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Regular paper

Calculation of Electric Fields underneath Six Phase Transmission Lines

The aim of this paper is to introduce a comparative study of calculating electric fields underneath six phase transmission lines and double circuit three phase transmission lines. Different configurations of six phase and three phase lines are presented. The first three phase line is operating at 138 kV, and the second one is at 220 kV while the first six phase line is operating at 80 kV and the last one is at 127 kV. The electric fields are calculated at one meter above the earth level for both three phase and six phase lines using the charge simulation technique (CST). The maximum electric field for the introduced three and six phase transmission lines are calculated. The percentage reduction for the maximum electric field reached 20% for the same dimensions and 58% for different dimensions at the same height of the lower conductors from the ground level.

Keywords: Electric Fields, Six-Phase Transmission, Charge Simulation Technique, Health Effect, Right of Way.

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1. Introduction

Nowadays transmitting large amounts of electrical power is needed to overcome the problem of the ever growth of power demand. Increasing the voltage of the transmission lines up to extra and ultra-levels is one of the methods adopted to solve the problem of power need through long distances, but this method has some difficulties in protection, insulation coordination, overvoltage, audible noise, corona power losses and electric field effects [1 –3].

Another method is the high phase order transmission lines used for transmitting large electrical energy such as six phase transmission. An example of six phase transmission line is a 93 kV demonstration line built by New York State Electric and Gas Corporation between Goudey and Oakdale in New York [4, 5].

Figure 1 shows a three-phase ac system consisting of three phase shifted by 120° and the six phase system having six phases shifted by 60°. In six phase system, there are combinations of phase and line voltages grouped into four categories. Group I which consists of six phase voltages, V_A, V_B, V_C, V_D, V_E and V_F. Group II consists of all adjacent phases V_{AB}, V_{BC}, V_{CD}, V_{DE}, V_{EF}, and V_{FA} with base voltage of phase ground voltage. Group III consists of all alternate phases, V_{AC}, V_{BD}, V_{CE}, V_{DF}, V_{EA}, and V_{FB} with base voltage equal root three phase to ground voltage. Group IV consists of all anti phases, V_{AD}, V_{BE}, and V_{CF} with base voltage of two times phase to ground voltage [6–14].

Three phase transmission was accepted as the standard for ac transmission for many reasons. The first is that three phases are the least number required for power flow that is constant with time; the second is that electrical machine power does not increase as phases are increased beyond three, and the last is that power system can be easily protected from

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electrical and mechanical faults [15]. Electrical power transmission with more than three phases has some advantages compared to three phase systems.

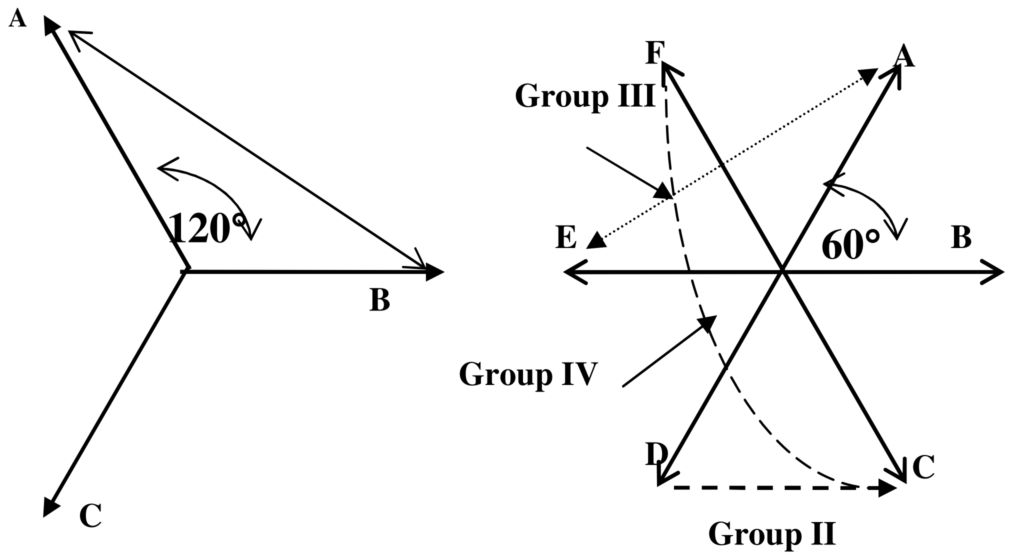


Fig. 1: Phasor diagrams for three phase and six phase systems

From Fig. 1, the ratio between line and phase voltage for three phases is root three but for six phases it is one, then the phase and line voltages are the same for six-phase systems. Thus for a phase to ground voltage of 79.6 kV the line to line voltage is 138 kV for three phase system and 79.6 kV for six phase systems [16–27].

