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Cost Effective Design of Extra High Voltage Transmission Lines for Minimizing Transmission Congestion Problems

Kaustubh Vyas, J. G. Jamnani

Abstract: ***In Country like India having dense population, laying down new transmission lines is a great challenge. Also country being on fast track development mode, there is unceasing demand of electricity due to ever increasing industrialization. With advent of Extra and Ultra High Voltage transmission lines, corridor width for transmission lines can be reduced significantly. This paper describes utilization of a novel objective function for optimizing the structural design of Extra High Voltage transmission lines. Right of way for transmission lines are decided based on the effects of electromagnetic fields and corona effects in vicinity of the transmission lines. Objective function developed here takes into account the combined effects of electromagnetic fields to optimize design of transmission line tower structure. With compaction of towers further Right of way reduces leading to cost benefits in land procurement. A real time case of a transmission line situated in Gujarat is considered for validating the results of Optimization algorithm developed by authors. MATLAB has been used as programming platform for mathematical modeling as well as a platform for developing GUI that facilitates plotting of fields in vicinity of transmission lines in 2D and 3D environment. Genetic Algorithm coding is used to solve the optimization problem. Significant cost benefits and compactness in transmission tower structure is achievable as is clear from the results shown in this paper. This optimization algorithm can be extended for Ultra High Voltage lines also.***

Index Terms: ***EHV AC transmission, electric field effects, line compaction, optimal design, right of way, transmission corridor***

I. INTRODUCTION

Electrical power industry is backbone of any developing nation. Power transmission if carried out at extra and ultra - high voltages, can play pivotal role in minimizing problems associated with transmission losses [1]. Even though transmission lines perform a fantastic task of transmitting bulk amount of power over long distances, a due consideration must be given to the fact that these high voltage lines are major source of low frequency non-ionizing electromagnetic interferences and of corona losses, Audible noise, Radio & TV interference etc. [2]. Detailed methodical modeling of electric and magnetic fields along with corona effects produced by overhead power lines is thus of utmost importance. Regularization of transmission corridor width and ROW distance for power lines includes consideration of non-ionizing electromagnetic fields [3]. Accurate analysis of all these fields in vicinity of overhead transmission lines is an obvious feature in transmission line design procedure. Increasing transmission line voltages are found to have effects related to health on human being and other living objects in its neighborhood [4]. Sufficient Transmission corridor width throughout the length of transmission line is the foremost requirement. Right of way is provided to confine immediate hazards due to Electric fields and long term health related issues due to Magnetic Field (EMF) on occupants [5]. Required corridor width for a transmission line is decided by peak value of electric field, dB value of audible noise, radio interference and magnitude of magnetic field in its surrounding area due to flow of power in the line. All the non-ionizing fields and corona effects must have their effective values within limits as specified in standards [5-7]. Major factors affecting Electric field strength are Voltage rating, Phase to Phase Distance, Conductor height above the ground, No. of sub conductors and conductor cross section area. Magnetic fields mostly are affected by current flowing through the line. Electromagnetic field and Corona effects near ground surface throughout the transmission corridor need to be plotted for analysis and minimization purpose. Fields values are measured at 2 meter height from ground level which is average human height and also on the edge of ROW the values are measured. Values of field effects and corona should be less than maximum permissible values within entire corridor width.

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II. PERMISSIBLE VALUES OF ELECTRIC FIELD

Electric field is produced by electric charges irrespective of their state of motion and thus has relation to the system voltage. Maximum Permissible Exposure (MPE) value of electric field has to be decided so as to keep as a constraint while designing the transmission line. International Commission on Non-Ionizing Radiation Protection (ICNIRP) [5] has provided guidelines to establish rules for limiting exposures to electric and magnetic fields to provide protection against all established adverse effects of these fields. Similarly IEEE Standard Guidelines are available that define the maximum exposure value of power frequency electric fields [7]. After studying these guidelines along with national literature published by Government of India [10-12], following criterion is established for designing transmission lines from view point of electric fields.

- For all the transmission lines, permissible value of electric field is 10 kV/m, directly below the outermost conductor and 2m above ground level.
- For all the transmission lines, permissible value of electric field is 2 kV/m, on the edge of ROW and 2m above ground level.

