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Steady State Analysis of Electric Field Distribution for Hybrid Power Transmission Corridor of Indian Power Grid

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Abstract*: *Close Proximity Operation of HVAC and HVDC transmission line is the recent trend for increase of power transmission capacity. Need for same is becoming vital day by day due to ever increasing power demand. Erection of HVAC lines has a requirement of high right of way (ROW) as compared to the HVDC lines. Also recent past has witnessed constraint in availability of ROW for many projects of Indian Power Grid. Raise in transmission voltage level of HVDC from Power Grid Corporation of India Limited (PGCIL) and its suitability to decentralized non-conventional grids has led to addition of many upcoming HVDC projects with the already existing ones. So the need of analysis for electric field distribution under this type of hybrid transmission corridor is necessary to meet the standards of engineering design, exposure limits to living beings and environmental protection. The most likely formation of close proximity operations for all the five power grid regions of India has been identified and the electric field distribution has been analyzed with COMSOL Multiphysics. Results so obtained has been discussed with reference to regulation of Indian Electricity Rule 1956 and International Commission on Non-Ionizing Radiation Protection (ICNIRP) guidelines.

Index Terms: COMSOL, Electric Field, HVAC, HVDC, Hybrid Transmission Corridor.

I. INTRODUCTION

Development of mankind has demanded increase in power generation and to utilize the same, thus need of increase in power transmission capacity for the existing power transmission corridors. For a rising economy like India the truth is nothing different. The far-flung generating spots of the country has to transmit more and more power to widely located consumer hubs over the expansive geographical area of the country. Advancements in technologies and increase of transmission voltage for HVDC transmission systems has proven to be a solution to this problem. From perspective of required ROW, HVDC transmission lines are more efficient as compared to the conventional HVAC transmission lines [1]. PGCIL has geared up for addition of many HVDC projects to the already eight alike operational projects. Presence of more than one line in same corridor results to close proximity operation and if both HVAC and HVDC transmission line exists, then such system is called as hybrid power transmission corridor. China with many other countries has also came up with such hybrid power transmission corridor with ±800 kV HVDC lines in close proximity to HVAC lines at separation of 50 m to 60 m [2]. Under this lines with mutual influence of AC and DC corona, space charges are created causing presence of hybrid electric field. This hybrid electric field at ground surface has to meet the safety requirements of various standards from the point of limit of exposure for electric and magnetic fields for living beings, and environmental protection [3]. Calculation methods for estimating hybrid electric fields in this conditions already exists [4] – [7]. All such methods exhibit uses of the Deustch assumption and is accepted internationally [4] – [8]. The assumption says that magnitude of hybrid electric field under such transmission lines is the affected parameter by the presence of space charges of HVAC and HVDC corona, while the direction of such field is independent. An extensive literature survey suggested that no such work has been done for analysis of hybrid electric field for Indian power grid. Present work uses a two dimensional modelling of hybrid transmission lines for computing the distribution of electric fields under the lines at ground surface. Validation of the modelling method has been done by comparison of simulated results with the analytically calculated results of Yang et. al. [9]. Close proximity operation possibilities for Indian power grid has been found from power maps of Central Electricity Authority (CEA), for all the five power regions of India. Electric field distribution so obtained has been discussed with reference to the standards governing limit of exposures to electric field & magnetic fields given by International Commission on Non-Ionizing Radiation Protection (ICNIRP) and World Health Organization (WHO) [10] – [11].

II. ELECTRIC FIELD CALCULATION

A two dimensional model of hybrid power transmission corridor was developed in COMSOL Multiphysics. This has been done for validation of model with analytical results available from work of Yang et. al. for 1000 kV HVAC and ±800 kV HVDC line in close proximity operation in Guandong province of east China [9].

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Separation distance for this case was found to be 50 m. The schematic of this system is given in Fig.1.

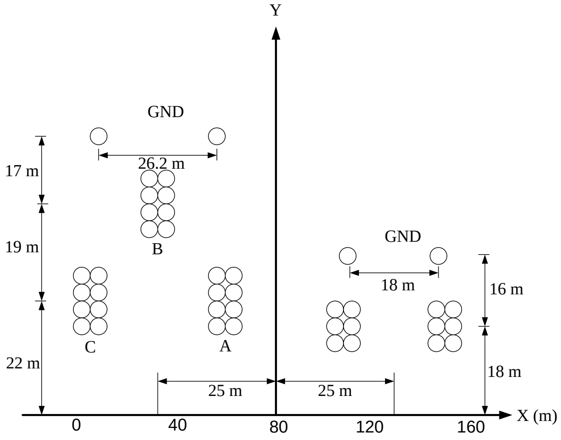


Fig. 1. Configuration of hybrid power transmission corridor from the work of Yang et. al. [9].