In the same way, for a phase to ground voltage of 132.8 kV the line voltage is 230 kV for three-phase and 132.8 kV for six-phase systems, and for 199.2 kV the line voltages are 345 for three-phase ac and 199.2 kV for six-phase ac, see Table 1. The maximum power that a six phase line can handle is

$P_{max}=6I_{line}V_{phase} \cos\phi$ (1)

While the maximum power that a double circuit three phase lines of the same phase voltage is:

$P_{max} =2(3I_{line}V_{phase}) \cos\phi$

$P_{max} =6I_{line}V_{phase} \cos\phi$ (2)

This is the same as a six-phase line. The power capacity of a six-phase line with the same line voltage as a double circuit three-phase line is

$P=6\sqrt{3}I_{line}V_{phase} \cos\phi$ (3)

Thus, the capacity of a six-phase line is 173% that of a double circuit three phase system with the same line to line voltage, power factor, and similar transmission line geometry.

Six-phase transformer connections are more complex than three-phase, which drive the installation cost up. Figure 2 represents the connection of two transformer banks consisting of six single phase transformers that are used for the three to six-phase conversions (27–30).

Table 1 (8, 19)

Number of Phases (N)	Phase Voltage (kV)	Required Line Voltage (kV)
3	66	114
	132	229
	220	380
	500	866
6	66	66
	132	132
	220	220
	500	500
12	66	33
	132	66
	220	110
	500	250

Protection of a six-phase line and fault current calculation are more complex than for a double circuit three phase line [15,30– 34].

Precise calculation of the electric field underneath and around line conductors of overhead transmission lines are very important aspect in transmission line design. Quantitative description of the electrostatic field around overhead transmission lines has been presented in many papers [35–36].

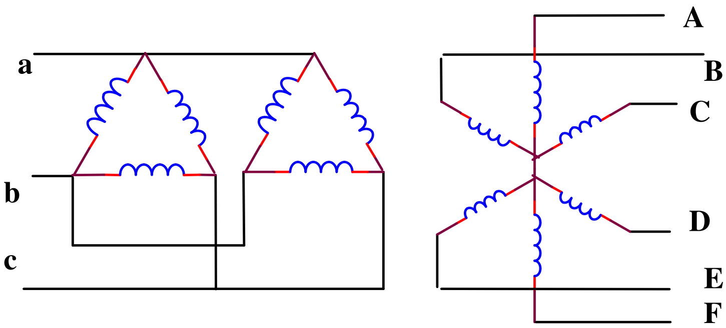


Fig. 2: Three phase to six phase conversion

The electric field effect on lines' maintenance crew isvery important issue that electric utilities are most often needed to respond to the potential health hazards. Theeffects of long term or chronic exposure to electric fields was presented in several papers[37–39].

One of the most common methods of calculating electric fields around transmission lines is the charge simulation technique (CST). CST requires no or little numerical integration in constructing the coefficient matrix for unknown charges and then in obtaining the field intensity. This makes the programming easier and the calculation faster. CST is very successful in the most of high and extra high voltage field problems. The charge simulation technique is also very suitable for 3-D fields with or without symmetry.

Therefore, the charge simulation technique is used in this paper for calculating electric fields underneath three phase and six phase transmission lines.

2. Electric Field Calculation Method

The main idea of CST [40-41] is very simple. For calculatingthe electric fields, the distributed charges on the conductor`s surface are replaced by N number of imaginary charges positioned inside the conductor at a radius R_f as shown in Fig. 3. In order to find the magnitudes of the imaginary charges, some boundary points are chosen on the surface of the conductor. The number of boundary point's n is chosen equal to the number of imaginary charges. Then, it is needed that at any boundary point the voltage resulting from superposition of all the imaginary charges effects is equal to the known conductor voltage. Let, Q_j is the j^{th}imaginary charge and V is the known voltage of the conductor. Then, according to the superposition principle,

$$V = \sum_{j=1}^{n} P_{ij}\, Q_j \tag{4}$$

Where P_{ij} is the potential coefficient, which can be calculated analytically for different types of imaginary charges. When equation (4) is applied to N boundary points chosen on the phase conductors of the transmission lines, it leads to the following system of N linear equations for N unknown imaginary charges, then:

$$[P][_{NxN}[Q]_N = [V]_N \tag{5}$$

Where [P] is the voltage coefficient matrix, [Q] is the column vector of known voltage of contour points, and [V] is the applied voltage for boundary points on the surface of conductor. Equation (5) can be solved for the unknown imaginary charges. As soon as the unknown charges are obtained, the voltage and the electric field intensity at any point, outside the transmission line conductors can be calculated. While the voltage is found by equation (4), the field components are calculated by the superposition of all the electric field vector components.

