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RESEARCH ARTICLE

Comparative Analysis of 500 kV Double-Circuit Transmission Line Electric Field Intensity: Ethiopian Lines Compliance With ICNIRP

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ABSTRACT The high-intensity electric fields, which are in the vicinity of power transmission lines, have adverse effects on human and other living beings if they are not within the specified limits. The International Commission on Non-ionizing Radiation Protection (INCIRP) specifies guidelines for these E-fields from the perspective of public exposure at the ground level and sets it to 5 kV/m at 50 Hz. Thus, this study was aimed at analyzing and comparing the E-fields intensity of differently configured double-circuit 500 kV transmission lines at a height of 1 m above the ground plane. Charge Simulation Method (CSM) using MATLAB as a programming platform is used for this study. Among the tower configurations studied, a configuration that provided minimum E-fields with minimum ground clearance was identified. From the actual built transmission lines included in the study, vertical lines configuration produces a minimum E-fields intensity of 4.565 kV/m root mean square and fulfills the INCIRP requirement. However, triangular line configuration is the preferable configuration for 500 kV double circuit transmission lines giving the least E-fields at the ground with minimum ground clearance using optimized phase sequence arrangements irrespective of other comparative parameters. Additionally, an evaluation of these line configurations based on the distribution of the conductor surface E-fields was conducted. The study reveals that the E-fields on the surface of the transmission line conductors included in the study remains significantly below the intrinsic breakdown strength of atmospheric air. Therefore, it was anticipated that the designs will remain free from corona discharge under fair weather conditions.

INDEX TERMS CSM, double-circuit 500 kV lines, E-field, INCIRP guideline, phase sequence arrangement, tower configuration.

I. INTRODUCTION

Bulk power is transmitted using high voltage (HV) power lines which are single, double, or quadrupole circuit arrangements on a single transmission tower. The assessment of the Electric field (E-fields) generated by these transmission lines at the ground level and the surface of the conductors of these lines has received increasing attention from researchers [1], [2], [3], [4], [5] over the past couple of decades. Conductor arrangement, clearances between conductors, and minimum ground clearances are some factors that affect the E-fields intensity at the ground and on the conductor surfaces in high-voltage power transmission systems [6]. The E-fields intensity due to these high voltage transmission lines has consequences on human health [3], [4], [5], [6]. Complementing these studies, some research findings have shown that long-time repetitive exposure to the E-fields may bring some changes in DNA in the cells (under certain conditions) [7]. The International Commission on Non-ionizing Radiation Protection (ICNIRP) has framed the guidelines for limiting

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E- fields which can be termed as safe from health perspective. The ICNIRP recommends that the rms value of the E-fields should be below 10 kV/m for occupational exposure and below 5 kV/m for public exposure at a system frequency of 50 Hz [8]. Hence, a study related to the analysis and estimation of E-fields intensity concerning public exposure is important.

Another technical and environmental problem of these extra high voltage (EHV) and ultra-high voltage (UHV) transmission lines due to the possibility of initiation of corona discharges. The magnitude of electric field distribution in the vicinity of the conductor surface is the decisive factor for corona inception in the given air insulation [9]. Thus, analysis of the E-fields strength on the surface of conductors was found to be important for the corona-free design and operations of transmission lines.

For the safe and economic designs of high-voltage electrical equipment computation, estimation, and analysis of E-fields distribution are very vital. Computation of E-fields distribution in the vicinity of lines can be obtained using numerical methods like Finite Difference Method (FDM), Finite Element Method (FEM), Charge Simulation Method (CSM), Surface Charge Simulation Method SCSM), and Boundary Element Method (BEM) [10], [11], [12]. CSM is one of the commonly preferred methods for E-fields computations in HV open-boundary problems as it does not involve the discretization of the solution region [11].