Electric field obeys Poisson's equations:

$$\nabla^2\phi(t) = \frac{-[\rho^+(t) - \rho^-(t)]}{\varepsilon_o} \quad (1)$$

where,

$\phi(t)$ = electric potential (V)

$\rho^+(t)$ / $\rho^-(t)$ = positive and negative charge densities respectively (C.m^{-3})

ε_o = permittivity of the free space; 8.854 x 10^{-12} (F.m^{-1})

From this, positive and negative current densities can be estimated as:

$$J^+(t) = \rho^+(t)[\mu^+ E(t) + W(t)] \quad (2)$$

$$J^-(t) = \rho^-(t)[\mu^- E(t) - W(t)] \quad (3)$$

where,

$J^+(t)$ / $J^-(t)$ = positive and negative ion current densities; (A.m^{-2})

μ^+ / μ^- = ionic mobility of the positive and negative ions, using 1.4 x 10^{-4} and 1.8 x 10^{-4} (m^2.V^{-1}.s^{-1})

$E(t)$ = electric field intensity (V.m^{-1})

$W(t)$ = wind velocity (m.s^{-1})

Equation (1) – (3) can be solved to form the continuity equation for current as follows:

$$\frac{\partial\rho^+(t)}{\partial t} = -\nabla.J^+(t) - R\frac{\rho^+(t)\rho^-(t)}{e} \quad (4)$$

$$\frac{\partial\rho^-(t)}{\partial t} = \nabla.J^-(t) - R\frac{\rho^+(t)\rho^-(t)}{e} \quad (5)$$

where,

R = recombination coefficient, 2.2 x 10^{-12} (m^3.s^{-1})

e = charge of an electron, 1.602 x 10^{-19} (C)

Solving the above equations can lead to formation of constraint equations for charge densities and current densities as follows:

$$\rho(t) = \rho^+(t) - \rho^-(t) \quad (6)$$

$$J(t) = J^+(t) + J^-(t) \quad (7)$$

$$\frac{\partial\rho(t)}{\partial t} = -\nabla.J(t) \quad (8)$$

The available methods of calculation for hybrid electric field suggests application for law of lateral distribution which is in accordance to Superposition theorem [5]. Procedure is to consider effect of only one type of charged ion for calculation of electric field at ground surface for a time instant, succeeded by the effect of other type of charged ion and finally taking resultant of both. With this, the constraint equations can further be solved for a point *p* with *r* as position vector on ground as follows:

$$\nabla.E(r,t) = \frac{\rho(r,t)}{\varepsilon} \quad (9)$$

$$J(r,t) = K\rho(r,t)E(r,t) \quad (10)$$

$$\nabla.J(r,t) = \frac{-\partial\rho(r,t)}{\partial t} \quad (11)$$

where,

r = radius vector of the point P(r)

t = time variable

E(r,t) , ρ(r,t) nd J(r,t) stands for hybrid electric field with space charge, the space charge density and the ion current density at P(r) on ground surface.

All this yields the final governing equation of hybrid electric field as:

$$KE(r,t).\nabla[\nabla.E(r,t)] + K[\nabla.E(r,t)]^2 + \frac{\partial\nabla.E(r,t)}{\partial t} = 0 \quad (12)$$

Steps of modelling and computation in COMSOL for the case has been elaborated with help of flowchart in Fig. 2.