For a Cartesian coordinates system, the x, y coordinate (E_x and E_y)for a number of N charges would be given by:

$$E_x = \sum_{j=1}^{N} \frac{\partial p_{ij}}{\partial x} Q_j \quad = \sum_{j=1}^{N} (f_x)_{ij}\, Q_j \tag{6}$$

$$E_y = \sum_{j=1}^{N} \frac{\partial p_{ij}}{\partial y} Q_j \quad = \sum_{j=1}^{N} (f_y)_{ij}\, Q_j \tag{7}$$

Where $(fx)_{ij}$, $(fy)_{ij}$ are "field intensity coefficients" in the x and y direction.

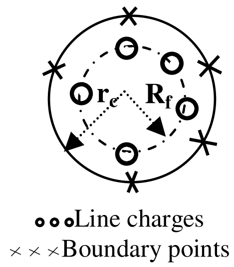


Fig. 3: Charge representation for the line conductor.

A computer program is developed by the authors to calculate the electric field for transmission power line with any configuration. To check the accuracy of the program, it is compared with previous results [23]. Fig. 4 shows the comparison between both results, and it can be seen that the deviation does not exceed 1%.

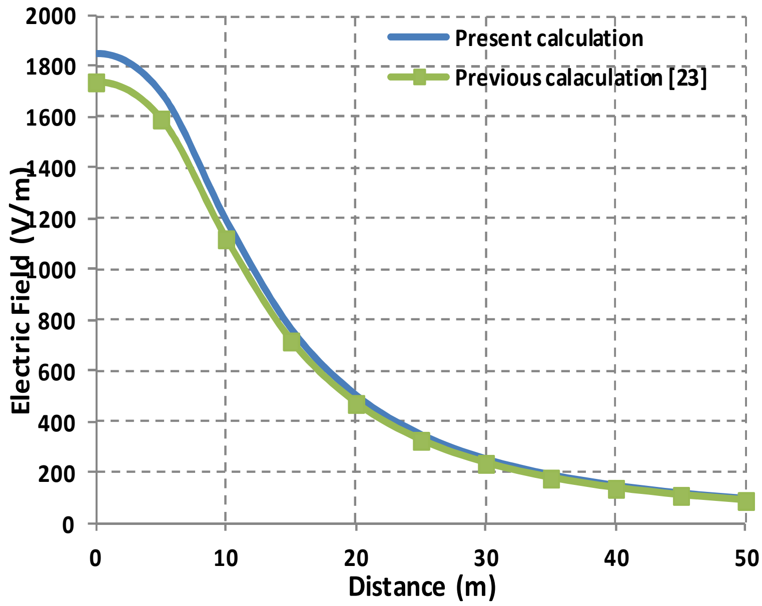


Fig. 4: Comparison between present and previous calculations.

3. Results and Discussions

3.1: A Three Phase 138 kV and Six Phase 80 kV Transmission Lines

The voltage vectors for the six phase can be denoted by any angles, e.g., $V_A\angle 30°$, $V_B\angle 90°$, $V_C\angle 150°$…… The voltage vector angle of the six phase do not affect the electric field shape and values as can be seen in Fig. 5. This is due to the fact that the six phase vectors are identical in magnitude and relative phase shift from each other.

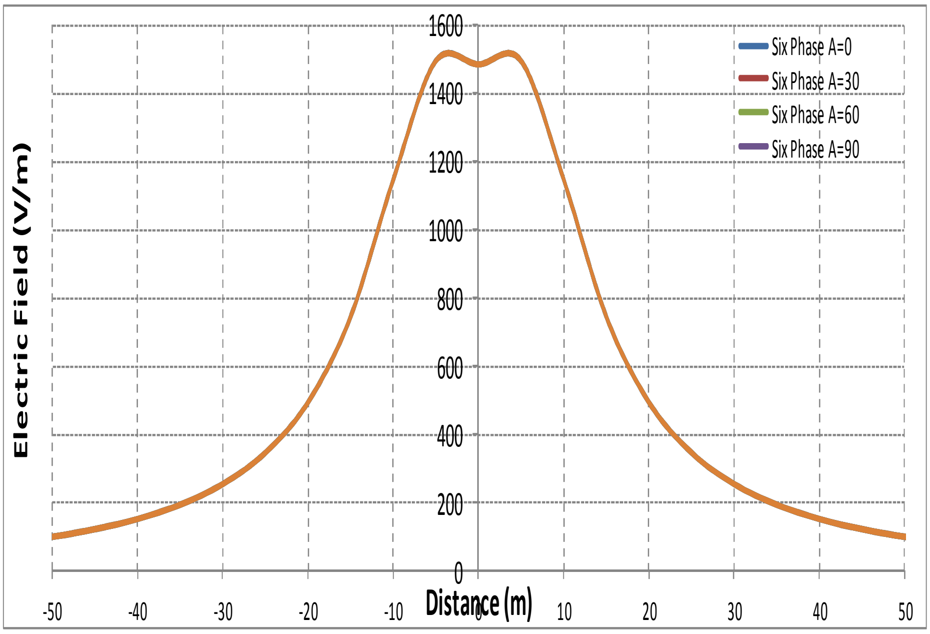


Fig. 5: Electric field profile at different phase angles.

