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Analytical Design Optimization of 765 kV Transmission Line Based on Electric and Magnetic Fields for Different Line Configurations

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ABSTRACT

EHV and UHV AC transmission lines that transmit power through overhead mode require piece of land identified as right-of-ways. These are approximated in relation to the operating effects of the energized line, major focus being given to electric field effects, magnetic field strength and physical clearances. A need exists to determine the distribution of these fields in transmission pathways. Accurate computation of the maximum value of the electric field stress at ground surface is of utmost importance from the view point of human safety. In the present research work, estimation of electric field distribution and computation of magnetic field strength in vicinity of the high voltage transmission lines is carried out for EHV AC transmission lines by a newly developed computer program. It uses concept of charge simulation method (CSM) along with most fundamental Maxwell's potential coefficient theory. Simulation results for different configurations of double circuit 765 kV EHV AC lines viz., simple vertical, delta and inverted delta configurations are presented. Profiles of Electric and Magnetic fields are plotted in lateral as well as in longitudinal directions considering catenary effect. Also 3D modelling of lines is carried out and resultant electric and magnetic field profiles along one span of lines are shown. Design optimization is also attempted for minimizing right of way along the length of transmission line.

Keywords: Right of Way, Electric Field, Magnetic Field, EHV AC Transmission, Line Compaction, Optimal Design

INTRODUCTION

Ever increasing power demand has necessitated strong transmission and distribution structure across the country. Transmission lines, performing a crucial role of power transmission, are pivot elements in the power system. As power generating units are at a far distance from end users, transmission of power to consumer is only possible via powerful structure of transmission and distribution lines in the form of interconnected grid. In order to ensure effective utilization of electrical energy, it is transmitted at extra high voltages through network of EHVAC transmission lines. Transmission of the electric power is accompanied with generation of low-frequency electromagnetic fields. Nowadays, of special concern is the possibility of detrimental environmental effects arising from the electrical and magnetic fields formed adjacent to the overhead transmission lines. As EHVAC lines are widely in use for transmitting bulk amount of power, possible effects of electric and magnetic fields underneath the lines have received increasing attention in research work. Electric and magnetic fields generated from transmission lines operated at extra high voltages play important role in design of lines. Precise calculation of EMF under overhead transmission lines is a very important aspect in transmission line design [1].

Potential implications for human health of low-frequency electric and magnetic fields (EMFs) have been looked at in a number of epidemiological studies. Common sources of low-frequency EMFs include overhead power lines (OHPLs), electrical substations and electrical appliances. High values of EMFs have been reported especially at sites in close vicinity of high voltage OHPLs therefore the OHPLs should be designed in such manner so as to minimize electric and magnetic field emissions.

Adequate Right of Way (ROW) along the transmission line is first and foremost requirement. ROW is provided to restrict the hazards due to EMF on inhabitants. The ROW requirement of a transmission line is decided by magnitude of electric field, audible noise, radio interference and magnetic field in its vicinity due to flow of power in the line. Electric and magnetic field values Within ROW must be well below the values specified in the standards [2-6]. If the values of fields are beyond permissible limits, design revision need to be considered.

The EMF below the transmission line conductors is high for higher operating voltages. The analysis and reduction of electric fields at ground level is the most direct objective of efforts to minimize the field effects of EHVAC transmission lines. In fact, most electric field effects occur close to ground level and are function of magnitude of the tranquil electric field at one meter above ground [7]. Values of EMF at the ground level primarily influence the costs for ROW. In order to decide the optimal ROW, the electric field and magnetic field distributions along both sides of the tower need to be plotted.

BASICS OF ELECTRIC AND MAGNETIC FIELDS

The electric field is associated with the system voltage and not to current level [8]. Electric fields from nearby power lines and appliances induce currents in the body as well as charges on the body's surface. The strength of an electric field near a power line depends on the voltage of the line, the distance between the power line to point of measurement, the arrangement of power lines, the radius of current carrying conductors and the balance of the phases [9]. Magnetic fields are defined in terms of the force exerted on a moving unit charge and thus are proportional to the flow of electric current, not having any kind of association with system voltage. There are several factors that affect the level of magnetic field produced by overhead transmission lines: the arrangement of transmission lines, the most important being amount of current flow though the lines, the height of conductors from the ground, the balance among phases, and the presence of earth conductor.