In the works of literature, one can find different line configurations of double-circuit EHV transmission lines. Tupsie et al. [13] analyzed the E-fields of inverted V arrangement of conductors of a double circuit 500 kV transmission line with special emphasis on the effect of transposition using FEM. Marungsri et al. [14] have reported the effect of tower grounding resistance on the back-flashover voltage across insulator strings. The analysis carried out is for a 500-kV double circuit transmission tower whose conductors are configured in an inverted V fashion. Truong Anh and Nguyen [15] used this double-circuit 500 kV configuration to compute associated magnet fields. They have suggested some measures for reducing the magnitudes of magnetic fields. The line performance related to lightning and electromagnetic interference radiation in the vicinity of an 'Inverted Y' type double circuit 500 kV conductor configuration was analyzed and reported in references [16] and [17]. References [18] and [19] have reported the E-fields inverse problem, analysis of safety and protection measures for maintenance work in a double circuit 500 kV 'triangular' lines configuration. Research related to induced current and voltage of double circuit of 500 kV vertical line configuration is reported in [20]. The list of references described in this paragraph have used different conductor configurations of 500 kV double circuit lines in analyzing associated E-fields and magnetic fields. Other references [21] and [22] have used conductor configurations of the type 'vertical', 'hexagonal', and 'inverted-V' for their study of different transmission line voltages (other than 500 kV).

As aforementioned in the previous paragraph, various studies have been conducted on 500 kV double-circuit power transmission lines with different configurations. However, no studies have compared the E-fields in view of ICNIRP guidelines for these differently configured double-circuited 500 kV lines operating at the same transmission voltage level. Furthermore, this study presents the first E-field analysis of the Ethiopian 'Inverted Y' double circuit, 500 kV line. Therefore, in the present work, E-fields distribution due to 500 kV double circuit transmission line conductor arrangement of 'inverted Y' type is analyzed and compared with E-fields computed for 'triangular', vertical, and inverted V type line configurations. The reported results are of E-fields at 1 m above the ground level. This E-fields computation is carried out using CSM and compared in the view of ICNIRP guidelines. The study aimed at identifying the best conductor configuration among the 500 kV double circuit lines adhering to INCIRP guidelines and also resulting in minimum ground clearances.

A. CHARGE SIMULATION METHOD (CSM)

Mathematical techniques to calculate the electromagnetic field quantifies necessarily require a model of the technical device to reflect the physical behavior of the high-voltage transmission line. Numerical methods were used to determine the field distribution for complex geometries where it is cumbersome and expensive to use analytical techniques or run laboratory tests. CSM is a very common numerical tool used to analyze the E- field from a different categories of numerical method analysis. It becomes a simple, efficient, and applicative numerical calculation method of the electromagnetic field belonging to the equivalent source [23]. According to Maxwell's equation and Green's theorem, the equivalent surface charge on the closed surface that surrounds the region can be used to replace the objective field source in that region. Therefore, the surface charge of a conductor is replaced with a set of discrete fictitious charges located inside the conductor. Each sub-conductor and ground wire is represented with line charges at the center of the conductors. Based on the Laplace equation, these hypothetical simulating charges are used to replace the continuous charge distributed on the electrode surface, which can be used to calculate the electric field strength at particular points using the superposition principle [24], [25]. The magnitude of the fictitious charge should be exactly determined by solving the system of linear equations to comply with boundary conditions at some points [26], [27].

$$[Q] = [P]^{-1}[V] \tag{1}$$

where [P]-potential coefficient matrix

[Q]- Charge quantity matrix

[V]-potential applied

The effect of an infinite ground plane is considered using image conductors. In the present study, CSM is used to analyze E-fields by simulating and modeling different tower configurations for 500 kV double circuit transmission

TABLE 1. Details of transmission line conductors' specifications and tower configuration.

Configuration	Line conductor Diameter [mm]	Space between bundles [mm]	Ground wire diameter [mm]	Mid-span ground clearance [m]
'Inverted Y' [28]	27.72	450	11.5	12.2389
Vertical [20]	33.6	400	15.8	20.3
Inverted V [13]	27.72	457	9.114	13
Triangular [18]	29.6	804.16	-	11

lines. The CSM programming code was developed using MATLAB. Instantaneous supply varying at an interval of 10 degree is considered for the simulation. The E-field was computed at a height of 1 m above the ground, with 0.1m interval both 50m to the right and 50 m to the left from the midway between the towers. The effect of an infinite ground plane is simulated by using the image conductors with appropriate potentials. A line was constructed by four conductors bundle (sub-conductors).Each sub-conductor was represented by a single line charge placed at the conductors' center. Thus, a total 52 sub conductors are simulated. Four test points for each sub-conductor and 1001 × 19 matrix size was used to the E-field of the simulation model. The maximum potential deviation error obtained during simulation is 0.1623% which exists on the line conductor.