The charge simulation technique is applied to the 138 kV three phase and 80 kV six phase transmission lines of the same dimensions shown in Figs. 6, 7. The number of conductors per phase is one for both transmission lines, the radius of a three phase conductor, and six phase conductor is 0.0112 m, the heights H_1, H_2, and H_3 are 10.9728, 14.9352 and 18.8976 m respectively. The tower arm lengths B_1, B_2, and B_3 are equal to 3.9624 m. The number of simulation line charges per each conductor is equal to six. The simulation charges are arranged around a cylinder of radius R_f equal to $0.05r_c$. The potential error at the chosencontour point's midway between boundary points- did not exceed 0.0001%.

Fig. 8 shows the electric field at one meter height above the earth level for the configurations shown in Figs. 6, 7. The maximum field strength for the 138 kV three phase lines is found to be about 1.614 kVm^{-1},while the maximum field for the six phase line of 80 kV is 1.496 kVm^{-1}.

Increasing the number of phases reduces the maximum field stress at the earth level. The percentage reduction is about 8%.

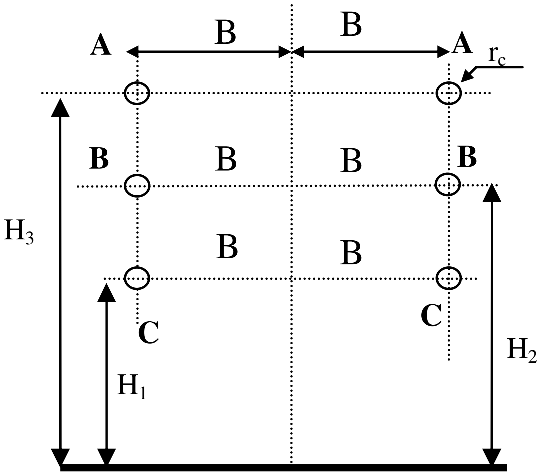


Fig. 6: A 138 kV three phase, double circuit transmission line.

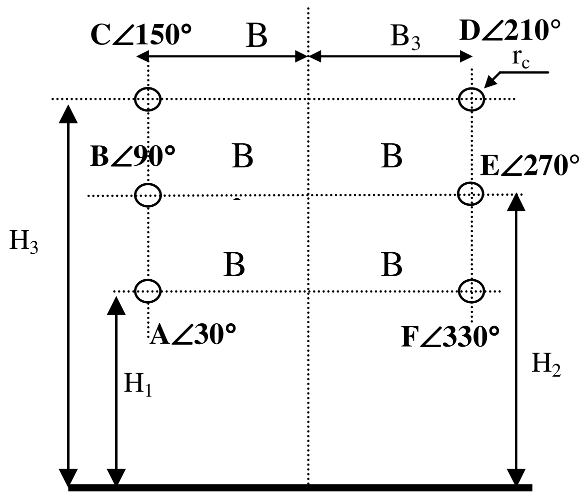


Fig. 7: A 80 kV, six phase transmission line.

Fig. 9 shows the field strength at one meter height above the ground surface when changing the phase sequence of three phase transmission line shown in Fig. 6 to be (ABC) for the left circuit and (ACB) for the right circuit, while the six phase transmission line is still having the same phase sequence as shown in Fig. 8.

From Fig. 9, it is clear that, the maximum electric field for the three phase transmission line is reduced to 1.2 kVm^{-1} when the phase sequence is changed from ABC to ACB.