Standard guidelines for maximum permissible exposure values of Electric and Magnetic fields

ICNIRP is an international commission of scientific experts in the area of biological and health effects of electric and magnetic fields [3]. The main objective of this guide is to establish guidelines for limiting exposure to electric and magnetic fields that will provide protection against all established adverse effects. Guidance is given for two categories: occupational and general public exposures. Occupational exposure refers to adults exposed to the fields at their workplace, generally under known conditions. General public exposure refers to individuals of all ages and of varying health status, who are unaware of their exposure to fields. Table I presents the ICNIRP reference levels for 50 Hz [10].

Table -1 ICNIRP Guidelines

Maximum Permissible Exposure (MPE) level for 50 Hz	Electric Field strength (kV /m)	Magnetic Flux Density (μT)
General Public	**5**	**200**
Occupational Exposure	**10**	**1000**

EMF COMPUTATION METHODOLOGY

Maxwell's Potential Coefficient method and ampere's circuital law are used for computation of electric field and magnetic fields respectively in the vicinity of the transmission line [10-15]

Computation of Electric Fields

Let q = total bundle charge and V = line to ground voltage then

$$\frac{1}{2\pi\varepsilon_0}[q] = [P]^{-1}[V] = [M][V] \tag{1}$$

Where

[q] = [q_1, q_2, q_3,...,q_n] is array containing charges

[V] = [V_1, V_2, V_3, …, V_n] is array containing applied voltages

[P] = n x n matrix of Maxwell's Potential coefficients

With reference to Fig. 1 horizontal and vertical components of electric field are

$$E_h = E_c cos\theta = \frac{q_i}{2\pi\varepsilon_0}\frac{(x-x_i)}{D_i^2} \tag{2}$$

$$E_v = E_c sin\theta = \frac{q_i}{2\pi\varepsilon_0}\frac{(y-y_i)}{D_i^2} \tag{3}$$

Where $$\mathrm{D_i^2} = (\mathrm{x}-\mathrm{x_i})^2 + (\mathrm{y}-\mathrm{y_i})^2, \quad \mathrm{E_c} = \left(\frac{\mathrm{q_i}}{2\pi\varepsilon_0}\right)\left(\frac{1}{\mathrm{D_i}}\right) \tag{4}$$

Similarly, fields due to image of the conductors below the ground need to be considered and ultimately effective horizontal, vertical or total electric field for the given transmission line geometry can be found.

Computation of Magnetic Fields

Fig. 2 shows the 3 overhead conductors and the ground surface replaced by image conductors below the ground surface. This assumes that the ground surface is a flux line. The origin of a coordinate system is placed on the ground underneath the centre-phase. The conductors are at height h above ground and the phase separation is s. At the point P (x, y), the components of magnetic field are as follows:

Due to the conductor current

$$H_c = \frac{I}{2\pi D_c}, where\ D_c = \sqrt{(x-s)^2 + (y-h)^2} \quad (5)$$

Due to the image current

$$H_i = \frac{I}{2\pi D_i}, where\ D_i = \sqrt{(x-s)^2 + (y+h)^2} \quad (6)$$

Total horizontal and vertical components of the field are as shown in following equations

$$H_h = \frac{I_c}{2\pi}\left[\frac{y+h}{(x-s)^2+(y-h)^2} - \frac{y-h}{(x-s)^2+(y+h)^2}\right] \quad (7)$$

$$H_v = \frac{I_c}{2\pi}\left[\frac{x-s}{(x-s)^2+(y-h)^2} - \frac{x-s}{(x-s)^2+(y+h)^2}\right] \quad (8)$$

Corresponding flux densities are

$$B_h = \mu_o H_h\ and\ B_v = \mu_o H_v, Tesla \quad (9)$$

DESIGN PARAMETERS FOR THE 765 KV LINE

Sample data for an EHVAC 765 kV double circuit line carrying maximum current of 2kA is shown in Table II. Simple Vertical, Delta and Inverted Delta configurations are considered for performance comparison purpose. Objective is to evaluate performance of the lines considering electric and magnetic fields in vicinity of line.

