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An Investigation into Magnetic Field Management under Power Transmission Lines using Delta Configurations

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Abstract: The increase of power demand has increased the need for transmitting huge amount of power over long distances. Large transmission lines configurations with high voltage and current levels generate large values of electric and magnetic fields stresses which affect the humanbeing and the nearby objects located at ground surfaces. This has in turn prompted increased activity in the documentation of calculation techniques to accurately predict field strengths in isolated conducting bodies coupled to lines of all voltages and design configurations.

Overhead transmission systems required strips of land to be designed as right-of-ways (R.O.W.). These strips of land are usually evaluated according to some aspects; the most important one is the operating effects of the energized line including magnetic and electric field effects. Therefore determination of the maximum value of the magnetic and electric field stress at ground surface is very necessary and important. It is always required to minimize the amount of land set for high voltage (or current) transmission facilities. This can be achieved by the reduction of the field stress at ground level which is also considered as the most object of efforts to minimize the field effects of such high voltage AC transmission lines.

This paper investigates the effects of the transmission line towers configurations, on the mitigation of the induced magnetic fields, around and near the transmission lines, of the 500 kV systems. The magnetic fields of the conventional 500 kV normal horizontal (flat) power transmission line configuration are compared with that of the normal delta, inverted delta, compact normal delta and compact inverted delta configurations, and in turn its effects on the right of way (R.O.W) distance around the transmission line. The obtained results show that, for compact normal delta, and full compact inverted delta configurations, the resultant magnetic fields produced are lower than that produced from the conventional flat line configuration.

Keywords: Electrical Power systems -Electro-magnetic field (EMF) Management, Transmission line compaction, Effects of delta configurations, Right of way distance (ROW).

1. INTRODUCTION

Magnetic and electric fields are a phenomenon that is found in the area immediately surrounding all electric power transmission and distribution lines, electrical wiring in homes and such common every day appliances.

The electromagnetic environment typically consists of two components, an electric field and a magnetic field. In general for time-varying fields, these two fields are coupled but in the limit of unchanging fields, they become independent. For frequencies encountered in electric-power transmission and distribution, these two fields can be considered independent to an excellent approximation [1].

- Magnetic fields (B) arise from the motion of electric charges. A magnetic field is only produced once the device is switched on and current flows. Magnetic field lines run in circles around the conductor (i.e. produces magnetic induction on objects and induced currents inside human and animal (or any other conducting) bodies causing possible health effects and a multitude of interference problems). The higher the current, the greater the strength of the magnetic field.
- Electric fields (E) exist whenever a (+) or (-) electrical charge is present. They exert forces on other charges within the field. Any electrical wire that is charged will produce an electric field (i.e. Electric field produces charging of bodies, discharge currents, biological effects and sparks). This field exists even when there is no current flowing. The higher the voltage, the stronger is electric field at any given distance from the wire.

Overhead electric power lines have been in operation now for many years. However, it is only in the last 50 years that health effects of their magnetic and electric fields have become a subject of interest [1].

The magnetic field produced from the transmission lines is our main concern and will be considered in this work. Designers of power lines are searching for technically and economically acceptable right-of-way (R.O.W.).

2. MAGNETIC FIELD EFFECTIVENESS

2.1. Factors Affecting The Magnetic Field Level

The magnetic field strength (B) produced from a transmission line is proportional to: load current, phase -to– phase

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spacing (i.e. line compaction), and the inverse square of the distance from the line.

Many previous works studied the effect of different parameters on the produced magnetic field (B) such as: the distance from the line, the conductor height, line shielding and transmission line configuration and compaction [2-23].

2.1.1. The Distance from the Line

Keeping all the parameters the same and the only variable is the distance from the line. The magnetic field dips rapidly beyond the outside conductor away from the line, at which the field from the three phases partially cancel each other at larger distances (i.e. place the line as far as necessary to reduce the field to the desired values). But it has a larger right-of-way (R.O.W) width associated with greater unused land.

2.1.2. The Conductor Height

Keeping all the parameters the same and the only variable is the conductor height. To reduce the magnetic field levels is by increasing the conductor height but it has the disadvantage of increased height of line tower and its cost.

2.1.3. Line Shielding

Line shielding in transmission line runs in parallel to the phase conductors. Line shielding is always used to mitigate the magnetic field. There are several techniques for line shielding (Passive, Active, and combined shielding). The passive shielding depends on current induced in the transmission line. This induced current generating a magnetic field. This magnetic field encounters or partially cancels the original magnetic field from phase conductor. The active shield is used to approximately cancel the dipole component of the source fields. The combining active and passive shielding techniques can produce results which are superior to either of the above mentioned technique when used alone [2].

2.1.4. Line Configuration and Compaction

Line compaction means that, bringing the conductors close together keeping the minimum (safe) phase-to-phase spacing constant. Compact high voltage lines allow transmission of equivalent amounts of power to conventionally designed lines of the same voltage, using less space than the conventionally designed lines [3-17].

Keeping all the parameters the same and the only variable is the phase-to- phase spacing. The magnetic field is proportional to the dimensions of the phase-to-phase spacing.

Other studies showed that, increasing the distance between phases by increasing the height of the central phase conductor above the level of the other phase conductors leads to the reduction of the peak value of the magnetic field [18].

Reducing the phase-to-phase distance, leads to the decrease of the magnetic field. This reduction between phases is limited by the electrical insulation level between phases.

a. For single circuit lines, compaction causes a great reduction to the maximum magnetic field values. This reduction of magnetic field allows for lower conductor heights above the ground. This leads to transmit the same power on shorter towers. This gives a great reduction of the tower cost [18].

b. For double circuit lines, some studies showed that, the use of optimum phase arrangement causes a drastic reduction to the maximum magnetic field values for both conventional and compact lines i.e. with vertical conductor configurations arranged in ABC/CBA phase order [19, 20].

3. EMPLOYED MAGNETIC FIELD COMPUTATIONAL MODEL

For the purpose of calculating the magnetic field in this work, a three-dimension technique (3D) is used. The 3D technique is based on the Biot-Savrt law and the segment model in which the line conductor (or catenary) is simulated as connected straight line segments (or current sticks) [24-27].

The Biot-Savrt law can be used to calculate the magnetic field at an arbitrary observer position (point P) associated with a current segment having an arbitrary location. The current segment is showing in Fig. (**1**) which is represented by a vector a. The current is assumed to be uniformly distributed along the current segment.

According to the Biot-Savart law in its general form, the magnetic field at point (P) is given by;

$$\vec{B} = \mu_{\circ}\mu_{r} \times \vec{H} \qquad \text{.....} \ (tesla)\text{.....}(1)$$

$$\vec{H} = \frac{1}{4\pi}\int_{v} \frac{\vec{J} \times \vec{Z}_{rr}}{\left[r - \vec{r}\right]^{2}} dv \quad \text{....} \quad A/m\text{.....}(2)$$

where $\vec{r}$ is the position vector of the current segment (a), r is the position vector of the observer point (P), $\vec{J}$ is the current density in the current segment and $\vec{Z}_{rr}$ is the direction vector between the segment (a) and point (P), $\vec{H}$ is the magnetic field strength and $\vec{B}$ is the magnetic field density. Integrating the Biot-Savart law over the current segment, the

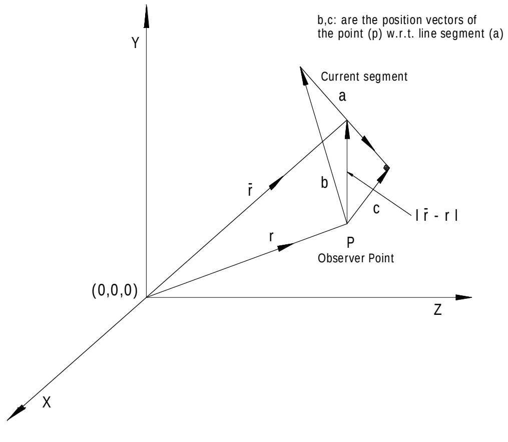


Fig. (1). A line segment representation in space.