II. ETHIOPIAN 500 kV TRANSMISSION LINE

The Ethiopian newly installed 500 kV transmission line covers 850 km from the Great Ethiopian Renaissance Dam (GERD) to Holeta station. It is a dual, double circuit, transmission line system that uses 4 bundle ACSR, "CONDOR" conductors with 450mm spacers dimensions, one optical fiber cable shield wire, and one galvanized steel shield wire. The ruling span of the transmission line is 400m. The minimum ground clearance given is 12m for normal ground. The suspension tower (DL type tower) height, from bottom conductor to ground is 26.7m. The transmission lines were configured in 'inverted Y' configurations [28].

III. TRANSMISSION LINE AND TOWER CONFIGURATION DETAIL

The physically existing detail specification of transmission lines with their tower configuration used in the study was presented in Table 1. The transmission line is 500 kV double circuits with one circuit on each side of the tower, 4-bundle, and two ground wires/OPGW at the top of the towers.

A. PHYSICAL MODEL

In the CSM model, the conductors are modeled at the midway between two towers with ground clearance as a reference. The actual existing bundle conductors are modelled and appropriate instantaneous value potentials are supplied with 100 phase angle intervals. The E-fields were evaluated 50 m to the right and left side from the midway between the towers. The sag and transmission tower effects are neglected. The details of the transmission line conductor's model and arrangements at the midway span for every configuration were given in Fig. 1 and Table 2.

TABLE 2. Physical model dimension for configurations.

Configu ration	Line clearance from ground[m]				Line clearance from tower axis[m]			
	D1	D2	D3	G	b1	b2	b3	g
Inverted Y [28]	12.2 4	23. 7	35. 3	45. 2	7.1	4.9	4.9	6.7
Inverted V[13]	13.0	24	35	48. 51	7.9 2	6.8 2	5.62	4.7
Vertical [20]	20.3	29. 7	39. 2	45	10. 3	10. 3	10.2 8	8.7 5
Triangul ar [18]	11	11	18	4.5	4.5	5.5	11.5	-

In this simulation work, the following assumptions were made. (i) Conductors are placed at a height corresponding to mid-span (midway between the towers) with minimum ground clearances. This is to show the worst scenario where the conductor ground clearance is minimal and the conductor's sag is neglected. (ii) Towers structures effect is neglected. The transmission line shown in Fig. 1 is a planar problem with the transmission line assumed to run perpendicular to the plane. Using the image conductors, the effect of an infinite ground plane is simulated with appropriate potentials. A total of 24 sub-conductors and 2 grounding wires were simulated for each configuration. The nominal voltage of the conductor is 500 kV line to line. The overhead earth wire has no potential assigned.

IV. SIMULATION RESULTS AND COMPARISON

An instantaneous time-varying potential is applied with the instantaneous values obtained using equations 2 to 4. The E-fields is computed over half a cycle (of 50 Hz) at every 10° θ intervals.