Table -2 Preliminary Design Parameters Line Design

Particular	**Line Configuration**		
	Vertical	***Delta***	***Inverted Delta***
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
Diameter of conductor in (cm)	3.18	3.18	3.18
Height of Phase A above ground at tower location (m)	48	40	40
Height of Phase B above ground at tower location (m)	38	30	40
Height of Phase C above ground at tower location (m)	28	30	30
Distance of phase A from tower (m)	10	10	12
Distance of phase B from tower (m)	10	12	8
Distance of phase C from tower (m)	10	8	10

Initially performance of the lines for line configurations shown in fig. 3 is evaluated. Then variation in various parameters for given configurations are tried to get best performance of the transmission lines from EMF view point and to achieve minimum ROW.

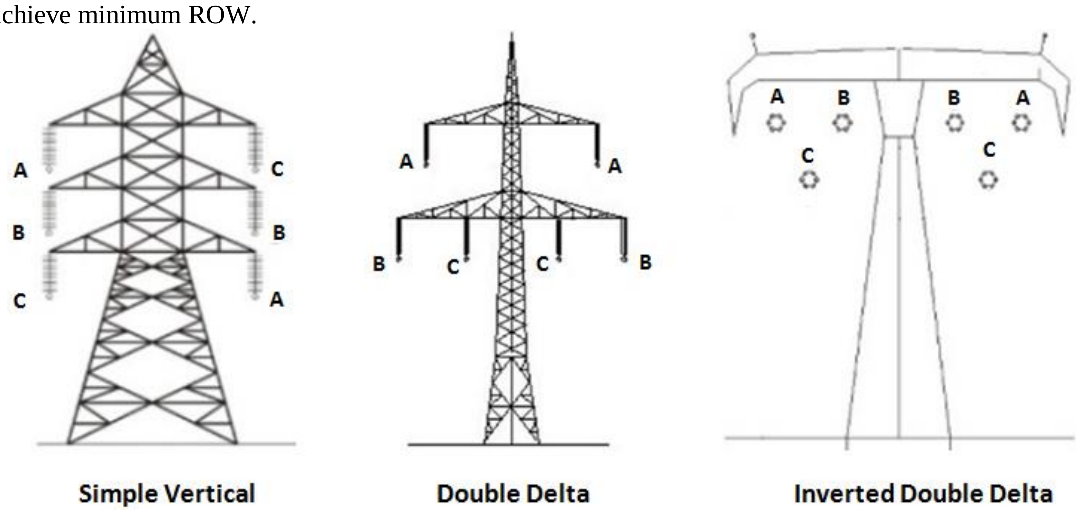

Fig. 1Vertical, Delta and Inverted Delta line configurations under study

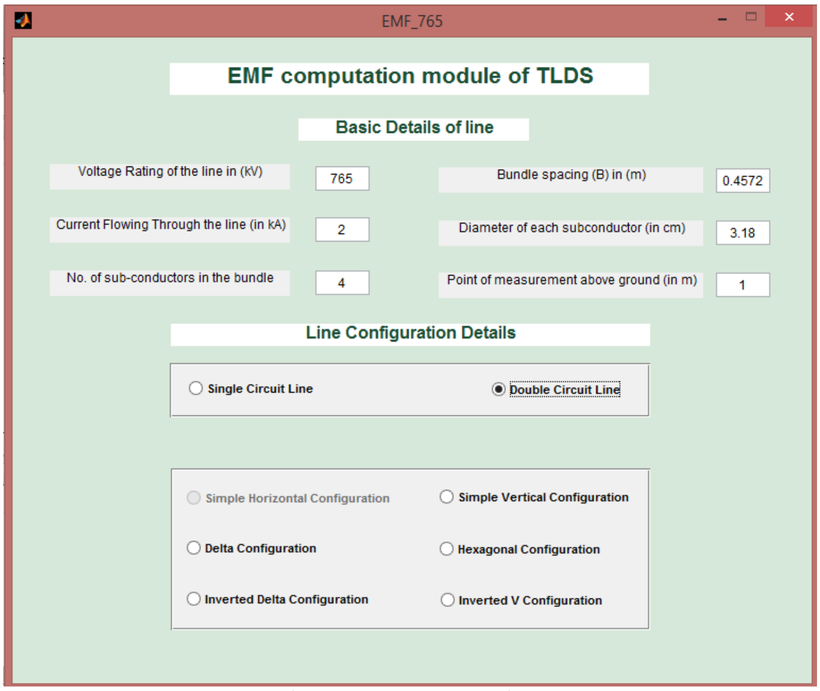

Fig. 2 GUI for EMF computation of various lines

PERFORMANCE EVALUATION AND DESIGN IMPROVEMENT OF PROPOSED 765 KV LINES

MATLAB coding along with GUI as shown in fig. 4 is designed to ease the performance analysis process. For all the three line configurations under study viz. simple vertical, delta and inverted delta, lateral profile of electric field in vicinity of the line is computed and plotted as shown in figure 5. As seen from the figure electric field for all the configurations within ROW is under tolerable limits as shown in table - 1.

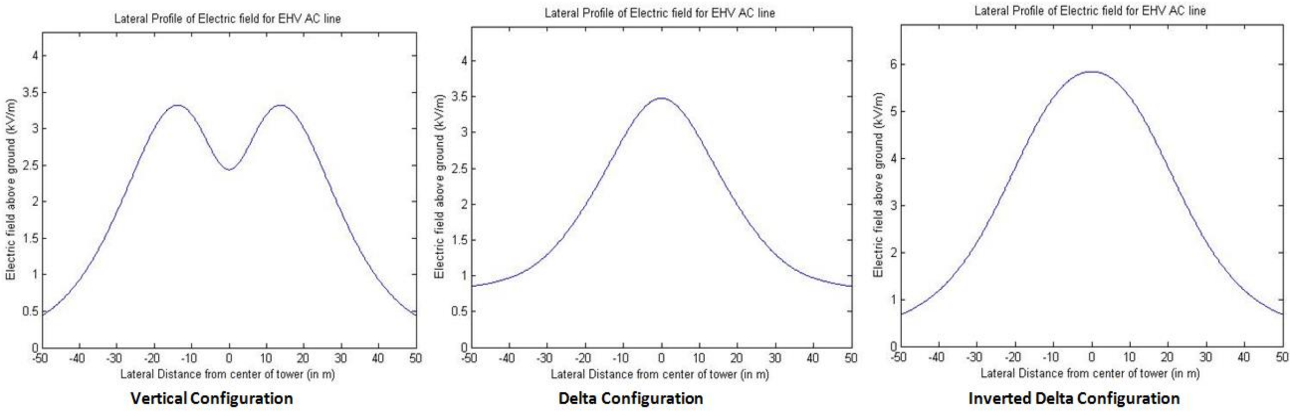

Fig. 3 Electric field of line configurations under study (in lateral direction)