A. Transmission Corridor Width (ROW) as per the MoEF Govt. of India guidelines [11]

Table 1 ROW values for different line voltages

Transmission voltages (in kV)	*Width of Right of Way (in m)*
132	27
220	35
440kV S/C	46
440 kV D/C	46
765 kV S/C (Delta)	64
765 kV D/C	67
1200 kV S/C	89

III. COMPUTATIONAL ASPECTS OF ELECTRIC FIELD

High voltage transmission line electric fields can be computed by numerical methods such as Finite Element, Boundary Element or Charge Simulation Method. In this paper the Charge Simulation Method (CSM) is used for computation of the electric field. Here actual electric field is simulated by a number of discrete simulation charges located on the conductors. Values of simulation charges are determined by satisfying the boundary conditions at a number of contour points selected at the conductor surfaces. Once the values of simulation charges are determined, then the potential and electric field of any point in the region outside the conductors can be calculated using the superposition principle [9]. In order to determine the magnitude of these charges, points on the surfaces of the equivalent conductors (contour points) are chosen, and it is required that at any of these points, the potential resulting from the superposition of the charges is equal to the conductor potential. Also, at each point of the contour points, Maxwell's potential coefficients are determined as follows [13].

$$P_{ii} = ln\left(\frac{2(H_{ave})_i}{(r_{eq})_i}\right) \quad (1)$$

$$P_{ij} = ln\left(\frac{I_{ij}}{A_{ij}}\right) \quad (2)$$

$$I_{ij} = \sqrt{(x_i - x_j)^2 + (y_i + y_j)^2} \quad (3)$$

$$A_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \quad (4)$$

Where

x_i, y_i Coordinates of the ith boundary contour point;
x_j, y_j Coordinates of the jth line charge;
P_{ij} Maxwell's potential coefficient between contour point (i) and line charge (j)
So, at any point (i) on the contour points

$$\sum_{j=1}^{n} P_{ij} Q_j = \varnothing_i \quad (5)$$

Where

$$Q_j = \left(\frac{q_j}{2\pi\varepsilon_0}\right)$$

q_j = discrete charge per unit length (Coulomb per meter);
$\varnothing_i$ = conductor potential where the point is located (in volts).
The application of (5) to the points leads to a system of n linear equations

$$[P][q]\left(\frac{1}{2\pi\varepsilon_0}\right) = [\varnothing] \quad (6)$$

Equation (6) is solved to determine unknown charge values. Then, the charge system is developed and the potential and electric fields can be determined at any point under a transmission line as follows [10 – 12].

$$E_{hi} = Q_i\left(\frac{x - x_i}{D_i^2}\right) \quad (7)$$

$$E_{vi} = Q_i\left(\frac{y - y_i}{D_i^2}\right) \quad (8)$$

$$E_{ti} = \sqrt{E_{vi}^2 + E_{hi}^2} \quad (9)$$

Where
E_{ti} = Total electric field at the ith point (in kilovolts per meter)
E_{hi}, E_{vi} = Horizontal and Vertical components of electric field at the ith point (in kilovolts per meter)

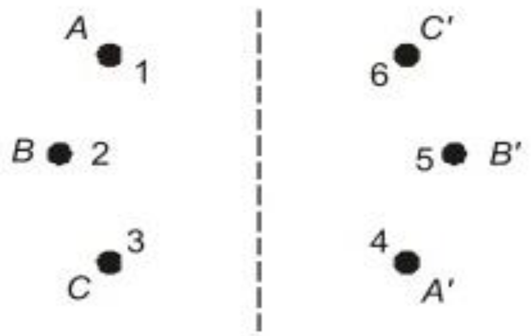

Fig. 1: Configuration of Double Circuit Transmission line.

A Generalized double circuit power transmission line having 6 conductors in 3 phase configuration is shown in Fig.1. This type of conductor arrangement in general gives superior performance as far as inductance and capacitance values are concerned. Depending upon distance of various phases from the center lines they can be differentiated as vertical, hexagonal or inverted V type of configurations. 6 conductors of two circuits are numbered as show in the fig. 1.

