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# Using Cost Efficient Extra High Voltage Transmission Line Design Methodology for Reduction of Transmission Congestion in India

***Abstract: -*** The nation's need for power has increased dramatically, and this tremendous demand for electricity has made technological advancements in transmission networks necessary for the long-distance delivery of significant volumes of electricity. As such, huge chunks of electricity cannot be moved without extra and ultra-high-voltage transmission lines, so the construction and installation of more and more EHV and UHV lines is going to be essential, which further tends towards increased interest in accurately assessing electromagnetic fields and the impacts of corona, such as radio interference and audible noise produced by overhead power lines. This work presents a new method for calculating the fields created by power lines using three-dimensional approaches, based on a graphical user interface (GUI). The analysis is conducted using a real-world example of an extra-high-voltage alternating current (EHVAC) power line. A graphical user interface (GUI)-based software is developed using MATLAB to analyze the fields along the whole length of the transmission lines under investigation. Newly developed software that allows the computation and presentation of electromagnetic fields and corona effects in 3D coordinates is used to analyze the transmission lines. The application of a unique objective function for improving the structural design of extra-high-voltage transmission lines is discussed in this work. The decisions about the right of way for transmission lines are made with consideration for the effects of corona effects and electromagnetic fields in the area surrounding the wires.

***Keywords:*** Electric fields, Magnetic fields, Graphical User Interface, 3D analysis, MATLAB, Extra High Voltage AC Transmission

## I. Introduction

The Indian power sector has been largely insulated from global competition because most of its assets are domestically owned or government-controlled. Power generation has been dominated by publicly owned firms mainly because it has traditionally been viewed as highly capital-intensive, risky, and lacking in financially viable returns for a competitive and vibrant private sector. Given that India has slid from being a power-surplus country in the 1980s to a power-deficit country in the mid-1990s and finally to a power crisis-ridden country in the early 21st century, the structure of the power sector deserves significant attention. About 85% of India's CO2 emissions from electricity generation are from coal-fuelled thermal power generation: coal is the mainstay of power production and accounts for 60 percent of the installed capacity. At the project level, investment in high voltage transmission lines is a prerequisite for investment in the next generation of generating capacity. The nation being on the fast track development stage, and due to exponential growth of industrialization, the ongoing demand for power is likely to be ramped up day by day. Electricity consumption is also constantly increasing due to steady population growth, and in order to meet this demand, an increase in electricity generation and effective transmission is mandatory. Since power producing facilities are typically situated distant from end customers, it is necessary to build an integrated transmission and distribution network to make it easier for end users to receive electricity. Electrical energy is transmitted at extremely high voltages to ensure its efficient usage. This creates a network of high-voltage transmission lines that is always present. Higher transmission voltages have the following benefits: less space needed, fewer circuits needed for the same amount of transmitted power, better voltage regulation, smaller conductor size, lower line costs per MW and km. At present, 765 kV lines cover a distance of 54,797 km throughout India [1]. Further India is the first country in the world that has successfully tested fully functioning 1200 kV UHV AC transmission line [2]

### I.1. Importance of Higher voltage in Indian Context

Numerous benefits are achieved with an increase in transmission voltage level. A few of them are as mentioned below.

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[1]

- Reduced amount of current is required in EHV systems for the same amount of power to be transmitted as compared to HV systems
- Lower current resulting in reduced losses
- Improved efficiency
- Lower amount of voltage drop in transmission lines and thereby improved voltage regulation
- Due to the need of carrying lower amount of current, required size of the conductor is reduced
- Reduction in weight of conductors and thereby saving in cost of transmission infrastructure

Following comparison will help understand the importance of higher transmission voltages [3].

The average power handling ability of one circuit is defined as per equation (1).