magnetic field at the observation point (P) can be expressed as:

$$\vec{H}=\frac{\vec{i}}{4\pi}\,\frac{\vec{c}\times\vec{a}}{\left|\vec{c}\times\vec{a}\right|^{2}}\left\{\frac{\vec{a}\cdot\vec{c}}{\left|\vec{c}\right|}-\frac{\vec{a}\cdot\vec{b}}{\left|\vec{b}\right|}\right\}\ \text{.....}\ (A/m)\text{............}(3)$$

And the magnetic flux density due to the nth current segment is given by:

$$\vec{B}(n)=0.1\left(\vec{i}\,\frac{\vec{c}\times\vec{a}}{\left|\vec{c}\times\vec{a}\right|^{2}}\left\{\frac{\vec{a}\cdot\vec{c}}{\left|\vec{c}\right|}-\frac{\vec{a}\cdot\vec{b}}{\left|\vec{b}\right|}\right\}\right)\ \text{.........}(\mu T)\text{......}(4)$$

Or

$$\vec{B}(n)=\left(B_{x}(n)\vec{i}+B_{y}(n)\vec{j}+B_{z}(n)\vec{k}\right)\ \text{...}\ (\mu T)\text{...}(5)$$

Where, i, j and k are the unit vectors in the X, Y, Z directions, respectively. And $B_x(n)$, $B_y(n)$ and $B_z(n)$ are the components of the magnetic flux densities in the X, Y, Z directions, respectively, due to the nth current segment.

For N current conductors, the total flux density in the coordinates (x, y, and z) at observation point are:

$$\vec{b}_{x}=\sum_{n=1}^{N}\vec{B}_{x}(n)\ \text{.......}\ (\mu T)\text{........}(6)$$

$$\vec{b}_{y}=\sum_{n=1}^{N}\vec{B}_{y}(n)\ \text{.........}\ (\mu T)\text{.....}(7)$$

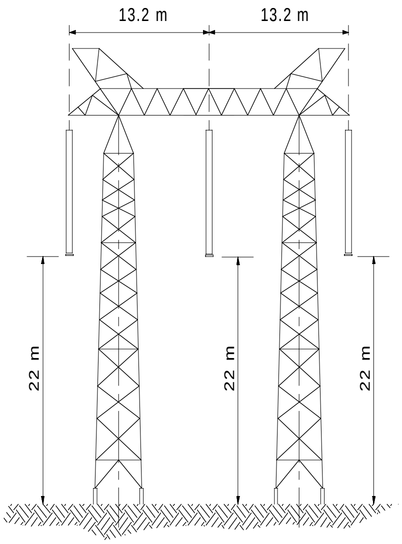
$$\vec{b}_{z}=\sum_{n=1}^{N}\vec{B}_{z}(n)\ \text{........}\ (\mu T)\text{....}(8)$$

The total instantaneous magnitude of the magnetic field (b_t) at a point in space is:

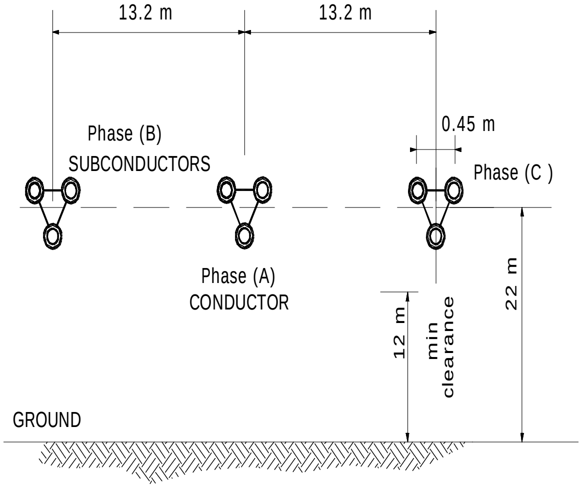
$$b_{t}=\sqrt{b_{x}^{2}+b_{y}^{2}+b_{z}^{2}}\ \text{.....}(\mu T)\text{.......}(9)$$

4. CASES UNDER STUDIES

A comparison between magnetic fields levels at mid-span in lateral direction of a 500 kV line for different configurations with the same line loading is carried out. The comparision between the magnetic field levels at the centeral phase of the line and the edge of the conventional right-of-way is also presented and discussed.



a) - Tower steel structure



(**b**) T.L. conductors' arrangement

a) - Tower steel structure **b**) - T.L. conductors' arrangement

Fig. (2). 500 kV power transmission line (normal Flat configurations).

All magnetic field values, in the present study, are evaluated for a line current of 1 kA (*i.e.* in μT/kA). Power transmission line of 500 kV with horizontal configuration, normal delta, inverted delta, compact normal delta and compact inverted delta configurations are considered. The main information data related to the considered power lines are as shown in Figs. (**2** and **3**). The minimum clearance to ground at the mid-span is 12 m, and the right-of-way (ROW) is at 25 m from the center line of the tower at both sides of the line. The magnetic field values are calculated at 1 m above ground level. No simulation is made for the tower steel structure and accordingly, some error is expected for the magnetic fields calculated near line towers.

For the purpose of the work in this paper, the following cases of studies are considered and carried out:

1- Calculation of the different magnetic field components, B_x, B_y, B_z and the total magnetic field B_{total} at the mid-span and ROW positions taking into account the effects of shifting up the suspension points of the two outer phases conductors by, 2 m steps, for inverted delta and compact inverted delta configurations and compare them with that, of the conventional flat configuration, of 500 kV power transmission line.

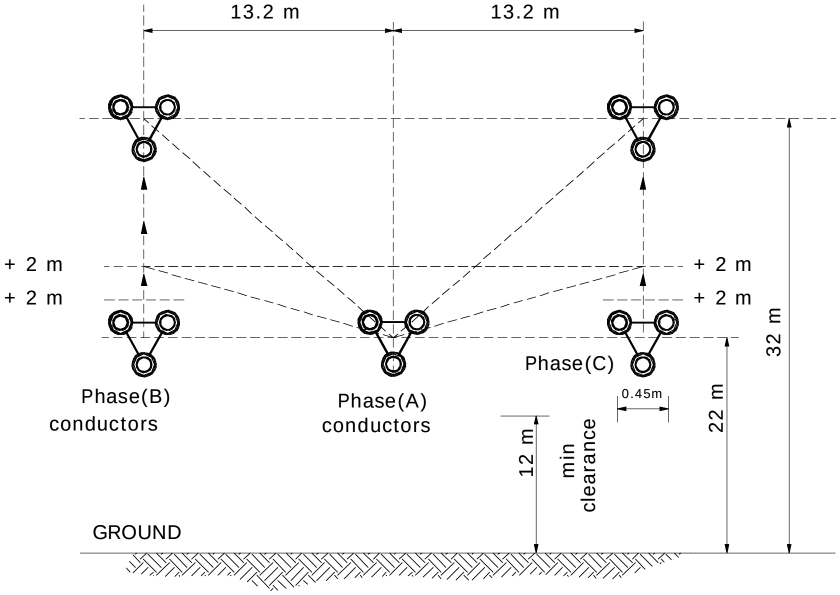


Fig. (3). 500 kV power transmission line with Inverted Delta configurations. (T.L. conductors' arrangement, with shifting the outer phases, 2 m, steps up).

2- Calculation of the different magnetic field components, B_x, B_y, B_z and the total magnetic field B_{total} at the mid-span and ROW positions taking into account the effects of shifting up the suspension points of the middle phase conductors, by 2 m steps, for normal delta and compact delta configurations and compare them with that, of the conventional flat configuration of 500 kV power transmission line.

3- Scanning the positions of the maximum magnetic field values with respect to the central phase, for each 2 m shift up step, for inverted delta and compact inverted delta configurations and compare them with that of the conventional flat configuration.