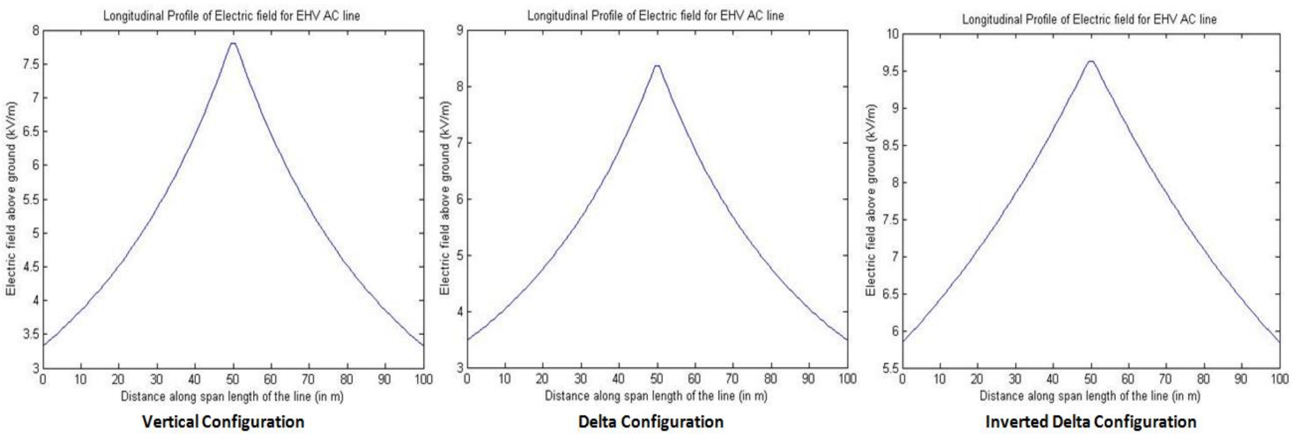

Fig. 4Electric field of line configurations under study (along one span length)

Graphs in fig. 5 show the Electric field values considering conductor height at tower which is highest within the span length. We also need to consider electric field values at mid-span where conductors will have maximum sag and will be at minimum height above the ground. In order to find the maximum value of field at places other than the tower location. Separate MATLAB code is developed and resultant maximum field values are plotted in longitudinal direction along the length of one span for all the configurations as shown in fig. 6.

As observed from above graph, even at the mid span where conductors are at minimum height above the ground level, maximum value of electric field is well below the acceptable maximum permissible exposure (MPE) value as specified by standards [3,18-19]. Hence there lies quite appreciable margin between actual value and permissible value of the maximum electric fields especially in case of vertical configuration. It is possible to change the dimensions of line and cost effectiveness can be achieved by allowing the electric field to have somewhat more value than that of existing which is below MPE value.

Also in case of magnetic field calculations, profile of magnetic field in lateral direction at tower location and longitudinal profile of maximum magnetic field along the length of one span are plotted and shown in figures 7 and 8. These figures also indicate ample reserve available of cost optimization to be applied. Also at the same time minimum clearance values need to be considered carefully. General observation made from all above results is that from the alternatives of vertical, delta and inverted delta line configurations the first configuration results into lower values of electric and magnetic field all along its length. Also due to reduced spacing between the phases and tower it leads to compact tower design requiring smaller size of cross arms though at increased tower height. Also reduced width of tower results in compact corridor requirement thereby lowering cost of ROW.