E represents the voltage at sending end, V presents voltage at receiving end, and length of the transmission line is represented by L in km and reactance (ohm) per km length of the line is shown by x. Resistance per unit length of line is taken as r ohm/km.

$$P = \frac{E*V*\sin\delta}{L*x} \qquad (1)$$

From this, a generalized equation of percentage power loss for transmission can be derived as shown in equation (2) assuming the same voltage at sending and receiving end side and value of power angle δ as $30^o$. [3]

$$\%P = \frac{100*\sin\delta*r}{x} \qquad (2)$$

Average parametric values of a line are shown in the following table 1 Line length is considered 400 km.

**Table 1.** Average values of line parameters

| ***Voltage (kV)*** | ***Bundle Conductor (n x mm)*** | ***Resistance (ohm /km)*** | ***% Power Loss*** | ***Power Transfer Capacity (MW)*** |
|---|---|---|---|---|
| 400 | 4 x 32 | 0.0310 | 4.760 | 670 |
| 765 | 6 x 32 | 0.0136 | 2.500 | 2860 |
| 1200 | 8 x 46 | 0.0027 | 0.584 | 8625 |

Looking at the above table it is observed that as transmission voltage keeps on increasing, percentage power losses decrease and power transfer capability of line increase in quadratic fashion. Also comparing power intensity of transmission corridor for different voltage levels, following table 2 is obtained

**Table 2.** Comparison of Power Intensities at different voltages

| ***System Voltage (kV)*** | ***Right of Way (m)*** | ***Power Handling Capacity (MW)*** | ***Power Intensity (MW / m)*** |
|---|---|---|---|
| 400 | 46 | 600-700 | 15 |
| 765 | 64 | 2000-2500 | 45 |
| 1200 | 90 | 6000-8000 | 90 |

From the above two tables following important observations can be made.

- The power intensity of a 765 kV line is 3 times higher than that of the 400 kV line.
- The power intensity of a 1200 kV line is 6 times that of the 400 kV line and almost twice in comparison with765 kV line.
- One circuit of 765 kV line is able to transmit power equal to that delivered by four 400 kV lines for the same length of transmission line
- A single circuit of 1200 kV line can carry the power of three 765 kV lines and that equivalent to twelve circuits of 400 kV line for the same distance of transmission.
- Looking to % loss figures of different lines, for the same amount of power to be transferred, 50% less power is lost if a 765 kV line is used in comparison to the 400 kV line
- Upon using 1200 kV line, power loss reduces to 1/8th in comparison to 400 kV line and it's is almost 1/4th of the amount of power lost in 765 kV line for transmitting an equal quantum of power over the same distance

A comparison of the requirement of total number of transmission corridors required for transmitting 8,000 MW power for the same distance at different voltage levels after satisfying (n-1) redundancy criteria is presented in table 3 below [nayak].

**Table 3.** Right of Way (ROW) Requirement of different voltages

| *Voltage (kV)* | *ROW / Ckt* | *No. Of ckt required* | *Total ROW* |
|---|---|---|---|
| 400 | 46 | 15 | 690 |
| 765 | 64 | 4 | 256 |
| 1200 | 90 | 2 | 180 |

As observed from this table, to transfer 8,000 MW power at least 4 transmission circuits are required even at 765 kV EHV level. This involves a huge need for Right of Way to be procured by transmission utility. Also, investment costs in terms of transmission tower infrastructure and conductor material would proportionally increase. Looking at all the above comparisons it is inferred that there is a strong need of adopting UHV level for power transfer over long distances.

All above discussion can be summarised and easily visualized from following figure 1