4- Scanning the positions of the maximum magnetic field values with respect to the central phase, for each 2 m shift up step, for normal delta and compact delta configurations and compare them with that of the conventional flat configuration.

5- Scanning the positions of the maximum magnetic field values with respect to the central phase, for each 2 m shift up step, for full compact delta and full compact inverted delta configurations and compare them with that of the conventional flat configuration.

4.1. Inverted Delta Configuration

To study the effect of the conversion of the transmission line three phases conductors from, conventional flat configuration to Inverted Delta configuration, on the resultant magnetic fields around and near the transmission line. Firstly, and for accurate calculation and analysis of the produced magnetic field, calculation of the different magnetic field components B_x, B_y, B_z and the total resultant magnetic field B_{total}, is carried out at the mid-span position, with the conductors of the three phases are at suspension points of 22 m height from the ground, for normal flat configuration, (for the Egyptian conventional 500 kV power transmission line) as can be seen in Fig. (**2**).

Secondly, the calculation of the different magnetic field components B_X, B_Y, B_Z and B_{total} at the mid span positions, with taking the effects of shifting up the suspension points of the two outer phases conductors by, 2 m steps, for the reason of studying the effects of the conversion of the line conductors configuration to inverted normal delta configuration, for 500 kV power line, is carried out as shown in Fig. (**3**).

Fig. (**4**) presents the X-components (B_X) of the magnetic field lateral profiles, for different configurations, with shift up steps of 2 m, starting from the normal flat configuration at a height of 22 m suspension points from the ground, till reaching 32 m height from the ground, for inverted delta configurations.

It can be noticed that the range of the maximum value varies and reaches a very high value compared with that, of the conventional flat configuration, at the case when shifting up the conductors of outer two phases to 32 m height from the ground. While the others maximum values for the other heights are small compared with that, of the flat configuration case. This is because the distances between the central phase and the outer two phases are getting larger. So, the cancellation effect is very small.

Fig. (**5**) presents the Y-components (B_Y) of the magnetic field lateral profiles, for the same case, for different configurations, by shift up steps, of 2 m, starting from the flat configuration at a height of 22 m from the ground, till reaching 32 m height, for inverted delta configurations.

It can be noticed that the range of the maximum value varies and reaches a very high value, compared with that, of the conventional flat configuration, at the position of shifting up the outer phases conductors up to 32 m height, while the other values are still small compared to that of the flat configuration and this is again, because of the larger distances

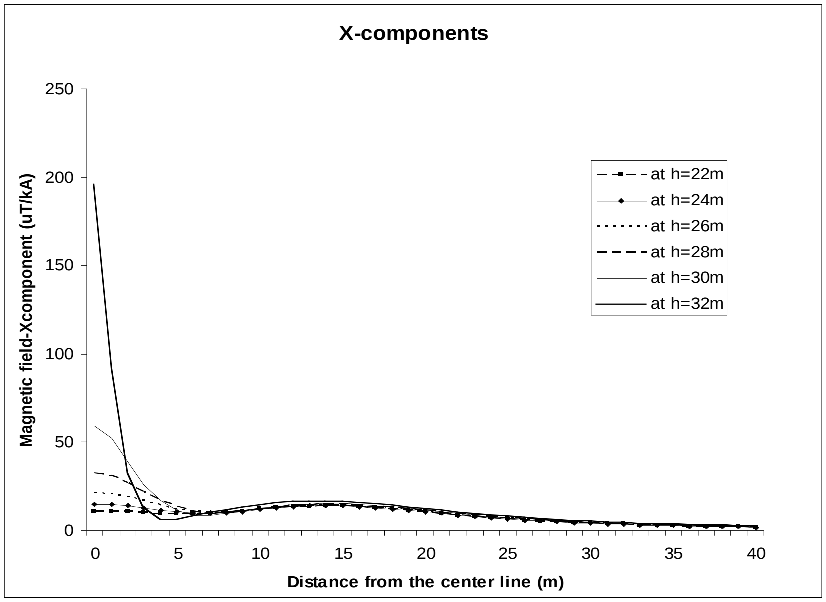


Fig. (4). The Magnetic field X-components Lateral profile at the mid-span, for inverted Delta configuration with 2 m shift up.

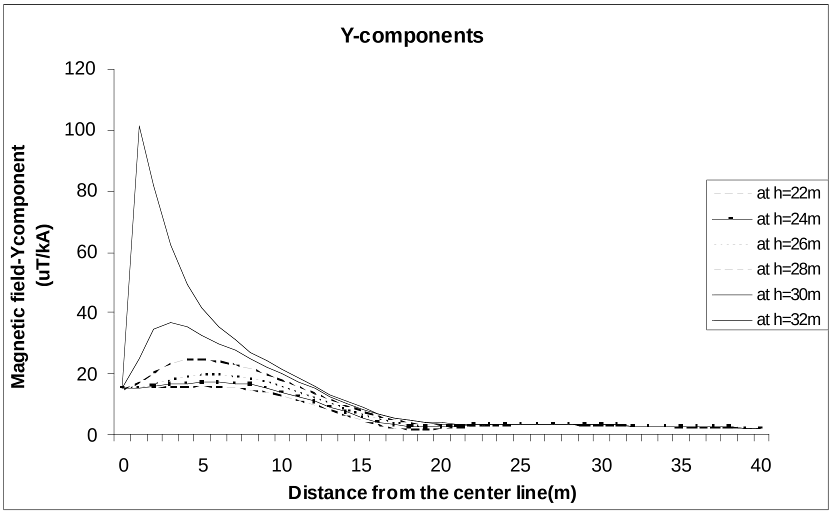


Fig. (5). The Magnetic field Y-components Lateral profile at the Mid-span, for inverted Delta configuration with 2 m, shift up.

between the center phase and the two outer phases. So, the cancellation effect is very small. Also, it can be noticed that the value of the field Y-component is maximum in the area under the center of the T.L., as the outer phases are shifting up, as their cancellation effect on magnetic field produced by the central phase become less (very low). Meanwhile as gating more faraway from this area the magnetic field will decreases.

Also, the results for the Z-components of the magnetic field lateral profiles are obtained, for the same case of study, for different configurations. It is noticed that the maximum values of the Z-components are nearly constant because there is no changing in the Z-directions and their values are small in magnitudes compared with that of the X and Y-components.

Fig. (**6**) presents the resultant total maximum magnetic field (B_{total}) lateral profiles for the different cases, with shift up steps of 2 m, starting from the normal flat configuration, with the three phases conductors points of suspension at 22 m height from the ground, until reaching the high of 32 m from the ground, converting the line, for Inverted Delta configurations. It can be noticed that the maximum values are obtained also at 32 m height shift up from the ground.

Table **1** presents the different maximum magnetic field values and its position with respect to the central phased conductors for inverted delta configurations. It can be noticed that the maximum magnetic field value is obtained at, the height level of 32 m and 34 m from the ground, (i.e. with shafting the two outer phases conductors up by 10 m and 12 m from the normal flat condition position, at 22 m). While

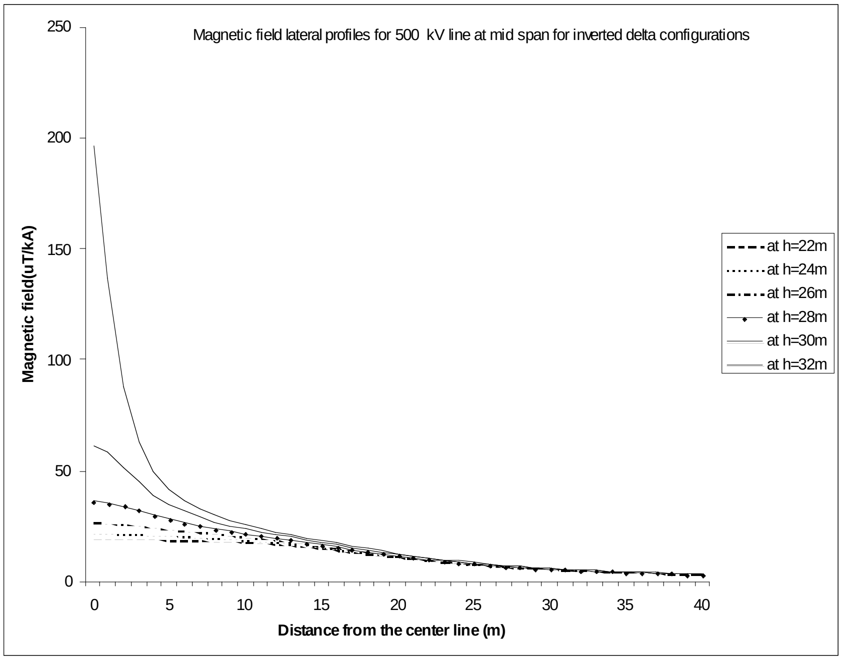


Fig. (6). The total maximum Magnetic Field Lateral profile at the Mid-span for, Inverted Delta configuration, with 2 m steps shift up.