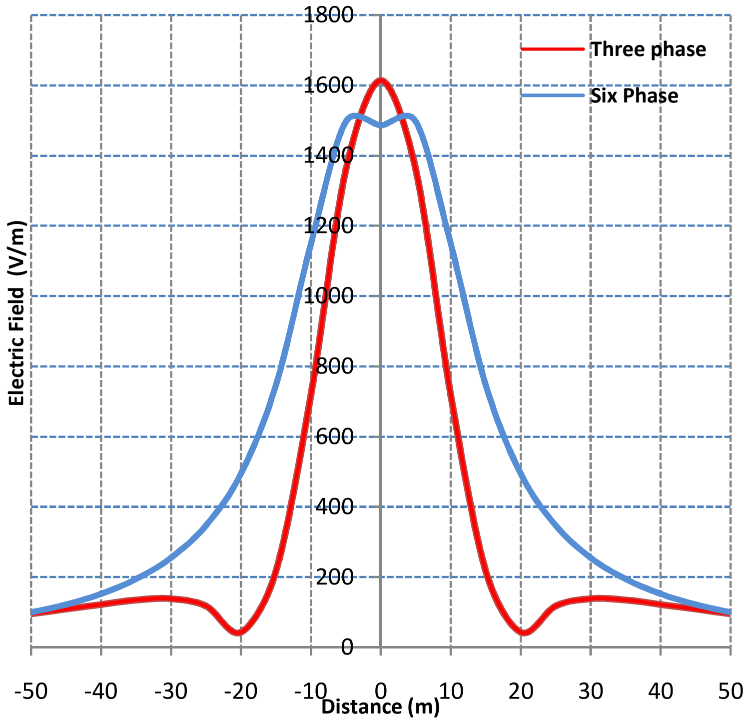


Fig. 8: Electric field distribution at 1m height above ground levelfor 138 kV three phase and 80 kV six phase transmission lines of Figs. 6 and 7.

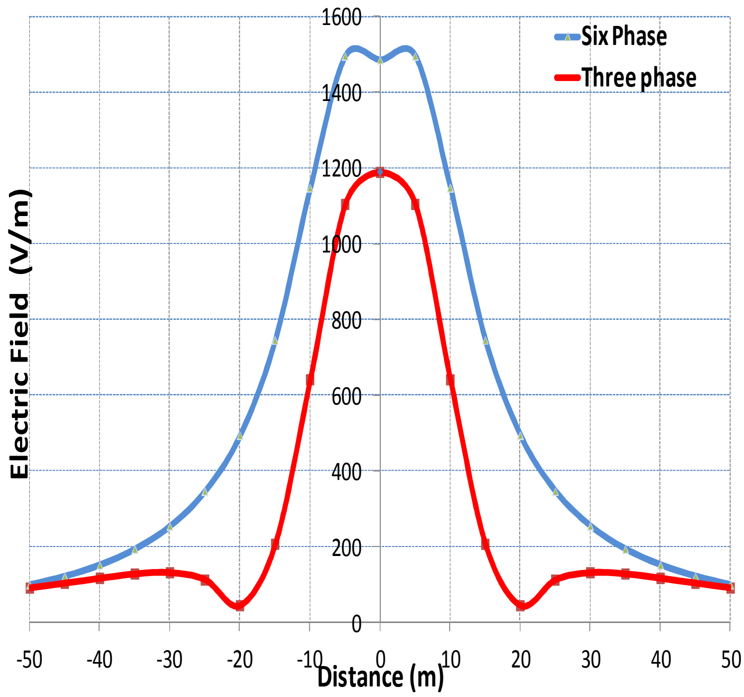


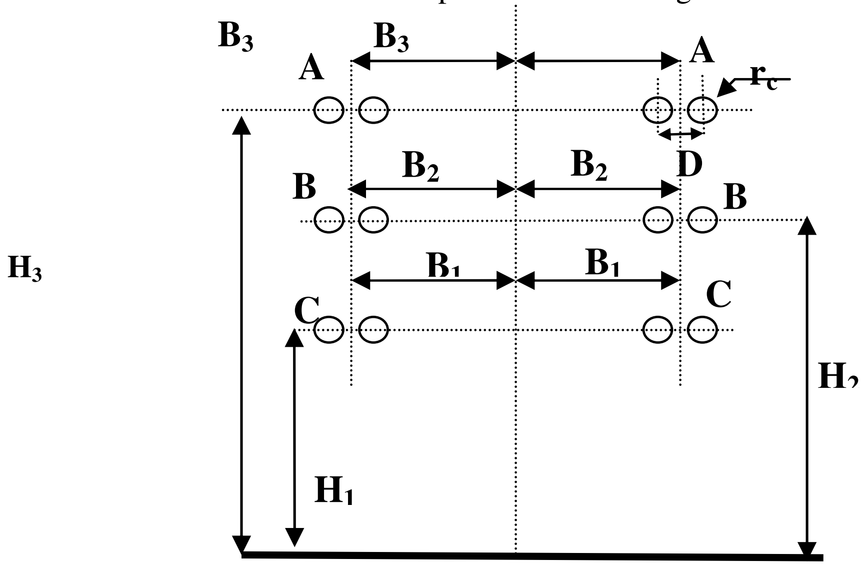
Fig. 9: Electric field distribution at 1m height above ground level for 138 kV and 80 kV transmission lines of Figs. 6, 7 when changing the phase sequence of the three phase transmission line circuits.