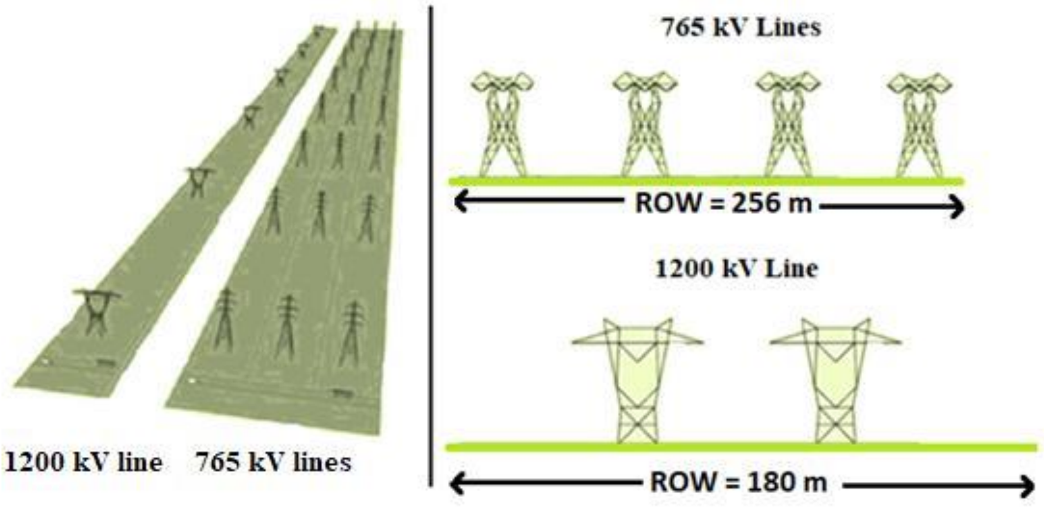

**Fig. 1.** Comparison of different voltage levels for bulk power transmission.

## II. Design Considerations for EHV and UHV lines

Transmission lines are essential to the electrical power industry because they move large amounts of power from generating units to load centers. Transmission line design is a challenging procedure since a lot of variables need to be taken into account, including radio interference, audible noise, magnetic field, and electric field, all of which must be kept within allowable bounds [3]. Accurate analytical modeling of the electric fields generated by overhead power lines is crucial since EHVAC wires are frequently used to transfer large amounts of electricity [4]. At higher operating voltages, the EMF beneath the transmission line conductors is considerable. The most direct goal of attempts to reduce the field effects of EHVAC transmission lines is to analyze and reduce electric fields at ground level [5].

Actually, the majority of electric field effects happens in close proximity to the ground and depends on the strength of the stationary electric field at a height of two meters [6]. In [7], the consequences of sag are mathematically investigated in the cases of varying tower heights and when the spans of the power transmission lines are not parallel to one another. One of the alternate methods for determining the electric field values near and along transmission lines is the Charge Simulation approach [8]. The influence of the line weight sag is either ignored in standard 2D techniques or approximated by providing an effective height for the horizontal line between the line's maximum and minimum heights. These presumptions lead to a model that produces distorted magnetic fields compared to actual magnetic fields [9]. The most important prerequisite is adequate transmission corridor width along the whole transmission line. In order to limit potential risks from electric fields and long-term health problems from magnetic fields (EMF) on occupants, right-of-way is granted [10]. The required corridor width for a transmission line is determined by the surrounding area's magnetic field magnitude owing to power flow in the line, radio interference, peak electric field strength, and audible noise decibel level. The effective values of all non-ionizing fields and corona effects must fall within the bounds given in standards [10-12]. Electric field strength is primarily determined by the following factors: voltage rating, conductor height above ground, conductor cross section area, number of sub conductors, and phase to phase distance. The main factor affecting magnetic fields is the current passing through the line. Plotting the electromagnetic field and corona effects close to the ground surface along the transmission corridor is necessary for analysis and minimization. The values of the fields are measured on the edge of the row of rows (ROW) and at a height of two meters above ground, which is the average human height. Field effects and corona values ought to be lower than the highest values that are allowed over the whole width of the corridor.

### II.1. **Permissible field values from safety view point**

The Maximum Permissible Exposure (MPE) value of the electric field must be determined in order to maintain it as a constraint when designing the transmission line. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) [13] has provided guidelines to establish rules for limiting exposures to electric and magnetic fields in order 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 [14]. These guidelines, along with national literature published by the Government of India [15–17], have led to the following criteria being established.