$$V_R = V_p \sin(\theta) \tag{2}$$

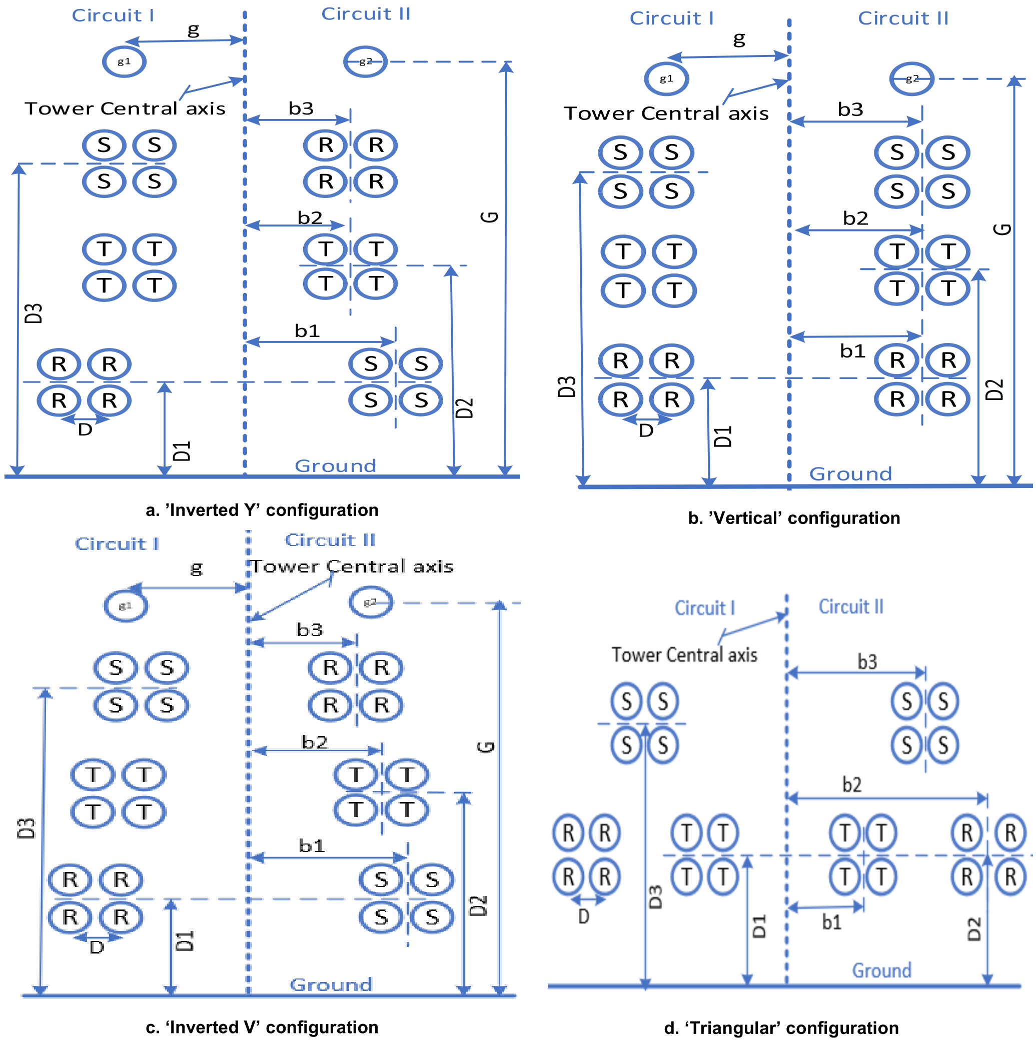
$$V_S = V_p \sin(\theta - 120^0) \tag{3}$$

$$V_T = V_p \sin(\theta - 240^0) \tag{4}$$

where $V_P = 500\sqrt{(2/3)}\, kV$

The E-fields at 1 m above the ground level at midway between two towers parallel to the conductors 50 m on either side of the midway span tower axis are computed. The variation of electric field intensity distribution around 500 kV double circuit transmission line with actual existing dimensions and optimized phase sequence arrangement are analyzed and the results are presented in Table 3.

As indicated in literatures [29], [30], [31], and [32], phase sequence arrangement is one method of reducing E-fields at the ground level of transmission lines. Therefore, an optimal phase sequence arrangement where the E-fields intensity at the ground became minimum was identified and used for the physical model to make it suitable for comparison as presented in Table 3.



a. 'Inverted Y' configuration

b. 'Vertical' configuration

c. 'Inverted V' configuration

d. 'Triangular' configuration

FIGURE 1. **500 kV double circuit conductors' physical model at midway between towers for different line configurations.**