Table 1. Max. Magnetic Field (B_{total}) Values and its Position w.r.t Center Line for Different Heights (with 2 m steps) for Inverted Delta Configuration

Vertical Shift up Calculation Distance (m)	Max. Field (B) Value (uT/kA)	Position w.r.t. Center Line (m)
Reference(Base case) (Flat configuration)	18.751	0
2	21.293	0
4	26.057	0
6	35.882	0
8	61.027	0
10	196.392	0
12	204.962	0
14	75.909	0
16	50.074	0
18	39.323	0
20	33.543	0

the positions of the maximum values, for all the other considered cases, produced under the central phase conductors.

Table **2** shows the maximum magnetic field values at central phase conductor (C.P.C) and at ROW positions and its percentage w.r.t. the normal conventional base case (*i.e.* flat configuration) for Inverted Delta configuration.

Table **2** and Fig. (**7**) present the maximum magnetic field (B_{total}) values w.r.t the base case values, with its percentage of the value of the conventional base flat case, of 500 kV power transmission line with inverted delta configuration.

It can be noticed that, with increasing the shift up of the conductors of two outer phases, from the ground, converting the line configuration from, conventional flat to inverted delta configuration, the higher maximum magnetic field (B_{total}) values are obtained, at both of, under the central phase conductor (C.P.C) and at the ROW positions. The increase of the resultant magnetic fields reaches a value of around 8.15 % at ROW, when the outer phases are shifted up by 8 m; this is because the distances between the central phase and the outer two phases become larger. So, the cancellation effect is very small.

Table 2. The Maximum Magnetic Field (B_{total}) Values at C.P.C and at ROW for Inverted Delta Configuration w.r.t. Base Case (Flat Configuration)

Case of Study	Magnetic Field Values					
	Max. at C.P.C		Max. Values		Max. at ROW	
	uT/kA	%	uT/kA	%	uT/kA	%
Flat (Base Case)	18.751	100	18.751	100	4.341	100
2 m shift up	21.293	113.557	21.293	113.557	4.379	100.875
4 m up	26.057	138.963	26.057	138.963	4.451	102.534
6 m up	35.882	191.361	35.882	191.361	4.557	104.976
8 m up	61.027	325.460	61.027	325.460	4.695	108.155
10 m up	196.362	1047.208	196.362	1047.208	4.859	111.933

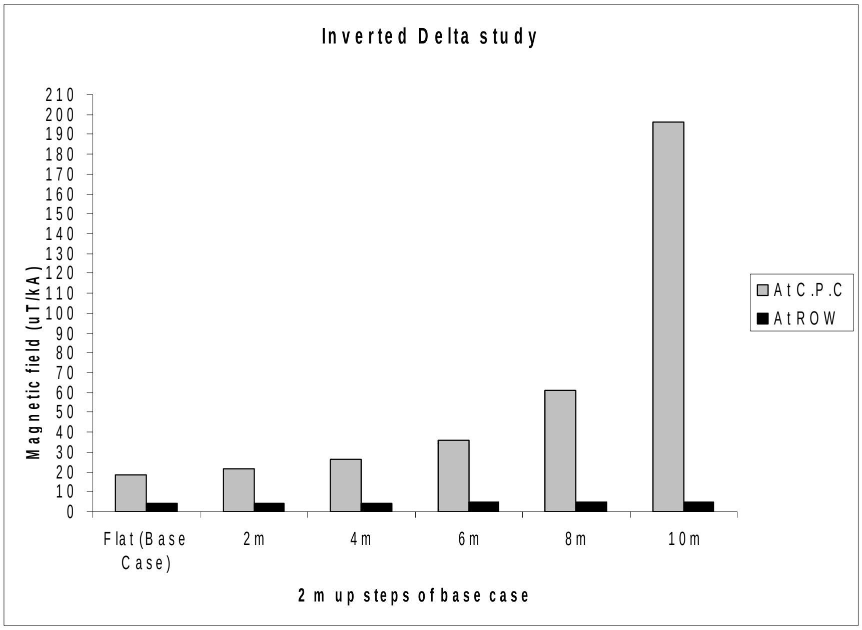


Fig. (7). The maximum magnetic field (B_{total}) values at C.P.C and at ROW for, Inverted Delta configurations, w.r.t. the base case (normal flat configuration).

4.2. Normal Delta Configuration

To study the effect of the conversion of the transmission line three phases conductors' configuration, from normal conventional flat configuration to normal Delta configuration, on the resultant and produced magnetic fields around and near the transmission line, many cases of study are carried. In these cases of the study, calculation of the different magnetic field components B_X, B_Y, B_Z and B_{total}, at the mid-span position, are carried out, taking the effects of shifting up the suspension point of the middle central phase conductors in, 2 m steps, up to the height of 32 m from the ground, starting from the case of normal flat configuration with 22 m suspension points height, for all three phases, from the ground, converting for normal delta configuration, with minimum clearance of 12 m from the ground, for 500 kV power transmission line as shown in Fig. (**8**).

Fig. (**9**) presents the total magnetic field (B_{total}) lateral profiles, for the different cases of shift up steps, of 2 m, starting from the normal conventional flat horizontal configuration till reaching 32 m height from the ground, for normal delta configurations.

It can be noticed that the range of the maximum (B) values varies and the higher value is obtained at the conventional flat configuration. Any shift up, of the central phase conductors increases the effects of the field cancellation factors and reduces the obtained maximum field values.

Table **3** presents the different maximum Magnetic field (B_{total}) values and it position with respect to the central phased conductors (C.P.C.) for the different considered and studied cases of (normal delta) configurations.

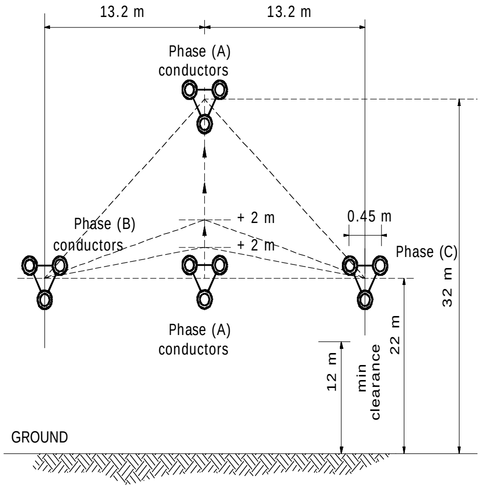


Fig. (8). 500 kV power transmission line, normal Delta, configurations. (T.L. conductors' arrangement, with the central phase, 2 m, steps shifting up).

It can be noticed that the maximum magnetic field (B_{total}) value is obtained at the case of normal conventional flat configuration, directly under the central line. There is a reduction of the magnetic field produced, as the central phase is shifted up, with the positions of the maximum value, for all the considered cases, is shifted away from under the central phase conductor of the power transmission line (for a distance of 2 m to a maximum distance of 9 m).