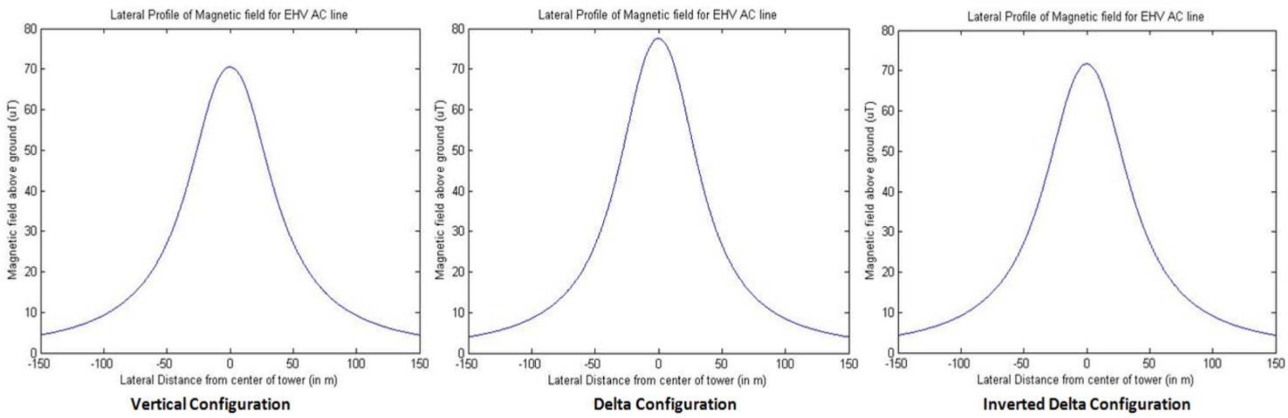

Fig. 5 Magnetic field of line configurations under study (in lateral direction)

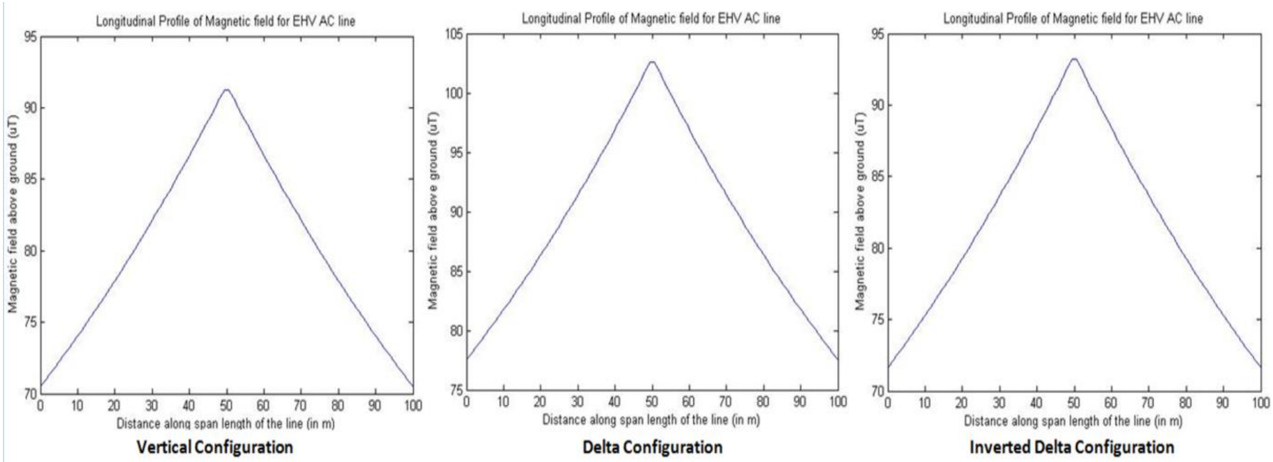

Fig. 6 Magnetic field of line configurations under study (along span length)

RESULTS AND DISCUSSION

For optimization main thing to be considered is that electric field limits should be in acceptable limits considering following regulation as lied by national guidelines [17-18]. Electric field at 1m above ground below the outer most phases should be equal to or less than 10 kV/m and equal to or less than 2 kV/m at the edge of right of way. After trying different values of phase spacing and conductor heights above ground level, considering minimum clearances as mentioned in [19-20] following results are found to get optimum design of the line.

For vertical configuration with phase spacing of 10 m from center of tower and minimum conductor height of 25 m at tower location, the ROW is found to be 60.4 m as is apparent from graph shown in fig. 9. For Delta configuration with phase spacing shown in table – 2 and minimum conductor height of 27 m at tower the ROW is found to be 72.8 m as is apparent from following graph. Further from graph of electric filed plotted for inverted delta configuration, with dimensions mentioned in table –2 and minimum conductor height to be 30 m at tower location, ROW value is calculated to be 63.8 m.