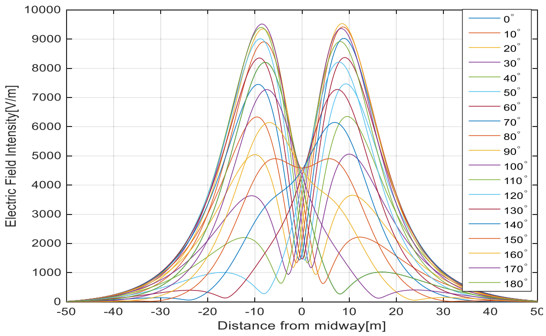
TABLE 3. **Tower configurations maximum E-fields magnitude at 1 m above ground level.**

Configuration Type	Actual existing arrangement maximum E-fields [kV/m-rms]	Optimized phase sequence arrangement maximum E-fields [kV/m-rms]
'Inverted Y' [28]	6.7394	6.7394
Vertical [20]	4.5654	2.7572
Inverted V [13]	6.1163	6.1163
'Triangular' [18]	11.165	7.5203

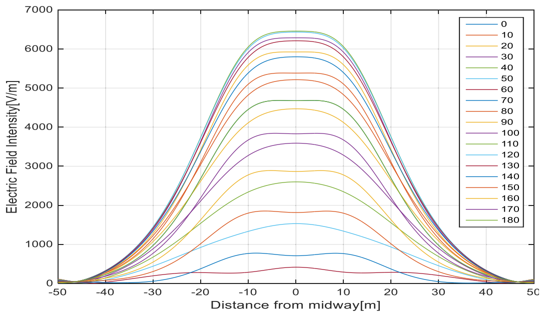
From Table 3 it is observed that the maximum E-fields for the actual existing structure at the ground level for 'Inverted Y', 'Inverted V', and 'triangular' tower configurations are greater than the minimum ICNIRP specified guideline requirement (> 5 kV/m) from the perspective of public exposure irrespective of other comparison parameters.

As inferred from Table 3, the maximum ground E-fields for both 'inverted Y' and 'inverted V' configurations remains the same for the existing configuration and optimized phase sequence arrangements. This implies that these transmission lines were initially constructed in their optimal phase sequence arrangement, resulting in minimal ground E-fields production. However, the 'triangular' and vertical line configurations were not initially arranged in such a manner, necessitating phase sequence adjustments for these configurations. During optimized phase arrangement, the maximum E-fields intensity was reduced by 39.60% for the vertical configuration and 32.64% for the triangular configuration. Even after the optimized phase sequence, only the vertical line configured met the minimum requirement specified by ICNIRP guideline.

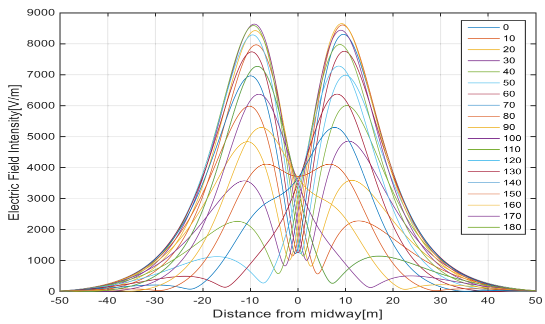
Another notable observation from Table 3 is that, irrespective of various comparison parameters such as conductor specifications, power transmission capacity, tower height, construction costs, and others, vertically configured lines exhibited the lowest E-fields intensity (below 5 kV/m) at ground level when compared to other configurations analyzed in this study. Conversely, the 'triangular' line configuration consistently generates the highest E-fields around ground



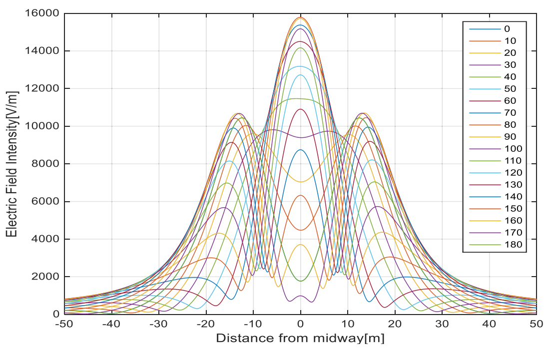
a. For Ethiopian ('Inverted Y') line configuration



b. For 'Vertical' line configuration



c. For 'Inverted V' line configuration



d. For 'Triangular' line configuration

FIGURE 2. Double circuit 500 kV transmission line E- field distribution at 1m above the ground level for different line configuration.