3.2: A three Phase 220 kV and Six Phase 127 kV transmission Lines with the Same Dimensions

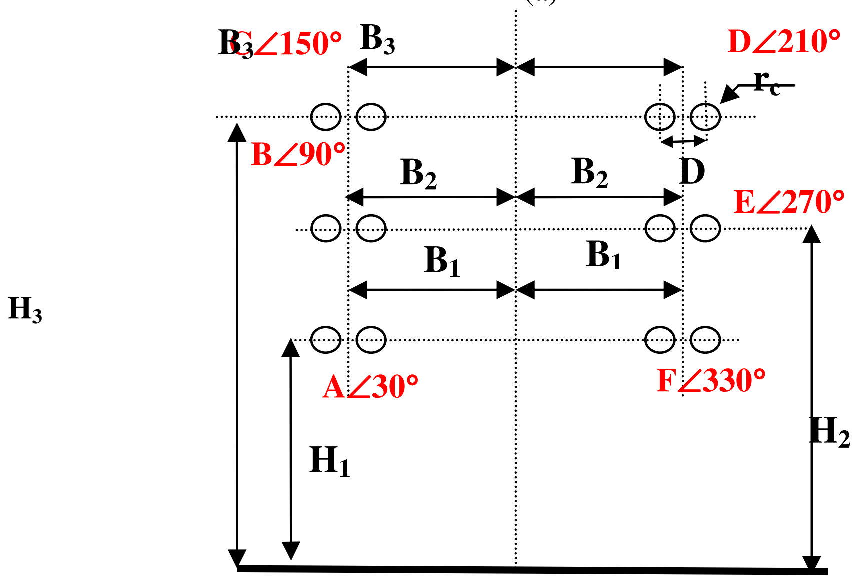
The charge simulation technique is applied to the Egyptian 220 kV transmission line shown in Fig. 10. The number of sub-conductors per phase is two, the single conductor radius r_c is 0.0135 m, the sub-conductor spacing, D is equal 0.3 m, the heights H_1, H_2, and H_3 are 15.7 m, 24.9 m, and 35.1 m respectively. The tower arm lengths B_1, B_2 and B_3 are equal to 8.55 m. The simulation line charges number per sub-conductor is equal to six. The simulation charges are arranged inside a cylinder of radius R_f equal to $0.05r_c$. The voltage error at the chosen contour point'smidway between boundary points did not exceed 0.0001%.

Figures 11 and 12 show plots of the electric fields at one meter height above the ground surface for the configuration shown in Fig. 10 for the same phase sequence (ABC) for both circuits of three phase transmission line, the six phase system starts with phase A at angle 30 as shown in Fig. 10.

It is noted that when using the same dimensions for three phase and six phase transmission lines, there is a noticeable difference between the maximum electric field for three phase and six phase lines as seen in Fig. 11. The maximum electric field stress of the three phase is 2.189 kVm^{-1} while for six phase is 1.756 kVm^{-1}. The percentage reduction of the maximum electric field is about 20 % for the six phase compared to three phase transmission line. Changing the phase sequence of the three phase from ABC to ACB reduces the electric field for the three phase as seen in Fig 12.



(a)



(b)

Fig. 10: An Egyptian 220 kV transmission line.

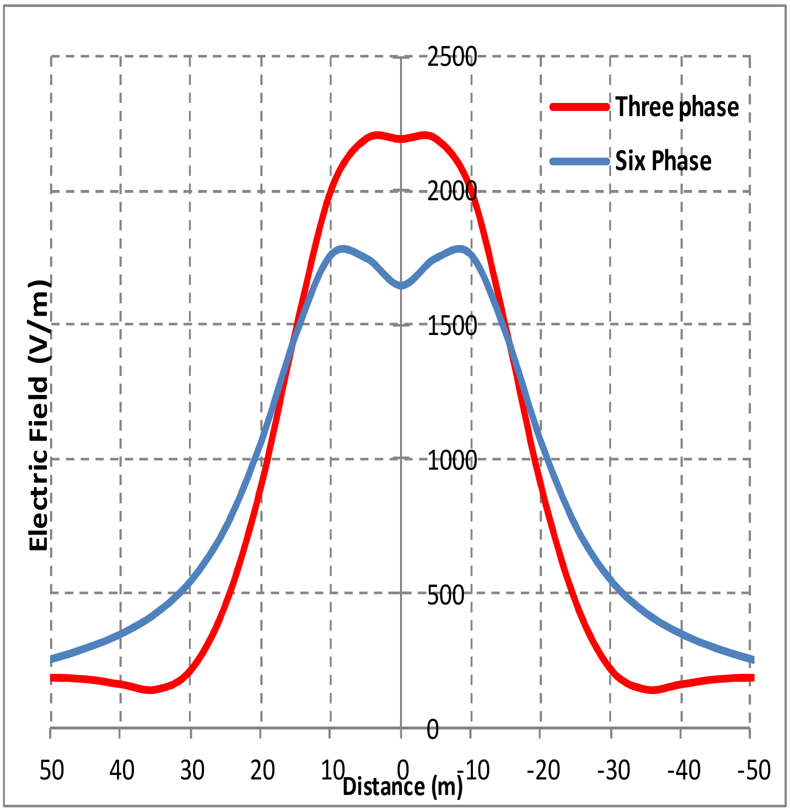


Fig. 11: Electric field distribution at one meter height above ground level of the 220 kV three phase transmission line with the same phase sequence of the two circuits and six phase transmission line of Fig. 10.