Table – 2 Dimensions of Tower and Lines After Optimization

Particular	Line Configuration		
	Vertical	*Delta*	*Inverted Delta*
Height of Phase A above ground at tower location (m)	48	37	40
Height of Phase B above ground at tower location (m)	35	27	40
Height of Phase C above ground at tower location (m)	25	27	30
Maximum Sag (m)	10	10	10
ROW calculated (m)	60.4	72.8	63.8

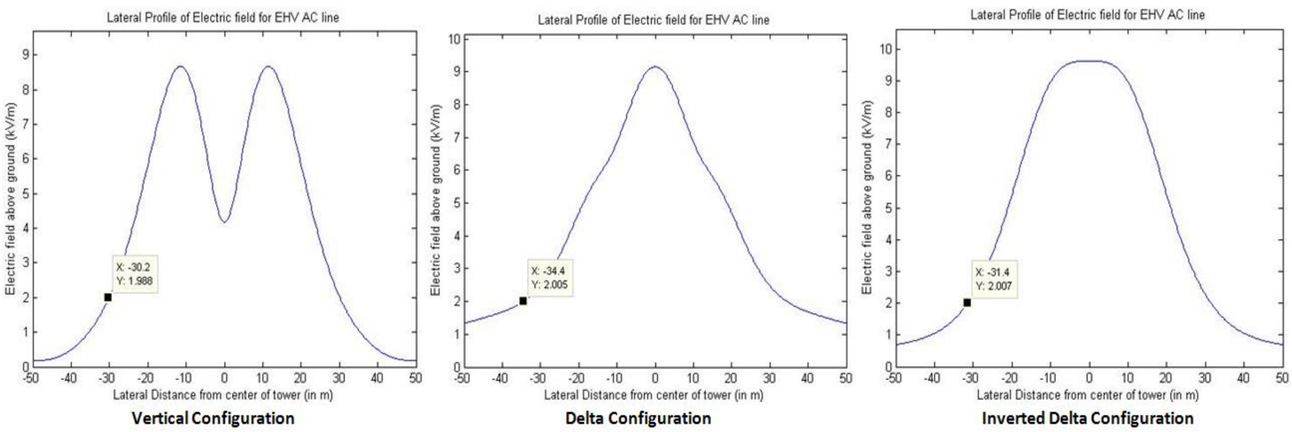

Fig. 7 Electric field profile of horizontal and delta configuration - optimized case