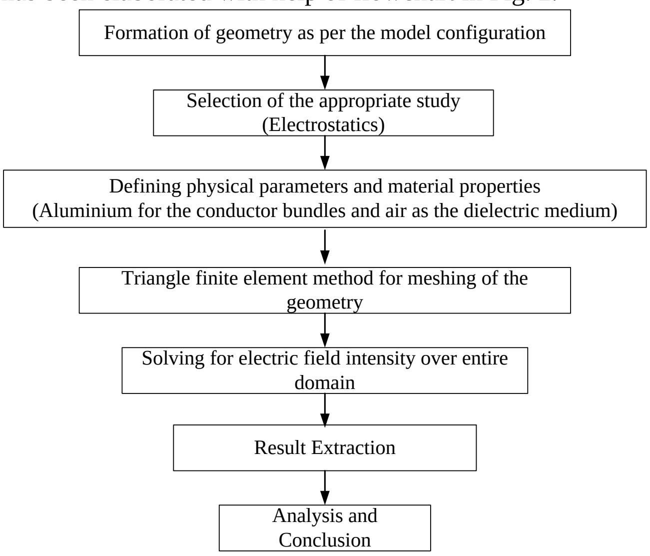


Fig. 2. Steps for simulation in COMSOL.

Electric field distribution was obtained at ground surface for validation. The comparison of results from literature survey and those obtained from simulation is given in Table I. Root mean square error (RMSE) of 0.0867 was obtained which indicates a good fit of results and validates the accuracy of simulation method.

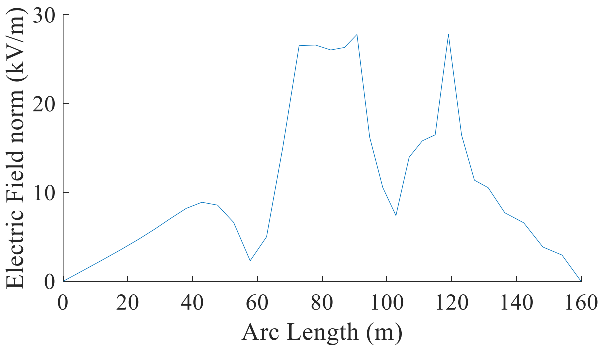


Fig. 3. Electric Field distribution at ground surface [9].

Table I Validation of COMSOL Results

Location on Ground Surface [m]	Hybrid Electric Field [kV/m] (COMSOL model) [A]	Hybrid Electric Field [kV/m] (Yang et. al.) [B]	Relative Error [C] (C=(A-B)/B)	Error[2] [D] ($D=C^2$)
45	10.75	10	0.0753	0.00567009
60	6.095	7	-0.12929	0.016714796
75	11.54	13	-0.11231	0.012613018
80	25.88	28	-0.07557	0.005711041
85	26.19	25	0.04776	0.002281018
86	26.74	28	-0.04507	0.002031434
SUM				0.045021396
SUM/n				0.007503566
RMSE				0.086623126

Table IV Details of Identified Cases

System	CASE 1		CASE 2		CASE 3		CASE 4		CASE 5		CASE 6		CASE 7	
Line	HVAC	HVDC	HVAC	HVDC	HVAC	HVDC	HVAC	HVDC	HVAC	HVDC	HVAC	HVDC	HVAC	HVDC
Transmission Voltage(kV)	400	±500	765	±500	400	±500	400(Quad) /400	±500	400	±500	765	±800	400	±800
Power Transmission Capacity	4 x 315 MVA	1500 MW	4 x 315 MVA	1500 MW	2 x 315 MVA	2500 MW	4 x 315 MVA / 2 x 315 MVA	2500 MW	4 x 315 MVA	2500 MW	1000 MVA	6000 MW	2 x 315 MVA	6000 MW
Type of Conductor	Quad Moose	Quad Bersimis	Quad Moose	Quad Bersimis	Twin Moose	Quad Bersimis	Quad Moose/Twin Moose	Quad Bersimis	Quad Moose	Quad Bersimis	Quad Moose	Quad Bersimis	Twin Moose	Quad Bersimis
Parallel Running Distance (km) *Approx..*	407		350		730		400		450		650		500	

III. SIMULATION OF INDIAN POWER GRID HYBRID CORRIDORS

The HVDC projects present in Indian power grid are listed in Table II.