- The maximum allowable electric field strength for all transmission lines is 10 kV/m at a distance of 2m above ground level and precisely below the outermost conductor.
- The maximum allowable electric field value for all transmission lines is 2 kV/m at the ROW's border and at a height of 2m above ground.

2m vertical distance is considered by assuming average height of 6 feet of any person.

## III. Right of Way Concept and Optimization for cost effective design of transmission line tower

Design equations for electromagnetic fields and corona effects are are available from previous work of author’s research contribution

The area of property that electrical transmission companies use for the construction, upkeep, and operation of transmission lines is known as the right of way (ROW). It is the total of the safety zones along a transmission line's side and breadth. The right of way designates the width of the transmission corridor that cannot be used for building projects or, more generally, as a public transportation route. A representative transmission line tower's right of way is depicted graphically in Fig. 2. Obtaining Right of Way for transmission corridors is challenging in country like India, a country with a vast land area, mostly because power generating stations are situated distant from end users. Higher power density transmission routes are preferred in order to mitigate this land purchase difficulty. Strong, dependable, and lengthy transmission networks are therefore required to transport electricity to far-flung, widely dispersed load centers. As a result of the necessity to transfer substantial amounts of electricity over long distances with restricted Right of Way (ROW), countries are upgrading their current transmission networks to Ultra High Voltage networks. Transmission lines require a sufficient right of way in order to function, particularly when operating at Extra High and Ultra High Voltage Levels.

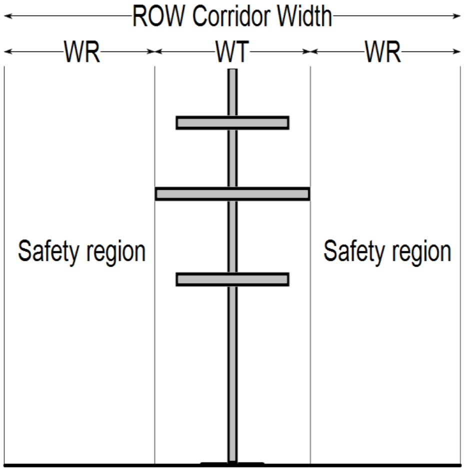

**Fig. 2.** Right of way for a transmission line

Transmission line design involves two costs that must be considered. The cost of the tower structure and line conductor materials comes first, followed by the expense of acquiring the right-of-way needed to create a public transmission corridor that is safe. As seen in the introductory part of section 1 increased voltage level results in significant reduction of the ROW requirements and hence cost saving on land procurement part. Now the task is to optimize the tower structure for getting cost effective design and at the same time resolve the transmission congestion problem in the power deficit country like India.

### III.1. Objective function development for optimization

Figure 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.