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Fig. 2 depicts various components of electric field. Electric field is to be measured at any point A(x, y) as shown in the figure. Electric field due to each conductor will have influence on the resultant field at point A.

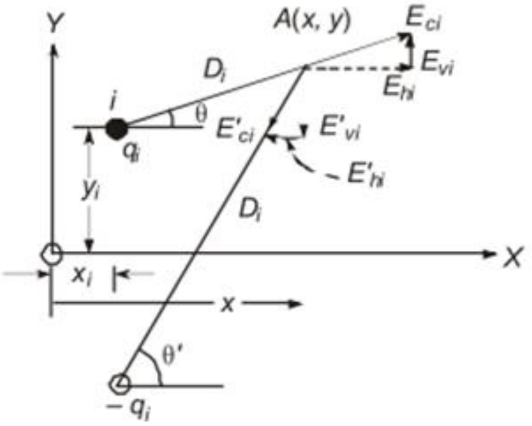

Fig. 2: Electrical field calculation at point A

IV. MODELING OF OBJECTIVE FUNCTION

Fig. 3 shows boundary condition model for optimizing the transmission line design problem. Upper limit of height and line width are governed by cost of transmission structure and lower limits are governed by minimum ground and phase to phase clearance requirements.

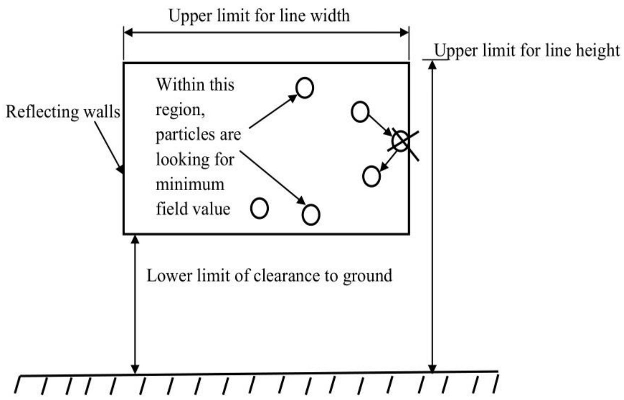

Fig. 3: Boundary conditions for optimization problem

Objective function shown below attempts to optimize the line design problem and make it safe and cost-effective design form electric field view point.

$$\min_{y,z}\left\{ f\left(E(y,z), B(y,z)\right)\right\} \qquad (10)$$

Subject to

$$y_n^{(L)} \le y_n \le y_n^{(U)} \quad \text{and} \quad z_n^{(L)} \le z_n \le z_n^{(U)}$$

Where n = 1, 2, .. , N

- E(y, z), B(y, z) – The objective functions , total normalized effective values of electric field strength and magnetic flux density respectively
- y, z - decision variable vectors(heights of conductor above ground and spacing between conductors)

N – Total no. of conductors

The objective function designed here is multi objective, nonlinear and unconstrained type of optimization problem. GA tool of MATLAB is used to solve the optimization problem by applying appropriate weights to both the objectives, major focus being given to permissible electric fields.

V. DOUBLE CIRCUIT 765 KV LINE DESIGN

Actual data for EHVAC 765 kV double circuit lines, situated in Gujarat – India, is shown in Table 2. Simple vertical, hexagonal and inverted V configurations as shown in fig. 4 are considered for performance comparison purpose. Objective is to evaluate performance of the lines considering fields nearby the line.

Table 2 Initial Design Data for 765 kV EHV line

Particular	Line Configuration		
	Vertical	Hexagonal	Inverted V
No. of sub-conductors	6	6	6
Bundle spacing (B) in (m)	0.4572	0.4572	0.4572
Bundle radius (R) in (m)	0.3233	0.3233	0.3233
Height of Phase A above ground (m)	49.41	49.41	49.41
Height of Phase B above ground (m)	39.11	39.11	39.11
Height of Phase C above ground (m)	28.81	28.81	28.81
Distance of phase A from tower (m)	8.156	7.828	7.828
Distance of phase B from tower (m)	8.156	8.156	8.156
Distance of phase C from tower (m)	8.156	7.828	8.484

Performance of the lines for tower configurations as shown in fig. 4 is evaluated based on actual values of Electric field generated in vicinity of transmission lines.