Table **4** and Fig. (**10**) present the maximum magnetic field (B_{total}) values, for normal delta configurations, and its percentage w.r.t. the base case (conventional flat horizontal configuration) value of the 500 kV power transmission line.

It can be noticed that, with increasing the shift up of the central phase conductors from the ground, the lower maximum magnetic field (B_{total}) values, are obtained at central phase conductor (C.P.C) position. This reduction reaches a value of around16.2 %, by shifting the central phase by 8 m up. On the other hand, it causes higher magnetic field values at the ROW position as the central phase conductor is getting higher, with 2.6 % for the same case.

4.3. Compact Delta Configurations Cases and Results

Line compaction means that, bringing the conductors of the three phase line close together, with keeping the minimum safe phase-to-phase spacing constant between phases. High voltage compact lines allow transmission of the same equivalent amounts of electrical power by the conventionally designed lines of the same voltage, while taking up and occupying less space than the conventionally designed lines. A conventional 500 kV power transmission line is considered

Table 3. Max. Magnetic Field Values and its Position w.r.t. Center Line for Different Heights (with 2 m Steps, Shift Up) for Normal Delta

ConfigurationVertical Shift Up Calculation Distance (m)	Max. Field Value (uT/kA)	Position w.r.t. Center Line (m)
Reference (Base case) (Flat configuration)	18.751	0
2	17.315	2
4	16.616	6
6	16.247	7
8	16.052	8
10	15.96	8
12	15.927	8
14	15.932	8
16	15.97	9
18	16.061	9
20	16.081	9

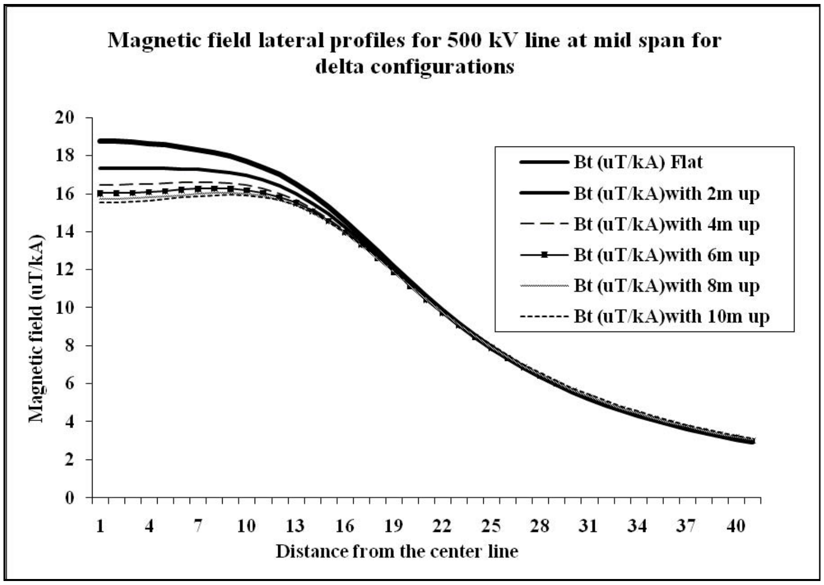


Fig. (9). The Magnetic field Lateral profiles at the Mid-span position for normal Delta configuration, with 2 m, steps shift up.

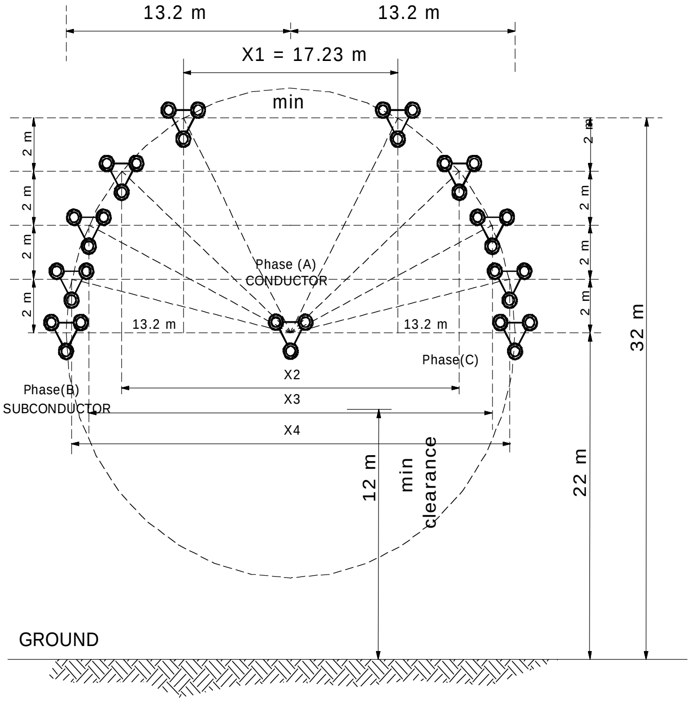


Fig. (11). 500 kV power transmission line with compact Inverted Delta configurations (T.L. conductors arrangement, with the outer phases, move on a 13.2 m circle, with 2 m, Step shift up (and constant distance between central phase and outer phases).

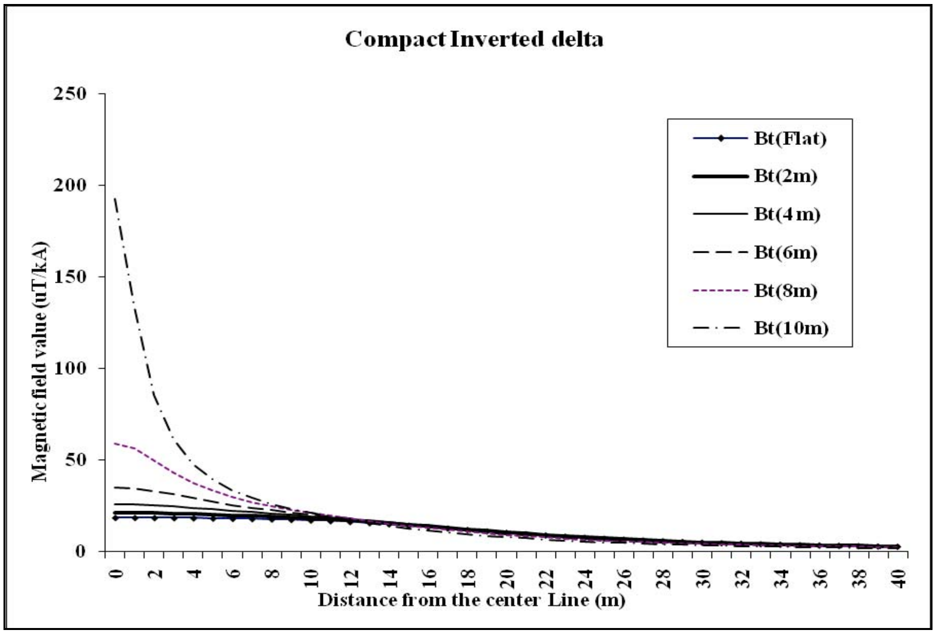


Fig. (12). Magnetic field values (uT/kA) for 500 kV Power line with Compact Inverted delta and shifting up the outer phases conductors with 2 m steps (on circle curve).

lation factor effect of the two outer phases conductors becomes small, so higher magnetic field values are obtained.

Table **5** and Fig. (**13**) present the obtained maximum magnetic field (B_{total}) values at, the central phase conductor (C P C) and at the ROW positions, for the compact inverted delta configuration, and its percentage w.r.t. the conventional base case of (the flat horizontal configuration) value, for the 500 kV power transmission line.