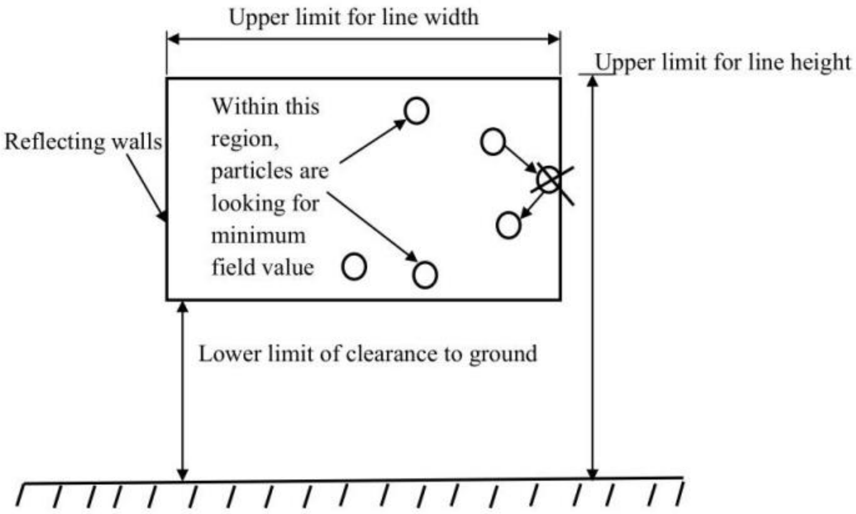

**Fig. 3.** Boundary conditions for optimization of transmission lines

Transmission line optimization aims to maintain all field effects under the maximum allowable exposure values while also lowering the line's ROW need. The maximum values of allowable exposure are displayed in table 4 below. These values are derived from several national guidelines and standards [19–22]. Every field needs to have a maximum value and a ROW value that is less than what is listed in this table. Therefore, it is now necessary to keep tower design safe while also making it compact [23].

**Table 4.** Right of Way (ROW) Requirement of different voltages

| ***Particular*** | ***Maximum Value*** | ***Value on Border of ROW*** |
|---|---|---|
| Electric field | 10 kV / m | 2 kV / m |
| Magnetic field | 1000 uT | 200 uT |
| Radio Interference | 55 dB | 50 dB |
| Audible Noise | 58 dB | 55 dB |

[illegible] maintaining all the field effects and corona phenomenon within prescribed limits. These limits are governed by national and international standards and summarized as above.

For obtaining optimal coordinates of conductors in single/double circuit overhead transmission lines, a multi-objective optimization function involving two different objectives to be minimized simultaneously, subject to certain constraints is formulated as follows

$$\min_{y,z}\{f(E(y,z),B(y,z))\} \tag{25}$$

Subject to $g_m(y,z) \leq 0$; m=1,2,…,M

$y_n^{(L)} \leq y_n \leq y_n^{(U)}$ *and* $z_n^{(L)} \leq z_n \leq z_n^{(U)}$; n = 1,2,…,N

Where

**E(y,z),B(y,z):** the objective function encompassing total effective values of electric field strength and magnetic flux density of overhead line respectively.

**y,z :** the decision variables (height and distance of conductor)

**$g_m$(y,z):** inequality constraints

**M:** No. of inequality constraints

$\boldsymbol{y_n^{(L)}, y_n^{(U)}, z_n^{(L)}, \leq z_n^{(U)}}$ **:** Lower and upper bounds of decision variables

**N:** no. of conductors

Search space is made up of decision variables (y, z). To minimize the objective functions, values of decision variables (coordinates of conductors) are changed and the algorithm searches for an optimal solution within the search region bound by upper and lower limits subjected to constraints. The result is a set of mutually non dominated solutions of optimization which are represented by the set of P objective vectors.

As genetic algorithm is used to solve the objective function defined by equation (25), the search space is initially populated randomly subject to bound values and constraints defined along with the objective function. In the next steps, the algorithm progresses to solve the optimization problem by finding a suitable solution within the boundaries of reflecting walls as shown in figure 3. Lower bounds on the solution are put by minimum clearance requirements as discussed previously. Upper bound values / outer reflecting walls are constituted by cost-based limitations. The exact mathematical modeling of cost function and minimization of cost is beyond the scope of this study and is not part of the research objectives. The main focus is on designing the line with minimum electric and magnetic field values produced subject to regulatory restrictions posed by various national and international standards and guidelines by central electricity authorities and the ministry of power and environment & forest departments.

## IV. Application of Optimization algorithm and its effect on conductor arrangements of 765 kV EHVAC line in India

Actual data for EHVAC 765 kV double circuit lines, situated in Gujarat – India, is shown in Table 5. 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 5: 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 |

### IV.1. Analytical results and discussion

Fig. 4 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 6: Electric field values at tower location**

| Particular | Vertical | Hexagonal | Inverted 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 6.