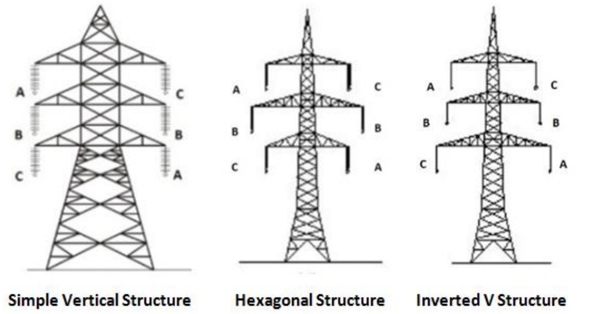

Fig. 4: Different tower configurations for double circuit lines

In order to find out values of electric fields in vicinity of line and along the length of transmission line, a GUI is developed in MATLAB as shown in Fig. 5.

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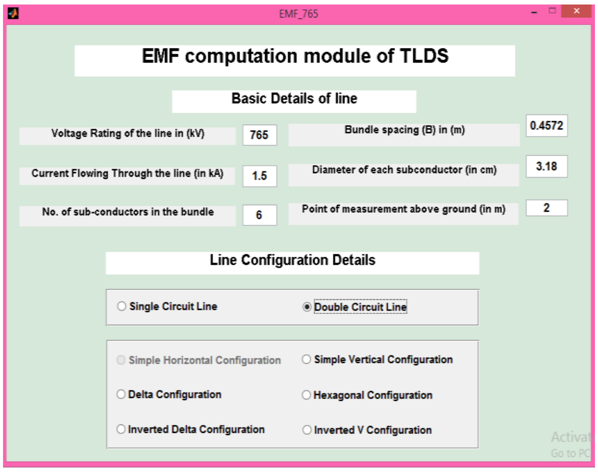

Fig. 5: MATLAB based GUI for computation and analysis of transmission line under study

Objective function developed here and as shown in equation 10 is solved using Genetic Algorithm toolbox of MATLAB. It searches for most optimal configuration of transmission lines. Flow chart for same is shown in fig. 6.

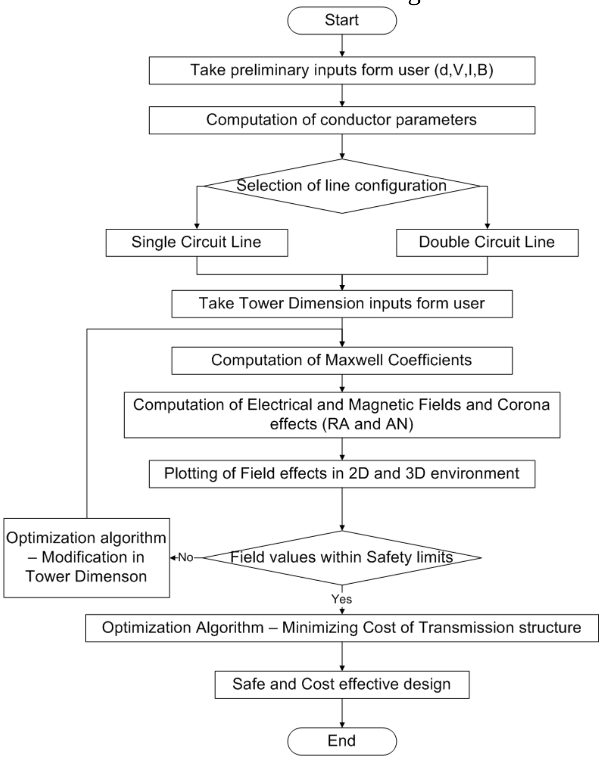

Fig. 6: Flowchart showing algorithm to analyze and optimize transmission line design

VI. ANALYTICAL RESULTS AND DISCUSSION

Fig. 7 shows results of electric field profile plotted for vertical line configuration, data for which is given in Table 2. As seen from fig 7, electric field value is well below 10 kV/m for line configuration under study. This shows that line is safe as per guidelines given in section 2.

