulation and Dielectric Phenomena, pp. 638–642, 2013.
10. Zhang G-Z, Cheng G-S, Wan B-Q, Lu Y, Wu X, Zhang X-W. Study on EM environment of UHV test line segment. High Voltage Engineering 2008; 34(3): 438–41.
11. Huang S, Liu Y, Chen S, Zhou G, Zhuang W. Corona Onset Characteristics of Bundle Conductors in UHVAC Power Lines at 2200 m Altitude. Energies 2018; 11: 1047.
12. Xie H, Cui X, Wan B, Zhang J. Statistical analysis of radio interference of 1000 kV UHVAC double-circuit transmission lines in foul weather. CSEE Journal of Power and Energy Systems 2016; 2(2): 47–55.
13. Manzoni G, Annestrand S, Cardoso R, et al. Electric power transmission at voltages of 1000 kV AC or ±600 kV DC and above. Electra 1989; 122: 40–75.
14. R. Lings, "Overview of transmission lines above 700 kV," in IEEE Power Engineering Society Inaugural Conference and Exposition in Africa, pp. 33–43, 2005.
15. A. Nakamura, "1100 kV AC transmission project in Japan," in International Symposium on International Standards for Ultra High Voltage, Beijing, pp. 1–10, 2007.
16. CIGRE, "Electric power transmission at voltages of 1000 kV AC or 600 kV DC and above: network problems and solution peculiar to UHVAC transmission," Electra, vol. 122, pp. 41–75, 198.
17. Bansal R. Power system protection in smart grid environment. CRC Press; 2019.
18. R.C. Bansal and T.J. Hammons, "A Discussion on the Restructuring of Indian Power Sector," in IEEE Power Engineering Society General Meeting, pp. 1–6, 2007.
19. S. Bharti, Performance Analysis of 1200 kV Ultra High Voltage Transmission System. PhD thesis, Chhattisgarh Swami Vivekanand Technical University, 2020.

20. K. Vyas, V. Joshi, D. Shah, K. Gopani, and S. Shah, ”A Novel GUI Based Approach for Computation of Extremely Low Frequency Fields and Corona Effects for UHVAC Transmission Line,” in Innovations in Power and Advanced Computing Technologies (i-PACT), vol. 1, pp. 1–5, 2019.
21. M.G. Unde and B.E. Kushare, ”Analysis of Electromagnetic Fields of 1200 kV UHV-AC Transmission Lines,” in 5th International Conference on Computational Intelligence and Communication Networks, pp. 580–584, 2013.
22. P. Bhurat, D. Sridhar, D. Yelamanchi, P. J. Pauly, and N. Vasudev, ”1200 kV Transmission line corona effects and electromagnetic fields,” in *International Conference on High Voltage Engineering and Technology*, pp. 29–30, January 2015.
23. Shu Y., ”Operation Experience of 1000 kV Ultra High Voltage AC Transmission Technology,” *CIGRE Session Technical Programme 2016*, B2(111): 1–10.
24. I.C. on Non-Ionizing Radiation Protection et al., ”Guidelines for limiting exposure to time-varying electric and magnetic fields (1 Hz to 100 kHz),” *Health Physics*, vol. 99, no. 6, pp. 818–836, 2010.
25. ”Draft Standard for Definitions of Terms Relating to Corona and Field Effects of Overhead Power Lines,” *IEEE P539 Draft*, 2020.
26. Anonymous, ”IEEE Standard Definitions of Terms Relating to Corona and Field Effects of Overhead Power Lines,” *IEEE Std 539-2005 (Revision of IEEE Std 539- 1990)*, pp. 0–41, 2005.
27. Anonymous, *FACE Technical Guide, FACE Online Help*, November 2018. 28. G. Ballou, ed., *Fundamentals of Audio and Acoustics*, 2008.
29. C.R. Nave, ”HyperPhysics: frequencies for maximum sensitivity of human hearing.”
30. Anonymous, ”A Comparison of Methods for Calculating Audible Noise of High Voltage Transmission Lines: A report prepared by a Task Force of the Corona and Field Effects Subcommittee,” *IEEE Power Engineering Review*, vol. PER-2, no. 10, pp. 60–61, 1982.
31. V. Chartier, ”Empirical expressions for calculating high voltage transmission corona phenomena,” in *Proceedings of the First Annual Seminar Technical Career Program for Professional Engineers*, pp. 75–82, 1983.
32. Anonymous, ”A Comparison of Methods for Calculating Audible Noise of High Voltage Transmission Lines,” *IEEE Transactions on Power Apparatus and Systems*, vol. PAS- 101, no. 10, pp. 4090–4099, 1982.
33. V.L. Chartier and R.D. Stearns, ”Formulas for Predicting Audible Noise from Overhead High Voltage AC and DC Lines,” *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-100, no. 1, pp. 121–130, 1981.
34. N.G. Trinh, P.S. Maruvada, and B. Poirier, ”A Comparative Study of the Corona Performance of Conductor Bundles for 1200 kV Transmission Lines,”
IEEE Transactions on Power Apparatus and Systems, vol. PAS-93, no. 3, pp. 940–949, 1974.
35. Anonymous, ”International Commission on Non- Ionizing Radiation Protection. Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz),” *Health Physics*, vol. 74, no. 4, pp. 494–522, 1998.
36. L. Zhao, J. Lu, and G. Wu, ”Measurement and Analysis on Electromagnetic Environment of 1000 kV UHVAC Transmission Line,” in *Asia-Pacific Power and Energy Engineering Conference*, pp. 1–4, 2012.
37. M. Klinger, S. Annestrand, G. Parks, and J. Lee, ”Experience of a 6-year 1200 kV transmission line test and development program at the Bonneville Power Administration,” *CIGRE Paper*, pp. 38–46, 1984.
38. Sarma Maruvada P., Turgeon A., Goulet D.L., ”Study of population exposure to magnetic fields due to secondary utilization of transmission line corridors,” *IEEE Trans. Power Delivery*, 1995; 10(3): 1541–8.