It can be seen that, with increasing the shift up of the conductors of the two outer phases, higher maximum magnetic field values are obtained at the central phase position. On the other hand there are lower values of the magnetic field obtained at the ROW, as the outer phases are shifting up. The reduction reaches a value of around 15.7 %, when the outer phases are shifted up by 8 m height, from the nor-

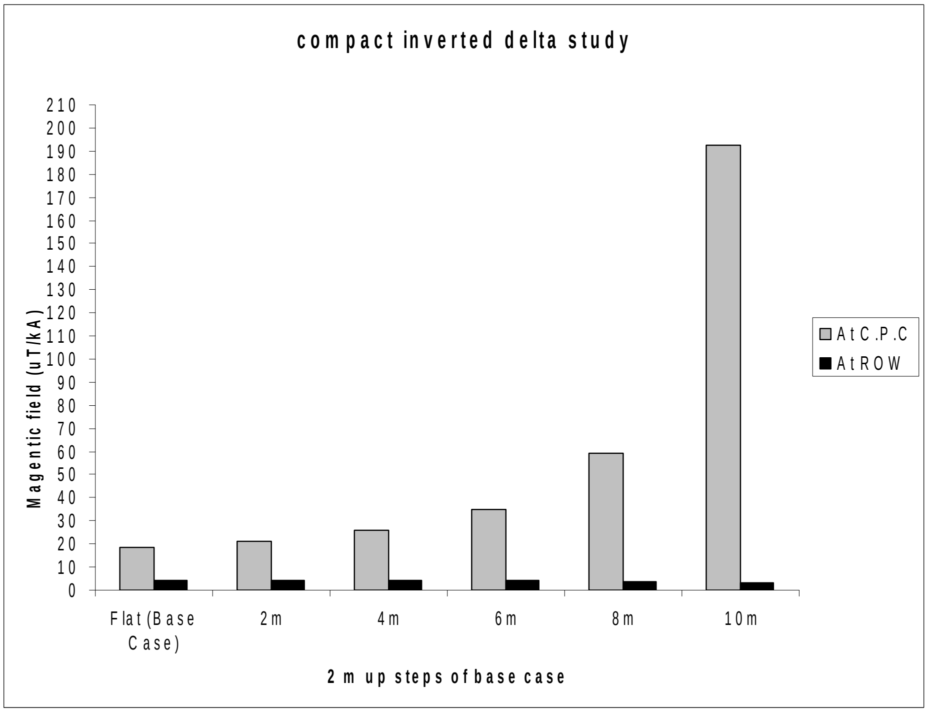


Fig. (13). The maximum magnetic field values for (compact inverted delta) at central phase conductor (C.P.C) and at ROW w.r.t. the Base Case (Flat horizontal configuration).

Table 5. The Maximum Magnetic Field Values for (Compact Inverted Delta) at Central Phase Conductor (C.P.C) and at ROW w.r.t. the Base Case (Flat Horizontal Configuration)

Case of Study	Magnetic Field Values					
	Max. At C.P.C		Max. Values		Max. At ROW	
	uT/kA	%	uT/kA	%	uT/kA	%
Flat (Base Case)	18.751	100	18.751	100	4.341	100
2 m shift up	21.246	113.306	21.246	113.306	4.314	99.378
4 m up	25.788	137.529	25.788	137.529	4.193	96.591
6 m up	35.059	186.971	35.059	186.971	3.976	91.592
8 m up	59.118	315.279	59.118	315.279	3.660	84.312
10 m up	192.582	1027.049	192.582	1027.049	3.239	74.614

mal flat conventional configuration, of 22 m height and with minimum clearance of 12 m from the ground.

4.3.2. Compact Normal Delta Configuration

Fig. (**14**) represents the simulation of the different cases of the study of the compact normal delta configurations of the transmission line. With shifting the central phase up on a vertical line, by 2 m steps, and moving the outer two phases on a horizontal line, closer to each other, in steps and at a 22 m suspension points from the ground, with minimum clearance of 12 m., and keeping the distance between the conductors of the central phase and the outer phases at a constant safe spacing of 13.2 m.

The following results are obtained for the case under study of the normal Compact Delta, as shown in Fig. (**14**).

The results obtained for the different considered cases of the study are shown in Fig. (**15**).

It can be noted that as the higher the central phase conductors the lower are the magnetic field values. This is because of, with shifting up the central phase conductors on a vertical line, with moving the two outer phase conductors to become closer to each other, and at a constant distance from the central phase, which increases the effects of the field cancellation factor. So, the lower magnetic field values are obtained.

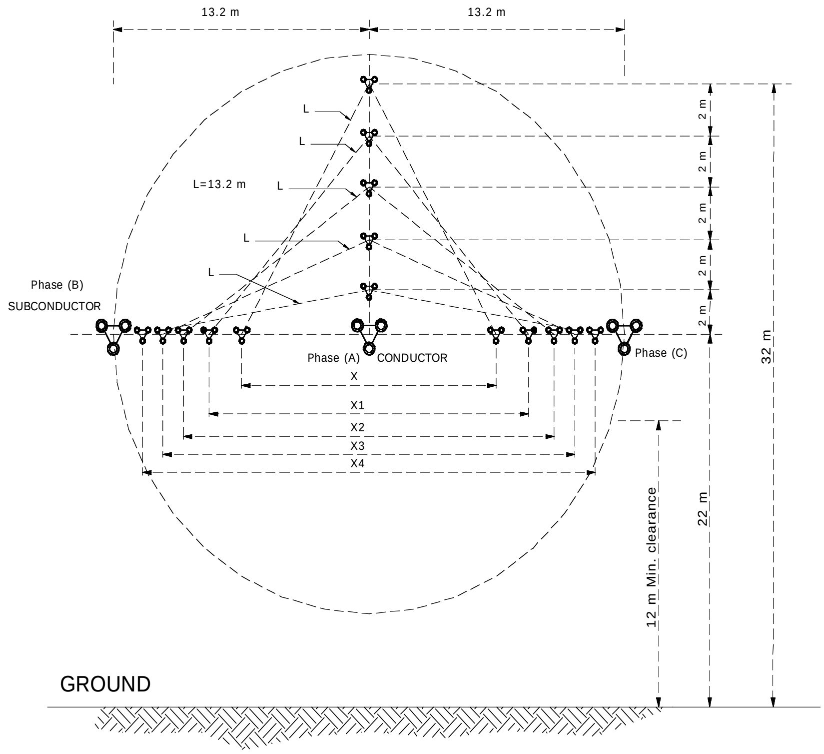


Fig. (14). 500 kV power transmission line, normal compact Delta configurations. (T.L. conductors arrangement, with the central phase is shifting up, on a central line, by 2 m steps up (and the outer phases moving on a horizontal line at 22 m).

Table 6. The Maximum Magnetic Field (B) Values at C.P.C and at ROW for Compact Normal Delta and its Percentage Values w.r.t. Base Case

Case of Study	Magnetic Field Values					
	Max. at C.P.C		Max. Values		Max. at ROW	
	uT/kA	%	uT/kA	%	uT/kA	%
Flat (Base Case)	18.751	100	18.751	100	4.341	100
2 m shift up	17.296	92.240	17.296	92.240	4.265	98.249
4 m up	16.514	88.070	16.514	88.070	4.095	94.333
6 m up	16.025	85.462	16.025	85.462	3.829	88.206
8 m up	15.692	83.686	15.692	83.686	3.461	79.728
10 m up	15.326	81.734	15.326	81.734	2.978	68.602

Table **6** and Fig. (**16**) present the maximum magnetic field (B_{total}) values and its percentage values w.r.t. the base case (flat horizontal configuration), values of 500 kV power line obtained with compact normal delta configuration.

It can be noticed that increasing the shift up of the central phase conductors from the ground, lower maximum magnetic field values are obtained, at both of the central phase conductor (C.P.C) and at the ROW positions, with a reduction of 16.3 % and 20.3 %, respectively for 8 m shift up case. This is because of the effect of the cancellation factor.