Table 3 Electric field values at tower location

Particular	Vertical	Hexagonal	*Inverte d V*
Maximum Electric Field (kV/m)	2.47	2.45	2.51

Also for hexagonal and inverted V configurations nearly similar results are obtained which are shown in Table 3.

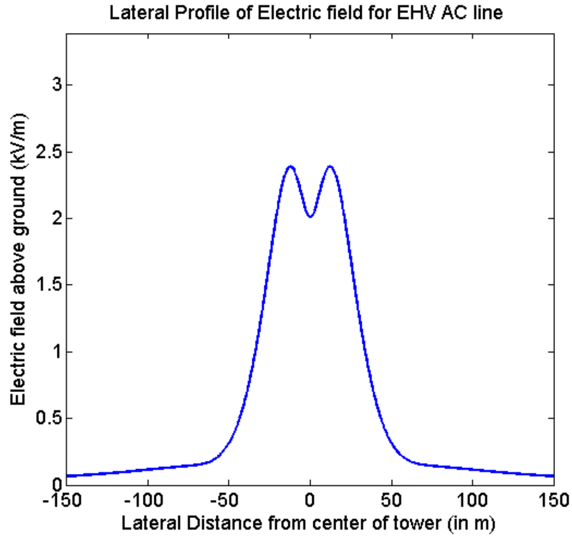

Fig. 7: Electric field for Vertical Line Configuration in Lateral Direction at tower location

Here Electric field profile is plotted in lateral direction at tower location. At this point conductors are at maximum height from ground level. However considering effect of sag along the length of transmission line, ground level clearance of conductors decreases and at mid-point this ground clearance is minimal. Fig. 8 shows electric field profile plotted for hexagonal line configuration.

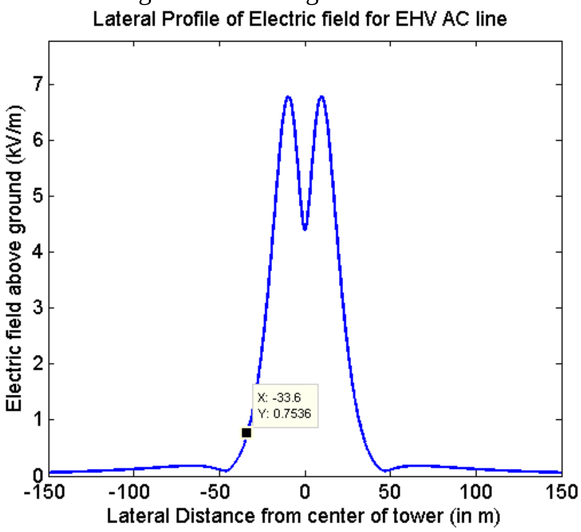

Fig. 8: Electric field for Hexagonal Line Configuration in Lateral Direction at mid-span

These electric field values are obtained at a point where conductors have minimum ground clearance considering catenary effect with sag of 12 m. Following Table 4 shows analytical results of all the three configurations.

Again these results indicate that even at maximum sag condition, electric field values are well below that specified in [5-7]. Furthermore according to Guidelines provided by MoEF, Govt. of India [11], ROW value for 765 double circuit lines should be 67 m as shown in table 1. Considering this value of ROW and measuring electric field on the edge of transmission corridor, there is quite appreciable margin available in transmission corridor width to achieve cost benefits in transmission structure establishment.

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Table 4 Electric field values at Mid Span

Particular	Vertical	Hexagonal	*Inverted V*
Maximum Electric Field (kV/m)	6.87	6.78	6.951

There exists a great potential of saving in ROW cost and also by applying compact tower design philosophy, saving can be achieved in cost of tower construction. Cost benefits due to compact tower design are however not discussed in this paper.

After running optimization algorithm through optimization toolbox of MATLAB, results as shown in Table 5 are obtained for different tower configurations. Also field value for optimized tower structure is plotted for inverted V configuration in Fig. 9.