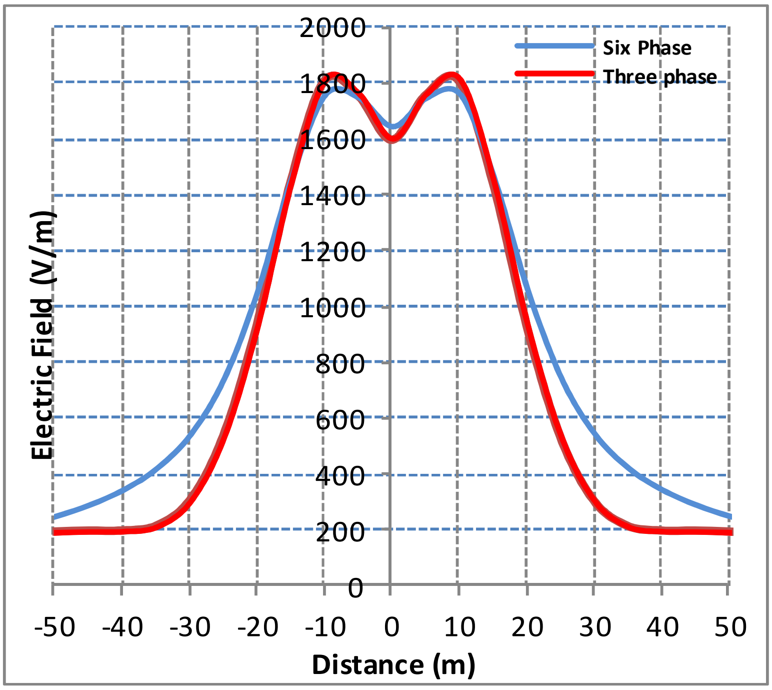


Fig. 12: Electric field distribution at one meter height above ground level of the 220 kV three phase transmission line with changing the phase sequence of the two circuits (ABC for the left and ACB for the right) and the same phase sequence for six phase transmission line of Fig. 10.

3.3: A Three Phase 220 kV and Six Phase 127 kV Transmission Lines with Different Dimensions

The configuration of three phase transmission line is the same as in Fig. 10 (a). The dimensions of the six phase line are completely changed, the heights H_1, H_2, and H_3 are 15.7 m, 21.1 m, and 24.7 m respectively. The tower arm lengths B_1, B_2 and B_3 are 4.1 m, 4.4 m, and 4.1 m as shown in Fig. 13. The radius of six phase transmission line conductor's r_{six} is 0.011 m.

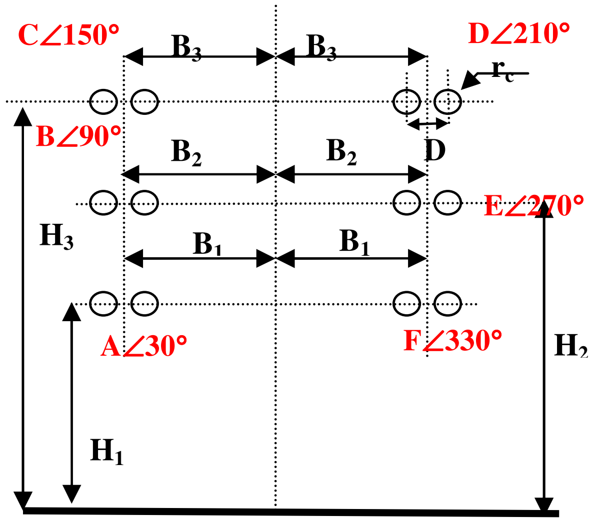


Fig. 13: A 127kV six phase transmission line.

The number of simulation line charges for both phase sub-conductors of three phase line and six phase transmission line is equal to six. The simulation charges are arranged inside a cylinder of radius $0.05r_c$ for phase sub-conductors of three phase line and 0.05rsix for six phase conductors. The voltage error at selected contour points on the line sub-conductor of 3 phase and six phase did not exceed 0.0001%.

Figures 14 and 15 show plots of the electric fields for the configurations shown in Figs. 10 a, and 13.