level even after optimization of the phase sequence arrangement. It is only the vertical configuration that meets the minimum ICNIRP guideline. Here it should be noted that the triangular line configuration result is without ground wires. As indicated in the literature [33], the ground wires can reduce the ground E-fields intensity from 1-2%. Taking this into consideration, the E- field magnitude for triangular

TABLE 4. Configurations' minimum ground clearance for minimum ICNIRP requirement.

Configuration type	Adjusted ground clearance[m]	Actual existing ground clearance[m]
'Inverted Y' [28]	14.5048	12.2389
Inverted V [13]	14.5665	13.0000
Vertical [20]	14.7278	20.2828
'Triangular' [18]	13.7414	11.0000

configuration is still the highest of all configurations considered in this study. The E-fields distribution of as built transmission lines were presented in Fig. 2. The E-fields values given in the plot are the instantaneous peak values. The E-fields analysis was done over half a cycle at every 10 degree interval. For each and every angle interval, the E-field at 1m height above the ground, 50 m to the right and left from the tower was computed for every 0.1 m interval. The E-fields plot for each angle interval is identified using different color.

Based on Fig. 2, the maximum E-field for 'inverted Y', 'vertical', 'inverted V' and 'triangular' line configurations are 9.531, 6.457, 8.650 and 15.790 kV/m peak (6.740, 4.565, 6.116 and 11.165 kV/m rms) respectively. It occur either on the left or right side of midway between the towers at a distance of 8.5 m and 9.2 m for 'inverted Y' and 'inverted V' respectively. But for the other two line configurations, 'vertical' and 'triangular', their maximum E-field exists at the center axis having 6.457 and 15.790 kV/m (4.564 and 11.165 kV/m rms) magnitude respectively (Fig. The E-field maximum values of all the three configurations are greater than the ICNIRP standard (5 kV/m) irrespective of other parameters that need to be considered in tower E-fields analysis except the 'vertical' configuration having 4.565 kV/m.

As observed on the respective figures (fig.2), the maximum E-field occurred in the right and left side of the midway between the towers for optimized phase sequence arranged configurations but occurred at the center for un-optimized phase arranged configuration.

To identify the best line configuration type, systematic adjustment of minimum ground clearance was done for each configuration where the E-fields at the ground can fulfill the ICNIRP minimum standard for public exposure at a system frequency of 50 Hz (5 kV/m). The adjustment was made by adjusting the lowest conductor ground clearance keeping the other parameters (line-to-line distance, line -to- earth distance, conductors' dimension, arm length) unchanged and the results were presented in Table 4.

It can be inferred from **Table 4** that the double circuit 'triangular' line configuration provided the minimum ground clearance at minimum ground E-fields (5 kV/m). It reduces the minimum ground clearance height by 6.70% when compared with the tower configuration having the worst ground clearance ('vertical' configuration - 14.7278 m) to get the minimum ground E-field 5 kV/m. This implies that for a double circuit 500kV transmission line, the 'triangular' line configuration seems to be the preferable line configuration

TABLE 5. Maximum electric (E_{max}) fields magnitude variation.

Configuration	Existing E_{max}-fields [kV-rms]	Adjusted E_{max}-fields [kV-rms]	E_{max}-fields variati on [%]	Variation description
Inverted Y' [28]	6.7394	5.00	25.81	reduction
Vertical [20]	4.5654	5.00	-9.52	incremental
Inverted V [13]	6.1163	5.00	18.25	reduction
Triangular' [18]	11.165	5.00	55.22	reduction

which provides the least ground E-fields relative to other configurations included in this study.

During the ground clearance adjustment, (correcting the maximum E-fields intensity magnitude to minimum ICNIRP standard, 5 kV/m), it is observed that the E-fields distribution pattern/fashion, the instantaneous angle at which maximum E-fields befell and the axis position at which the maximum E-fields occurred are remain unchanged but the E-fields magnitude changed. The magnitude difference variation percentage and description are provided in Table 5.