Table 5 Electric field values at Mid Span

Particular	Vertical	Hexagonal	*Inverted V*
Maximum Electric Field (kV/m)	8.82	8.79	9.1

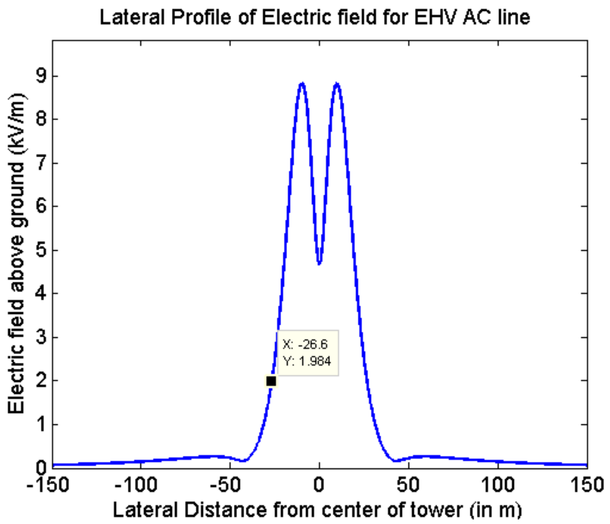

Fig. 9: Electric field for Inverted V Line Configuration in Lateral Direction at mid-span for optimized design

Optimization of the tower structure design has resulted in full utilization of Maximum Permissible Exposure (MPE) value of electric field. Further Optimization algorithm developed here has resulted in reduction of tower height thereby aiding cost benefit in constructional aspects along line length in addition to Right of Way cost benefits.

For optimized tower configurations dimensions are as shown in Table 6 below. With these heights and spacing of conductors and checking against MPE value under outer most conductors and 2 m above ground level it is found that actual value of Electric field is less than permissible value i.e. 10kV / m in all cases. At the edge of ROW value of field should be 2kV / m at a height of 2 m above ground level. This results into Corridor width as shown in Table 7

Table 6 Tower Dimensions for optimized 765 kV lines under analysis

Particular	Vertical	Hexagonal	Inverted V
Height of Phase A above ground (m)	35.11	35.41	34.91
Height of Phase B above ground (m)	25.31	25.11	25.61
Height of Phase C above ground (m)	14.11	14.81	14.51
Distance of phase A from tower (m)	8.156	7.828	7.828
Distance of phase B from tower (m)	8.156	8.156	8.156
Distance of phase C from tower (m)	8.156	7.828	8.484

Table 7 Optimized corridor widths for savings in ROW payments

Configuration	Optimized Corridor	ROW suggested	*Reduction in ROW*
Vertical	52.8 m	67 m	14.2 m
Hexagonal	52 m	67 m	15 m
Inverted V	53.2 m	67 m	13.8 m

Table 8 Details of cost benefits after optimizing the corridor widths based on Electric fields

Particular	Line Configuration		
	Vertical	Hexagonal	Inverted V
Length of line (km)	100	100	100
ROW (before)	67	67	67
ROW (After)	52.8	52	53.2
Land in ROW along the line for original case (hectare)	670	670	670
Land in ROW along the line after optimization (hectare)	528	520	532
Saving in Land due to optimization (hectare)	142	150	138
Average rate of land (in Rs. / hectare)	16 Lac	16 Lac	16 Lac
Saving in cost due to reduced ROW	22.7 Cr	24 Cr	22.08 Cr
% Savings in land cost	21.19 Cr	22.39 Cr	20.6 Cr

Owing to this reduction in transmission corridor width, significant savings are obtainable in ROW payment as indicated in table 9. Details of ROW payments are taken from a case study given in [12]. These are not however exactly applicable values but can be used as a bench mark for the purpose of comparison. As observed from the Table 8, significant saving is obtainable if transmission corridor width is decided taking into consideration the Maximum Permissible exposure values as laid down by standards instead of using simple thumb rules. Almost 20% savings in cost of land acquisition is achievable in all the cases.

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Furthermore this has results in compaction of tower design as well those results into cost cutting in tower construction. Looking to all above factors it can be said that optimizing of transmission structure has resulted in safe and cost effective design for all configurations of transmission tower under study.