4.3.3. The Cases of Full Compaction

The full compaction means, keeping the spacing between all three phases, constant at the safe distance of 13.2 m. Fig. (**17**) presents the results obtained for the two full compaction cases of compact normal delta and compact inverted delta transmission line configurations. These results are obtained with keeping the spacing between all three phases, constant at the safe distance of 13.2 m. These obtained results are compared with those obtained for the case of normal conventional flat configuration of the 500 kV power transmission line.

The obtained results show that, the magnetic field values obtained for the case of full compact inverted delta configuration (Inv.Delta) is lower than those obtained for the case of the conventional configuration up to the ROW distance (at 25 m) from the center line of the transmission line. Then the produced magnetic field values of the (Inv.Delta) become

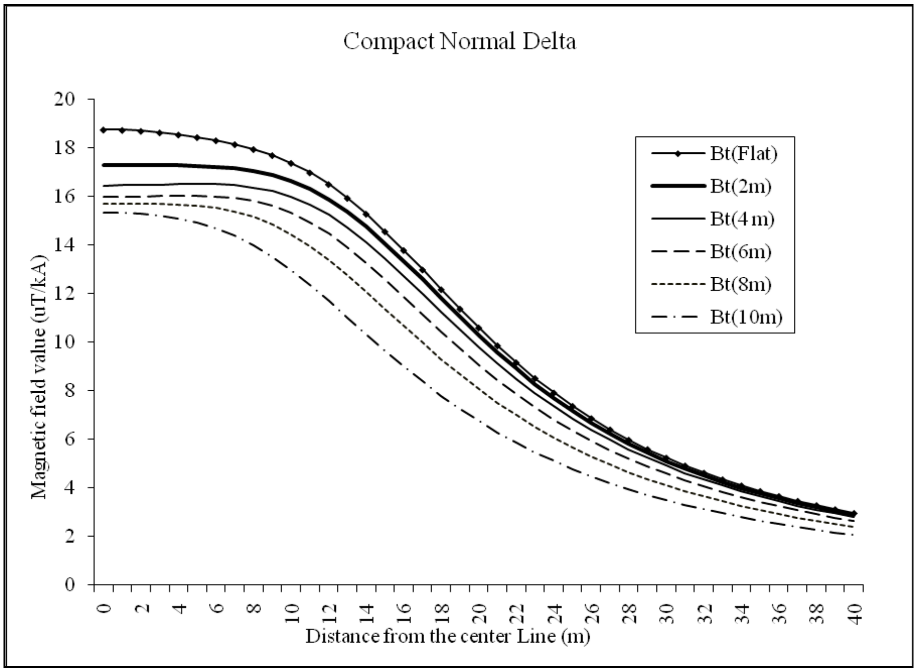


Fig. (15). Magnetic field values (uT/kA) for 500 kV Power line with Compact normal delta and shifting up the central phase conductors, with 2 m steps, and keeping a constant safe distance of 13.2 m from the outer two phases of the power line.

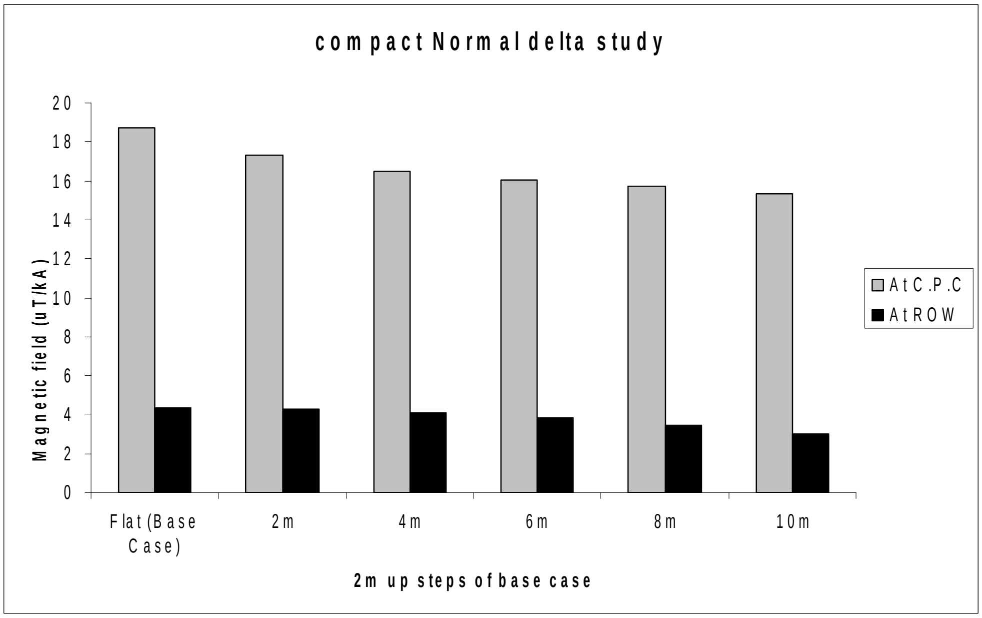


Fig. (16). The maximum magnetic field (B) values at C.P.C. and at ROW for, Compact normal delta and compared with the field value, of the Base Case.

higher than those of the conventional configuration (Conv.Delta) beyond this distance. While the resultant magnetic field values of the full compact delta configuration (D) are the lowest.

Table **7** shows the magnetic field components and total values at different lateral distances, from the central line positions of the power transmission line, with normal conventional configuration.

From Table **7**, Table **8** and Fig. (**13**), it can be seen that, for the full compact inverted delta configuration (Inv.Delta), compared with the conventional flat case, there is a reduction of the magnetic field values, in the area covering the distance from under the central phase conductor (CPC) position up to the ROW position. The average of this reduction in the magnetic field values is around 14.6 %. There is an increase of the magnetic field values beyond the ROW position, compared with that of the normal conventional flat case with an average of around 7.3 %.

The result of the reduction of the produced magnetic fields, in the case of full compaction case, as can be seen from Table **8** compared with those of Table **7**, will result in obtaining a big saving of the land around the power transmission line.

It can be seen from Table **7**, Table **9** and Fig. (**17**) that, the resultant magnetic fields produced with the full compact inverted delta configuration, are lower than those produced from the conventional flat line configuration, with a reduction of around 31.9%. Also, from a comparison of the results on Tables **7** and **9**, it can be noticed that, the maximum produced magnetic field value at the ROW position, (at 25 m from the center line), for the case of the normal conventional flat line, is 7.492 uT/KA. This value is obtained at a distance of (between 15 m and 16 m), for the case of full compaction inverted delta configuration, with a reduction of around 36 %.

This means that, there is a big saving of the land around and along the transmission line, which can be obtained by using the full compaction delta configuration.

5. CONCLUSIONS

From the results obtained for the different cases of studies, the following conclusions are obtained:

1) - For inverted delta configurations, the maximum magnetic field value are obtained, with the outer two phases are at the height level of 32 m and 34 m from the ground. While the positions of the maximum values, for all the considered cases remain directly, under the central phase conductors.

2) - For normal delta configuration, the maximum (B) values varies and the higher value is obtained at the case of flat configuration. With any shift up, of the central phase conductors, will increase the effects of the field cancellation factors and then reduced the maximum values.

3) - For compact inverted delta configuration (with shifting up the outer phases conductors with keeping them moving on circle curve), as higher outer phases conductors from the ground, the higher of the magnetic field (B) values are obtained under the central line.

4) - For compact normal delta configuration (with shifting up the central phase conductor and moving the outer phases horizontally at a constant height), as higher central phase conductors the lower and a reduction of the magnetic field values. With a reduction of around 31%, at the ROW is obtained.

5) - For full compact inverted delta configuration (Inv.Delta), (with constant safe distance between the three phases), compared with the conventional flat case, there is a reduction of the magnetic field values, in the area covering the distance from the under the central phase conductor (CPC) position up to the ROW position. The average of this reduction in the magnetic field values is around of 14.6 %.