V. CONDUCTORS SURFACE E-FIELDS DISTRIBUTION ANALYSIS

The electric field distribution on the surface of the conductor is important from the point of designing the insulation systems. With an increase in system voltages, operating E-fields at the conductor surfaces become higher [34]. The E-fields around the surface of the conductors at different instants with an interval of 10 degrees is computed and compared for the four different line configurations. During our analysis, 13 equidistant points (interval of 300 angular displacements) are considered along the circumference of each sub-conductor. The analysis was done for existing phase arrangement and ground clearance, optimized phase sequence arrangement with existing ground clearance, and optimized phase sequence arrangement with adjusted ground clearance. The computation results were presented as shown in Tables 6, 7, and 8 respectively. All the 4 line configurations included in the study have a surface E-fields of less than the breakdown strength of free air (2,122 kV/m rms).

From Table 6, it can be inferred that having the same ground E-fields (5 kV/m) and transmission line voltage, the triangular configuration has the highest surface E-fields around its sub-conductors- whereas the vertical line configuration provides the least surface E-fields relative to others. Though the triangular configured conductors showed the highest surface E-fields, the surface E-fields magnitude is less than the breakdown strength of free air (2,122 kV/m rms). Therefore, the conductor surface E-fields of transmission lines included in the study is below the intrinsic strength of atmospheric air and hence, the design is corona-free under fair weather conditions.

The bundles and sub-conductor representation used for surface field analysis also exist in Fig. 3.

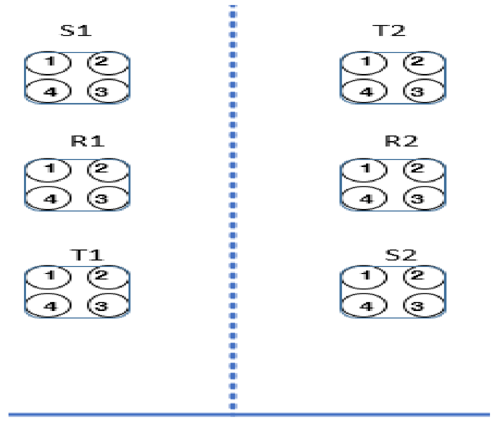


FIGURE 3. Bundles and sub-conductors representation used
Key: S1 represents the S line of Circuit I and S2 represents the S line of Circuit II
S11- Line S1 sub-conductor 1, S12- Line S1 sub-conductor 2,
S13- Line S1 sub-conductor 3, S14- Line S1 sub-conductor 4,
S21- Line S2 sub-conductor 1, S22- Line S2 sub-conductor 2,
S23- Line S2 sub-conductor 3, S24- Line S2 sub-conductor 4 and similar for other lines.

TABLE 6. Maximum E-fields around conductors' surface for an existing (as built) phase sequence and ground clearance.

Configuration Type	Maximum surface E-fields [kV/m rms]	Sub-conductor where maximum surface E-fields occurred
'Inverted Y' [28]	1499.56	S13
Inverted V [13]	1477.78	S13
Vertical [20]	1155.77	S23
'Triangular' [18]	1722.44	T12

TABLE 7. Maximum E-fields magnitude around conductors' surface for an optimized phase sequence and existing ground clearance.

Configuration Type	Maximum surface E-fields [kV/m rms]	Sub-conductor where maximum surface E-fields occurred
'Inverted Y' [28]	1499.56	S13
Inverted V [13]	1477.78	S13
Vertical [20]	1220.54	T24
'Triangular' [18]	1722.44	T12

If the transmission lines were built in an optimized phase sequence arrangement, the surface E-fields of the conductors would have been the results shown in Table 7. The inverted V and 'inverted Y configurations were already built in their optimized phase sequence arrangement. Variation of surface E-fields (magnitude and line where maximum surface E-fields occurred) is observed for the vertical line configuration. Though maximum E-fields magnitude difference is observed for the existing and optimized phase sequence arrangement at 1m for triangular line configuration, there was no variation on the surface E-fields between the existing and optimized phase sequence arrangement.