Table II HVDC Projects in India

Name of Project	Transmission Voltage (kV)	Transmission Capacity (MW)	Year of Commission	Transmission Length (km)	Erection Company
Sileru Barsoor	±200	100	1989	196	BHEL
Rihand Dadri	±500	1500	1990	814	ABB, BHEL
Chandrapur Padghe	±500	1500	1999	752	ABB
Talcher Kolar	±500	2500	2009	1450	Siemens
Ballia Bhiwadi	±500	2500	2010	800	Siemens
Mundra Mohindergarh	±500	2500	2012	960	Siemens
Champa Kurukshetra	±800	6000	2016	1365	Alstom
North East Agra	±800	6000	2016	1728	ABB
Raigarh* Pugalar	±800	6000	2019	1830	ABB

* not yet operational

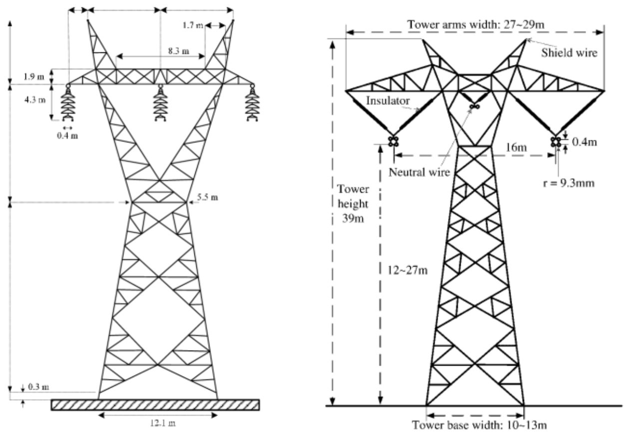
Sileru-Barsoor, comparatively being a line of smaller transmission length does not have any close proximity operation of HVAC lines. However, the operational seven lines which form hybrid transmission corridors, details of which are given in Table III. The details of such corridors are enlisted in Table IV.

Table III Hybrid Transmission Systems of Indian Power Grid

	HVAC Line	HVDC Line
CASE 1	400 kV Karchawa-Orai	±500 kV Rihand – Dadri
CASE 2	765 kV Chadrapur – Parli	±500 kV Chandrapur-Padghe
CASE 3	400 kV Rengali – Mukhiguda	±500 kV Talcher-Kolar
CASE 4	400kV Ballia – Lucknow 400 kV (Quad) Ballia – Shahjahanpur	±500 kV Ballia-Bhiwadi
CASE 5	400 kV Mundra – Radha Nesda	±500 kV Mundra-Mohindergarh
CASE 6	765 kV Champa – Dharamjaigarh	±800 kV Champa – Kurukshera
CASE 7	400 kV Balipara - Bongaigaon	±800 kV North East - Agra

Case 4 has three lines operational, one HVDC and two HVAC with parallel run in hybrid transmission corridor unlike others which has only two lines in same corridor.

Two dimensional model for this cases has been developed with in COMSOL Multiphysics. For straight run of HVAC transmission lines with angle deviation of 0-2 degress, PGCIL uses Suspension Tower configuration. While typical bipolar tower configuration has been used for HVDC transmission lines. The geometrical configuration of transmission towers so used is presented in Fig. 4 (a) and (b) [12]- [13].



(a) (b)

Fig. 4 (a) and (b) Configuration of HVAC and HVDC Transmission Tower respectively.

Ground and Horizontal clearances for modelling parameters has been referred to clause 77 and clause 82 of Indian Electricity Rule 1956, details of which is given in Appendix I.

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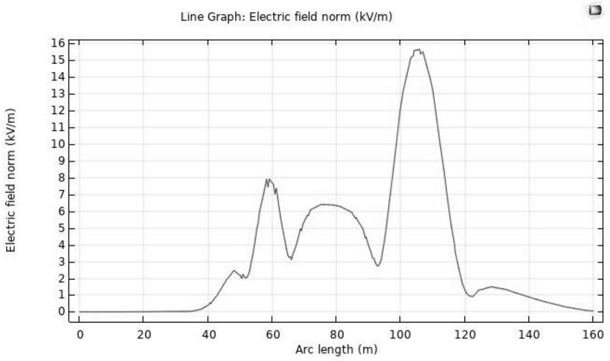
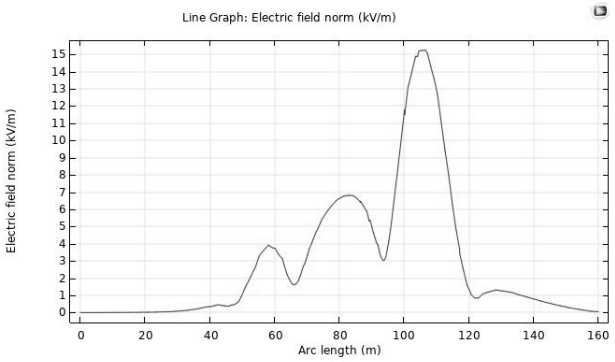
The limit of exposure to electric field for living beings is supposed to be <10 kV/m at height of 2 m from ground surface, under hybrid transmission line and <2 kV / m at height of 2 m from ground surface, for a point 45 m away from center of separation of both lines. This is in accordance to the standards of ICNIRP [11]. The hybrid electric field distribution at 2 m height from ground surface for all the cases enlisted in Table IV has been simulated.