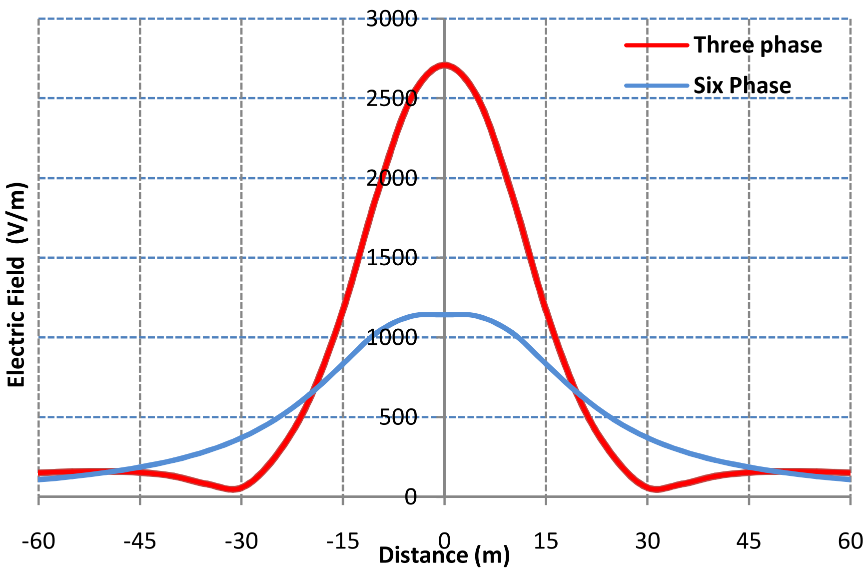


Fig. 14: Electric field distribution at one meter height above ground level of the 220 kV three phase transmission lines with the same phase sequence of the two circuits and six phase transmission line with the new dimensions of Fig.10.

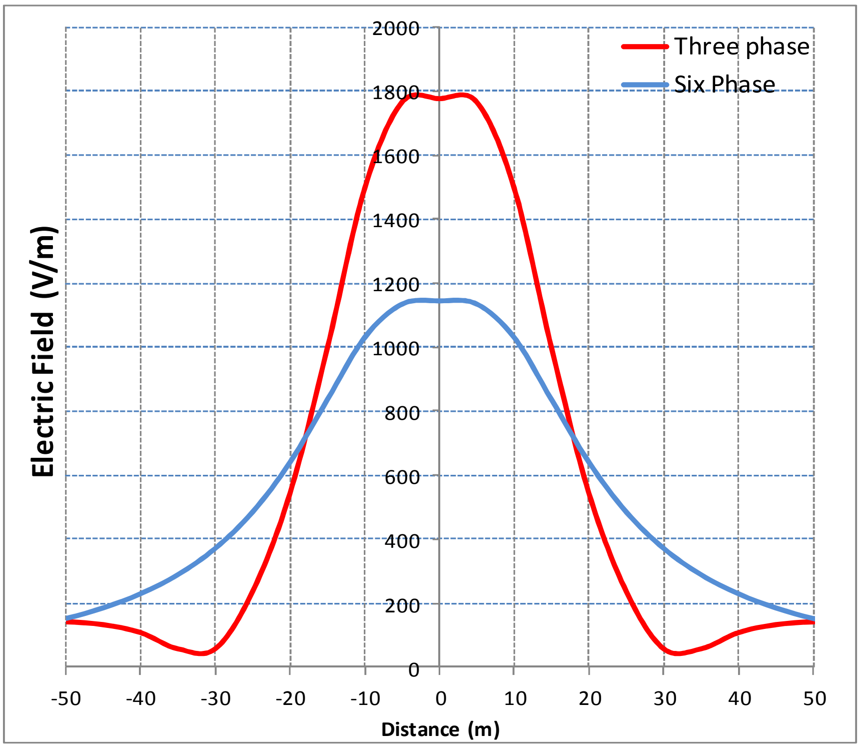


Fig. 15: Electricfielddistributionat1mheightabovegroundsurface of the 220 kV three phase transmission lines with changing the phase sequence of the two circuits (ABC for the left and ACB for the right) and the same phase sequence for six phase transmission line with the new dimensions of Fig. 10.

From Figs. 14 and 15, it is clear that the maximum electric field for the six phase line and is 1.14 kVm^{-1} while for three phase line is 2.71 kVm^{-1}. In this case the percentage reduction is equal to 58%. When the phase sequence of the three phase line is changed to ACB and keeping the same phase sequence of six phase line, the percentage reduction is 35.7%.

4. Conclusions

The use of six phase transmission has considerable benefits over three phase transmission. The electric field produced by the six phase system is less than that for three phase lines. The reduction of the electric fields for the six phase transmission lines can reach 58%. However the reduction is 35% when changing the phase sequence of the three phase system. Moreover the dimensions of the tower and the right of way of the six phase transmission systems is less than the three phase system. This is due to the fact that the line voltage of the six phase is equivalent to three phase line voltage divided by root three.

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