When the maximum E-fields at 1m above the ground for each line configuration is adjusted to the minimum ICNIRP

TABLE 8. Maximum E-fields magnitude around conductors' surface at an optimized phase sequence and adjusted ground clearance.

Configuration Type	Maximum surface E-fields [kV/m rms]	Sub-conductor where maximum surface E-fields occurred
'Inverted Y' [28]	39.74	S12
Inverted V [13]	61.96	S12
Vertical [20]	14.09	T24
'Triangular' [18]	37.24	T12

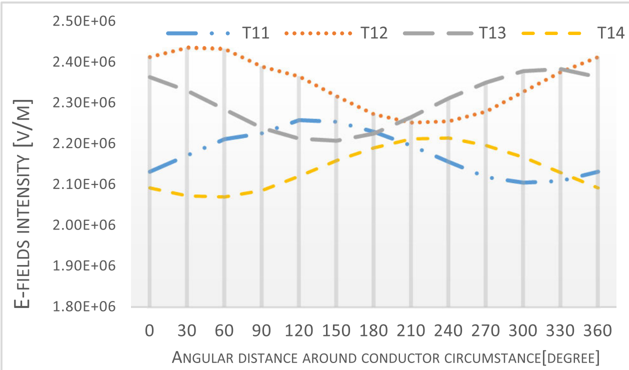


FIGURE 4. Surface E-field around sub-conductors of having the highest stress for 'triangular' line configured tower.

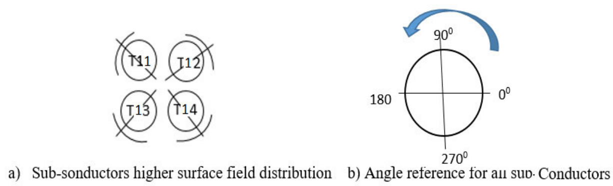


FIGURE 5. Triangular configuration surface E-field distribution location around bundles.

standard, by adjusting the ground clearance, the surface E-fields of the conductors is reduced as shown in Table 8.

As shown in Tables 7 and 8, though the magnitude of surface charge and specific sub-conductors on which it occurs changed, the line where maximum surface E-fields occurs remains the same. The sub-conductor surface E-fields distribution across the highest bundle of the triangular configured tower is presented and compared in Fig. 4.

From Fig. 4 the place where the higher and lower E-fields around each sub-conductors occurred is observed. For all sub conductors the higher surface field exists at the corner edges of bundle sub-conductors and the lower exists at the inner edge towards the bundle center. To be specific, the highest field occurred between 120^0-150^0 for T11, 30^0-60^0 for T12, 300^0-330^0 for T13 and 210^0-240^0 for T14. The lower field occurred at 300^0-330^0 for T11, 210^0-240^0 for T12, 120^0-150^0 for T13, and 30^0-60^0 for T14 as shown in Fig. 5. From these, the maximum surface E-fields occurred at the T23 sub-conductor having 2460 kV/m. This result has a similarity to Zhang Shiling's finding [35] done for double and triple bundle conductors' surface E-fields distribution.

VI. CONCLUSION

CSM-based model for four different tower configurations was developed and their E-fields intensity at the ground level was analyzed for their existing and optimal phase arrangement. By setting minimum ground E-fields standard magnitude to INCIRP guideline, a comparison of the configurations was done. The result showed that the triangular tower configuration is the best economic and environmental configuration for a double circuit 500 kV transmission system when compared with other configurations addressed in this study. It reduces the minimum ground clearance height by 6.70% when compared with the worst ground clearance included in the study (14.7278 m) to get the minimum ground E-field 5 kV/m.

It was seen that optimized phase sequence arrangement will reduce the ground E-fields. The optimal phase sequenced arrangement of 'vertical' and 'triangular' configurations reduced the ground E-fields by 39.60% and 32.64% respectively. The configurations were also compared in terms of their conductor surface E-fields distribution to observe their corona effect and found that all the four configurations conductors' surface E-fields were below the intrinsic breakdown strength of atmospheric air. Therefore, it is predicted that the designs will remain free from corona discharge under fair weather conditions.

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