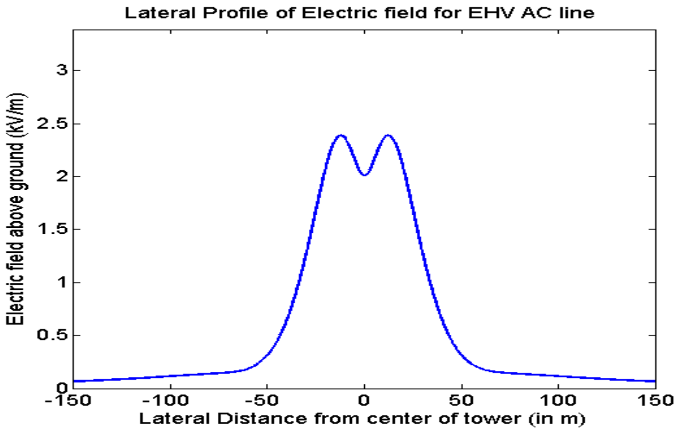

**Fig. 4: Electric field for Vertical Line Configuration in Lateral Direction at tower location**

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.

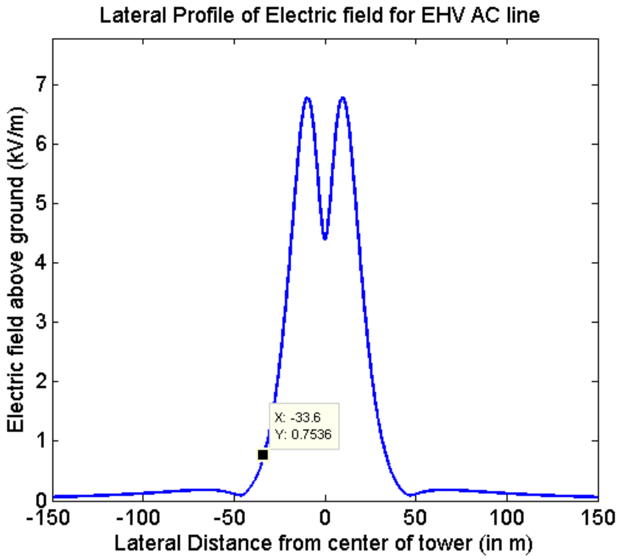

**Fig. 5: Electric field for Hexagonal Line Configuration in Lateral Direction at mid-span**

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.

**Table 7: 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 8: Electric field values at Mid Span**

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

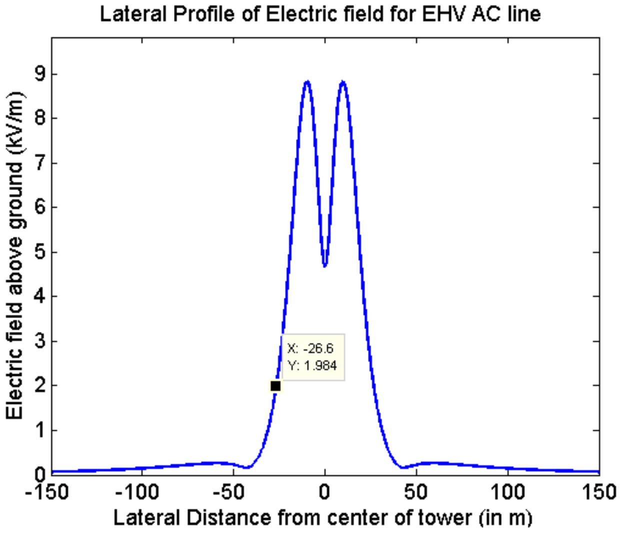

**Fig. 6: Electric field for Inverted V Line Configuration in Lateral Direction at mid-span for optimized design**

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.

**Table 9 Tower Dimensions for optimized 765 kV lines under analysis**

| Particular | Line Configuration | | |
|---|---|---|---|
| | 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 |

For optimized tower configurations dimensions are as shown in Table 9 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 10

**Table 10: 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 |

Owing to this reduction in transmission corridor width, significant savings are obtainable in ROW payment.

Also 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. 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.

## 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, Significant reduction in land requirements is observed. 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.

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