(a)



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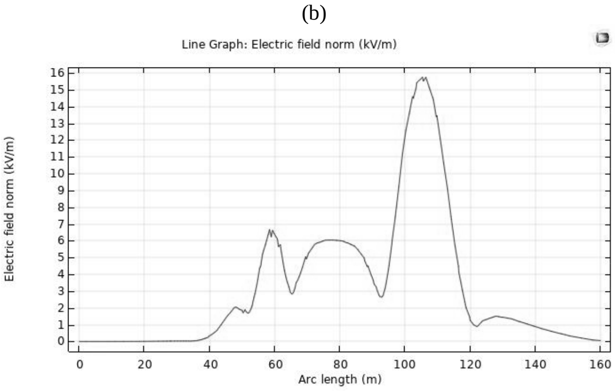

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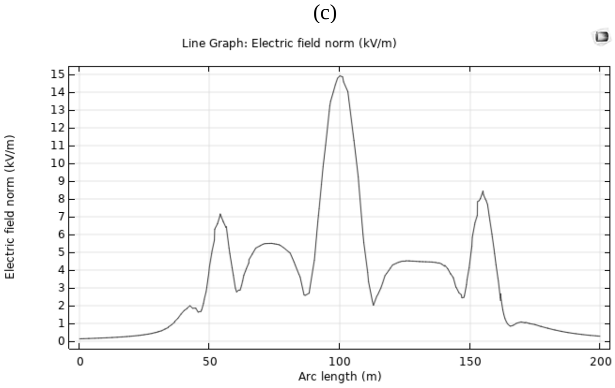

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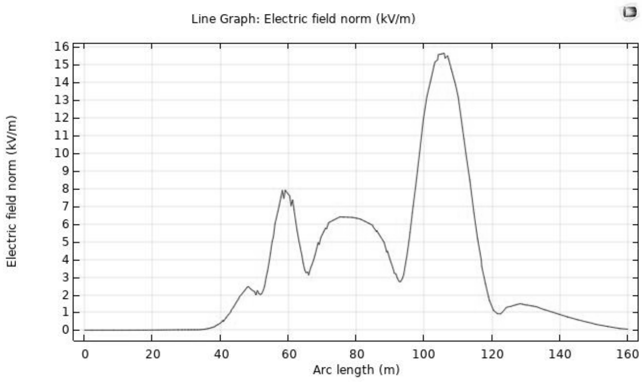

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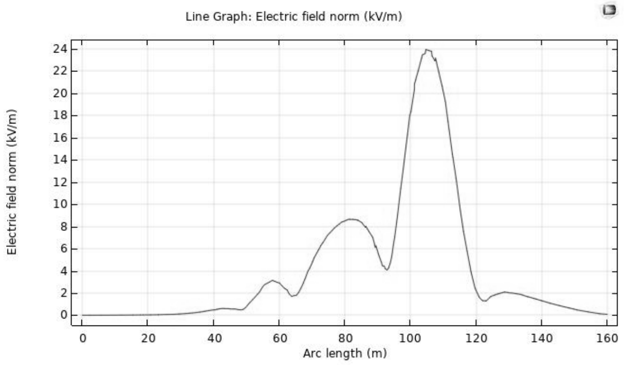

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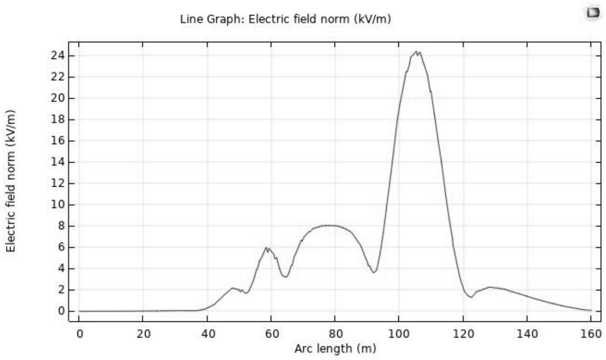

(g)

Fig. 5. Hybrid Electric Field Distribution at 2m height from ground surface for (a) CASE 1, (b) CASE 2, (c) CASE 3, (d) CASE 4, (e) CASE 5, (f) CASE 6 and (g) CASE 7.