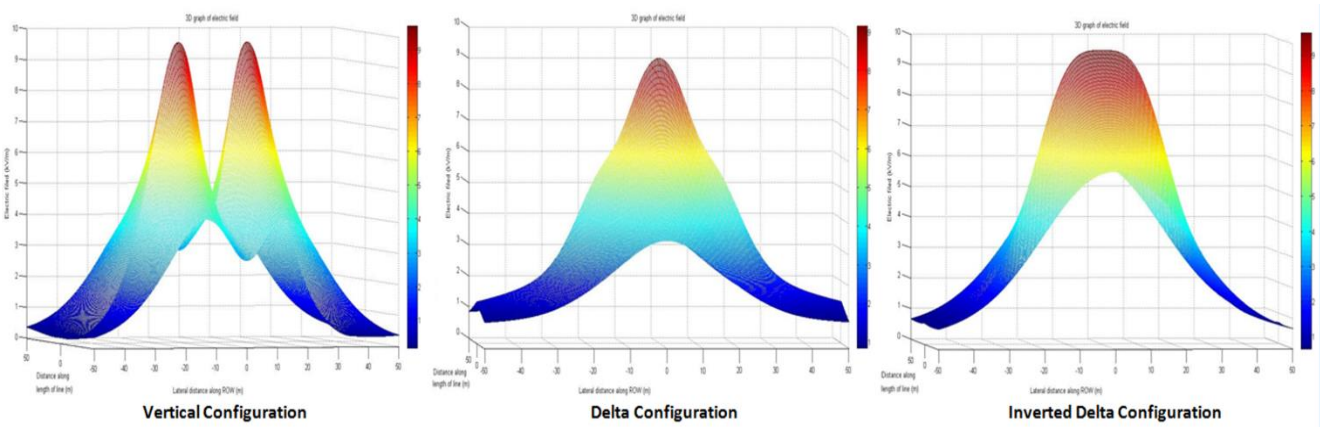

Fig. 8 Electric field profile of line configurations under study in 3 dimensions

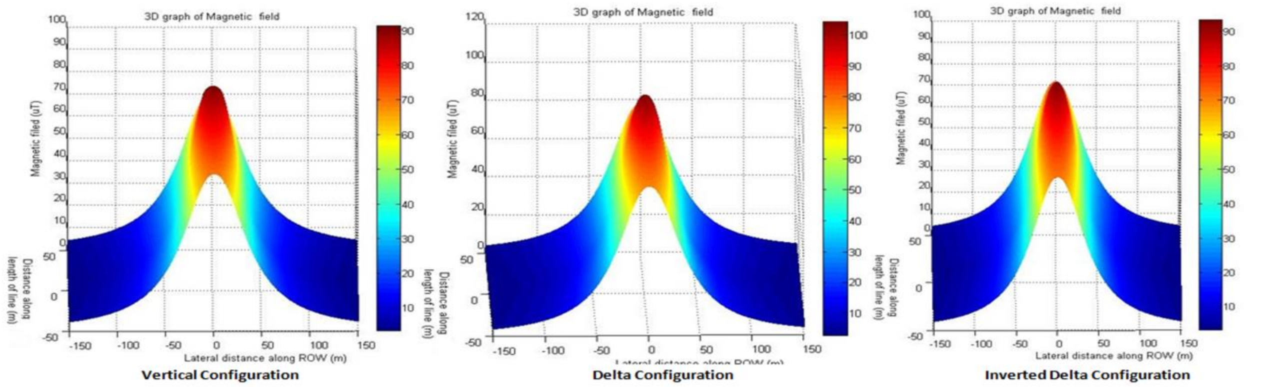

Fig. 9 Magnetic field profile of line configurations under study in 3 dimensions

Fig. 9 has been plotted at mid span where conductor is nearest to the earth. Even at the mid span the maximum electric field is less than 10 kV/m under outer most conductors. Also in case of magnetic fields the computed values are far below the MPE values. Fig. 10 shows variation of electric field in 3 dimensions for all the three configurations.

As far as performance of lines from view point of magnetic fields in vicinity of the lines is concerned, there is no such great issue as magnetic field values for all the line configurations is far lower than the acceptable values indicated in relevant standards [3, 5, 17]. Following figure 11 indicates magnetic field profile in 3 dimensions along one span length of the transmission line. Here compact tower dimensions are considered for which electric field profiles are plotted in figure 10. Thus it is observed that while compacting the tower gives cost effectiveness, at the same time it is not putting at threat as far as human safety from electric as well as magnetic fields in vicinity of the lines are considered.

CONCLUSION

Performance evaluation of 765 kV transmission line is entertained by keeping electric and magnetic fields in vicinity of the lines as major consideration. Simple vertical, double delta and inverted delta configuration are attempted for comparative analysis. It has been found that vertical configured transmission lines exhibit better performance as far as EMF criterion is considered. Making use of compact tower design with vertical configured line as against double delta and inverted delta line improves performance of line by lowering the EMF values in vicinity of the line. Also by making the compact line design, corridor width requirement (ROW) is also reduced resulting in cost benefit to the utility. Here it is found that vertical configuration with 25 m minimum conductor height from ground level at the tower and 15 m at mid span and 10 m phase spacing from center of tower results in optimal design of the line that gives best results in terms of acceptable maximum electric and magnetic field exposure values and also it gives lesser ROW requirement as compared to other two configurations. Also vertical configuration results in compaction of tower, as it requires smaller cross arm compared to other designs. From above analysis it is suggested that as far as possible vertical configured lines should be used whenever double circuit line is encountered as preferred over delta or inverted delta lines.

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