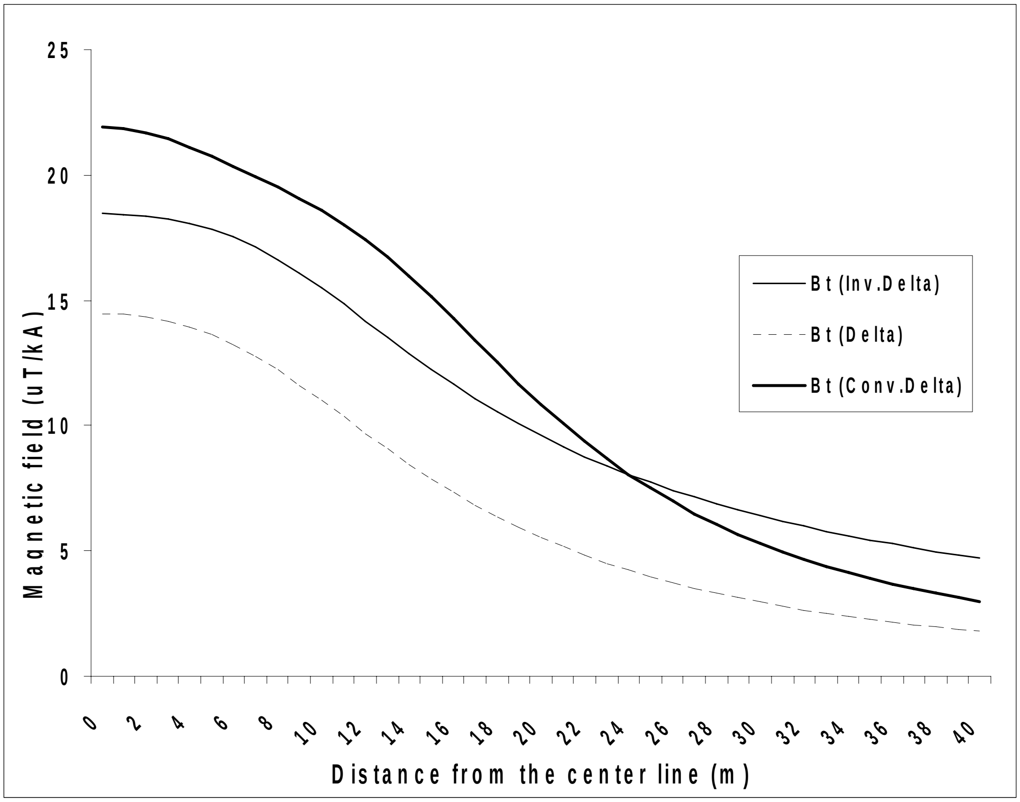


Fig. (17). The magnetic field profiles, at the mid-span of the transmission line, for full compaction normal delta (Delta), full compaction inverted delta (Inv.Delta) and the conventional configurations(Conv.Delta).

Table 7. Magnetic fields Results Obtained at Different Distances from the Central Line, at the Mid-Span, for the Conventional Configuration with 13.2 m Space Between All Phases

Distance from the Central Line(x m)	(bx) Component (uT/kA)	(by) Component (uT/kA)	(bz) Component (uT/kA)	The Total Magnetic Field (bt) (uT/kA) (Conv. Delta)
0	15.595	15.403	0.002	21.919
2	14.475	16.156	0.002	21.691
4	11.950	17.402	0.002	21.110
6	9.929	17.774	0.002	20.359
8	9.952	16.805	0.002	19.531
10	11.547	14.555	0.002	18.579
12	13.193	11.349	0.002	17.403
14	13.916	7.792	0.002	15.949
16	13.48	4.703	0.002	14.276
18	12.173	2.968	0.002	12.53
20	10.469	2.880	0.001	10.858
22	8.744	3.329	0.001	9.357
24	7.200	3.627	0.001	8.062
25	6.520	3.690	0.001	7.492
26	5.903	3.706	0.001	6.970
28	4.848	3.634	0.001	6.059
30	4.002	3.474	0.001	5.300
32	3.327	3.272	0.001	4.666
34	2.786	3.055	0.001	4.135
36	2.352	2.839	0.001	3.687
38	2.000	2.633	0.001	3.306
40	1.713	2.439	0.001	2.981

+ROW distant considered = 25 m from the central line.

Table 8. Magnetic Fields Results Obtained at Different Distance from the Central Line, at the Mid-Span, for the Full Compact Inverted Delta Configuration with 13.2 m Space Between all Phases

Distance from the Central Line (x m)	(bx) Component (uT/kA)	(by) Component (uT/kA)	(bz) Component (uT/kA)	The Total Magnetic Field (bt) (uT/kA) (Inv. Delta)
0	12.375	13.695	0.001	18.458
2	12.891	13.097	0.001	18.377
4	13.994	11.469	0.001	18.094
6	14.811	9.372	0.001	17.527
8	14.728	7.738	0.001	16.637
10	13.679	7.245	0.001	15.479

Table 8. contd….

Distance from the Central Line (x m)	(bx) Component (uT/kA)	(by) Component (uT/kA)	(bz) Component (uT/kA)	The Total Magnetic Field (bt) (uT/kA) (Inv. Delta)
12	12.008	7.544	0.002	14.182
14	10.141	7.935	0.002	12.877
16	8.374	8.107	0.002	11.655
18	6.842	8.044	0.002	10.560
20	5.572	7.817	0.002	9.600
22	4.543	7.497	0.002	8.767
24	3.716	7.136	0.002	8.046
25	3.366	6.950	0.002	7.722
26	3.052	6.764	0.002	7.421
28	2.516	6.4	0.002	6.877
30	2.081	6.053	0.002	6.400
32	1.726	5.726	0.002	5.981
34	1.435	5.423	0.003	5.609
36	1.194	5.141	0.003	5.278
38	0.994	4.881	0.003	4.981
40	0.828	4.641	0.003	4.714

+ROW distant considered = 25 m from the central line.

Table 9. Magnetic Fields Results Obtained at Different Distance from the Central Line, at the Mid-Span, for the Full Compact Delta Configuration with 13.2 m Space Between all Phases

Distance from the Central Line (x m)	(bx) Component (uT/kA)	(by) Component (uT/kA)	(bz) Component (uT/kA)	The Total Magnetic Field (bt) (uT/kA) (Delta)
0	4.528	13.739	0.001	14.466
2	5.851	13.091	0.001	14.339
4	8.203	11.268	0.001	13.937
6	9.972	8.685	0.001	13.224
8	10.579	6.101	0.001	12.212
10	10.070	4.406	0.001	10.991
12	8.860	3.946	0.001	9.699
14	7.412	4.069	0.001	8.455
16	6.035	4.164	0.001	7.332
18	4.867	4.086	0.001	6.355
20	3.937	3.875	0.001	5.524
22	3.218	3.591	0.001	4.822
24	2.672	3.282	0.001	4.232

Table 9. **contd….**

Distance from the Central Line (x m)	(bx) Component (uT/kA)	(by) Component (uT/kA)	(bz) Component (uT/kA)	The Total Magnetic Field (bt) (uT/kA) (Delta)
25	2.450	3.127	0.001	3.972
26	2.257	2.975	0.001	3.734
28	1.939	2.687	0.001	3.313
30	1.692	2.423	0.001	2.956
32	1.498	2.187	0.001	2.650
34	1.341	1.976	0.001	2.388
36	1.212	1.789	0.001	2.161
38	1.104	1.624	0.001	1.963
40	1.011	1.478	0.001	1.791

+ROW distant considered = 25 m from the central line.

So, a saving of the land around the power transmission line can be obtained.

6) - For full compact normal delta configuration, (with constant safe distance between the three phases), the resultant magnetic fields produced with the full compact inverted delta configuration, are lower than that produced from the conventional flat line configuration, with a reduction of around 31.9%.

This means that, there is a big saving of the land around and along the transmission line, which can be obtained by using the full compaction delta configuration.

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Received: December 02, 2008 Revised: March 10, 2009 Accepted: May 30, 2009