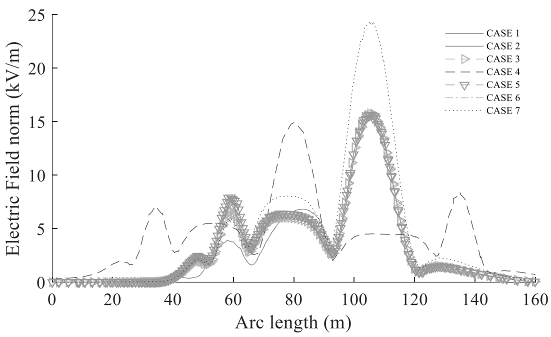

Fig. 6. Overlapped Hybrid Electric fields of all the simulated cases.

From the above plots it is evident that in all of the cases, magnitude of electric field has remained quiet high as compared to reference levels of ICNIRP. The peak values of hybrid electric field for each cases under the HVAC and HVDC lines at 2 m height from ground surface is recorded in Table V.

Table V Peak Value of Electric fields obtained from simulations

Line / Cases	Peak Value of Electric Field under HVAC Line (kV/m)	Peak Value of Electric Field under HVDC Line (kV/m)
CASE 1	8	15.5
CASE 2	6.9	15.3
CASE 3	6.78	15.8
CASE 4	7.07 / 8.02	14.98
CASE 5	8	15.5
CASE 6	8.5	24
CASE 7	8	24.06

IV. CONCLUSION

The two dimensional modelling of hybrid transmission corridor with validation by comparison of analytical method of Yang et. al. has been done. From reference to the power maps of CEA, possibilities of close proximity operation of hybrid transmission corridor for Indian power grid has also been presented. Two dimensional modelling using COMSOL Multiphysics for all such configurations of hybrid transmission corridors was analyzed. The study reflected the effect of change of configuration, transmission voltage levels and bundle conductors on distribution of hybrid electric field on ground surface.

Electric field under HVDC lines has remained high for all the cases simulated. However, for all of the cases above, the value has gone below 2 kV/m for locations of 45 m away from center of separation of lines on both sides along arc length i.e. ground surface, which is in accordance to standards of ICNIRP. This is exception to Case 4, where the same fact is not true to 45 m span on both sides of HVDC lines. The same is depicted from overlapped figure for hybrid electric fields for all the above discussed cases as shown in Fig. 6. Case 4 has two HVAC lines operating on both sides of the HVDC line. Both HVAC lines has same transmission voltage but one at left side of HVDC line has Twin Moose as the bundle conductor while the other has Quad Moose which is similar to HVAC line of Case 1. The Twin Moose exhibited a reduced peak of electric field by value of 1.0 kV/m than the later two which almost had same value of peak hybrid electric field. Overall highest peak was observed in Case 6 for HVAC lines which is also having the highest HVAC transmission voltage value while for HVDC lines, Case 7 and Case 8 should highest peak, having the highest value of HVDC transmission voltage. The study presented here has made it obvious that computation of such field for varying configuration is complex and is governed by several parameters. Value of electric field under this transmission lines has remained alarming for all the cases.

Also the center area of lines is the part where mutual effect of HVAC and HVDC lines can be seen on field distribution. Otherwise electric field under extremities of lines is hardly affected by change in transmission voltage or configuration of any one line.

APPENDIX I

Clause 77 of Indian Electricity Rule 1956

Transmission Voltage / Types of Clearances	**132 kV**	**200 kV**	**400 kV**	**765 kV**
Ground Clearance (m)	6.1	7	8.84	15.5
ROW (m)	27	35	52	85

Clause 82 of Indian Electricity Rule 1956

Transmission Voltage	**Horizontal Clearance (m)**
< 11 kV	1.219
11 kV – 33 kV	1.829
> 33 kV	1.829 + 0.305 for each increase of 33 kV

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