VII. CONCLUSION

In this paper performance evaluation of 765 kV transmission lines is carried out by keeping electric field in vicinity of the lines as major criterion. Simple vertical, hexagonal and inverted V configurations are used for comparative analysis. It has been found that hexagonal configuration of transmission lines serves well as far as performance in relation to MPE values of electric field is considered. Also by making compact line design, transmission corridor width requirement is concentrated subsequently benefitting the utility in terms of reduce cost of ROW payments. Use of the newly developed software using MATLAB allows analysis of any complex circuit using 2D techniques. Only basic data pertaining to the transmission line is required by GUI of software. As optimization is performed for different line configurations, cost benefits of almost 20% are obtainable in all configurations. This analysis gives preliminary insight of transmission line design. However detailed and rigorous analysis need to be performed for specific line under consideration by taking all the factors into considerations such as weather effects and associated corona phenomena that is generally predominant in case of EHVAC transmission lines.

REFERENCES

1. Kaustubh A. Vyas, J. G. Jamnani, "Analysis and Design Optimization of 765 kV Transmission Line Based on Electric and Magnetic Fields for Different Line Configurations", *International Conference on Power Systems, ICP –2016*, New Delhi, India, March 2016, pp. 1 – 6.
2. Abdel-Salam, M., Mohamed Abdallah, H., "Transmission line electric field induction in humans using charge simulation method", *IEEE Trans. Biomedical Engineering*, vol. 42, issue: 11, Nov. 1995, pp. 1105 - 1109.
3. R. Amiri, H. Hadi, M. Marich, "The influence of sag in the Electric Field Calculation around High Voltage Overhead transmission lines", *IEEE Conference on Electrical Insulation and Dielectric Phenomena*. Kansas City – USA 2006, pp. 206 – 209.
4. EPRI: "AC Transmission Line Reference Book – 200 kV and above", *Electrical Power Research Institute*, Third Edition, 2005
5. International Commission on Non-Ionizing Radiation Protection (ICNIRP), "Guidelines for limiting exposure to time-varying electric, magnetic and electromagnetic fields (up to 100 KHz)", *Health Physics*, vol. 99, no. 6, 1998, pp. 494-522
6. IEEE Standard C 95.6, "IEEE Standard for safety levels with respect to human exposure to electromagnetic fields 0 – 3 "kHz, 2002.
7. IEEE Standard C 95.3.1, "IEEE recommended practice for measurements and computations of electric, magnetic and electromagnetic fields with respect to human exposure to such fields, (0 – 100 kHz)", 2010,
8. Radwan, R. M., Mahdy, A. M., Abdel-Salam, M., "Electric field mitigation under extra high voltage power lines", *IEEE Trans. Dielectrics and Electrical Insulation*, Vol. 20, No. 1, 2013, pp. 54 – 62
9. Babouri, W. Tourab, M. Nemamcha, "A study of the electromagnetic environment in the vicinity of high voltage lines", *International Conference on Power Engineering, Energy and Electrical Drives*, Istanbul, Turkey, May 2013, pp. 1181 – 1184
10. CBIP: "Transmission line manual", *Central Board of Irrigation and Power*, New Delhi, India. Publication No. 268, 1998.
11. Ministry of Environment and Forests, Govt. of India guidelines dated 5.5.2014
12. Govt. of India: "Guidelines for payment of compensation towards damages in regard to Right of Way for transmission lines". Govt. of India Guidelines, October 2015.
13. Rakosh Das Begamudre, "Extra High Voltage AC Transmission Engineering", *New Academic Science Ltd*., 2014, 4th Edition.
14. Adel Z. El Dein, Mohamed A. A. Wahab, "The Effects of the Span Configurations and Conductor Sag on the Electric-Field Distribution Under Overhead Transmission Lines", *IEEE Transactions On Power Delivery*, Vol. 25, No. 4, October 2010, pp. 2891 – 2902
15. Abdullah H. Al-Bedi, "Measurement and analysis of extremely low frequency electromagnetic field exposure in Oman", *Journal of Electromagnetic Analysis and Applications*, Vol. 4, 2012, pp. 333-339
16. Dong Il Lee, Koo Young Shin, "Technique to decrease the electric field intensity on conductor surface using the asymmetrical sized conductor bundle", *Transmission and Distribution Conference and Exposition*, Chicago, April 2008, pp. 1-6

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