# A SIMPLE INNOVATIVE METHOD TO REDUCE EXTREMELY LOW FREQUENCY MAGNETIC FIELD BY CONDUCTOR SPLITTING AND PHASE MIXING

**P.Damodaran[1], R. Rengaraj[2], D.Rohit[3], G. R. Venkatakrishnan[2], G. Aadithya[2]**
[1,3] Siechem Wires & Cables, Siechem Technologies Pvt Ltd
[2]Department of Electrical and Electronics Engineering, SSN College of Engineering

## ABSTRACT

With the advent of modern day technologies, substantial increase in man-made magnetic fields was observed. At frequencies of 50 and 60 Hz, Extremely low frequency (ELF) magnetic fields are mainly from electrical energy generation, transmission, distribution and usage. One of the most commonly found source of ELF magnetic fields are electric cables as they are inevitable in a power system. Public concern on potential health problems has raised because of exposure to ELF magnetic fields. The biological effects associated with exposure to ELF magnetic fields, like leukemia, brain tumor, neurological effects and cardiovascular effects has unavoidably led to imposing legal limits. Popular methods mitigating this problem were cable twisting, active shielding, conductor splitting and phase mixing. The aim of this paper is to determine a simple, innovative and cost effective method of cable design to reduce the ELF magnetic field produced at the vicinity of single phase electric cable. The proposed method incorporates conductor splitting and phase mixing simultaneously. Conductor splitting distributes the area of a single conductor into N sub-conductors and phase mixing rearranges the conductors of N phases in specific orders. Its effectiveness was verified with theoretical calculations and computer simulation results. The cables were modeled using Finite Element Analysis (FEA) based software package Magnet, developed by Infolytica Corporation. The result from the study reveals that the magnetic field at the vicinity of the electric cable could be reduced by a staggering 80%. The proposed method significantly improves the efficiency by harnessing the synergy of combining two individual solutions.

**Keywords:** conductor splitting, phase mixing, MagNet Software, Extremely low frequency magnetic field

## 1. INTRODUCTION

Humans are revealed to magnetic and electric fields from both natural and man-made sources. The strength of fields from natural sources is very low when compared to man-made sources; it requires immediate attention in order to reduce them. Extremely Low Frequency (ELF) magnetic fields produce adverse biological effects on humans like differentiation of bone marrow stromal cells [1], neurological and cardiovascular diseases which has motivated the researchers to assess the intensity and to control the magnetic field under power lines available in the vicinity of the houses, factories and schools and keep the emissions under permissible values [1].

In addition, power towers are increasingly utilized to deploy communication equipment such as telephone trans-receivers. Workers installing and maintaining such equipment experience higher field exposures which are extremely dangerous to the health [3][4]. In real world, ELF magnetic fields is present everywhere and it is important to have a knowledge about the exposure limit both at work and home. Across the world, a lot of research has been carried out to find the connection between the prolonged exposure to ELF magnetic fields and the potential cause of cancer and the results show that there exist a stable relationship between sustained exposure to ELF magnetic fields and Leukemia [5][6]. The pooled analysis of the results from several studies, [7][8] published, found that there was increased incidence of childhood Leukemia associated with time-averaged magnetic fields greater than 0.4μT. The research findings have been reviewed by experts around the world including the World Health Organization (WHO) [9]. The exposure limit according to the ICNIRP standard is 100μT for magnetic fields generated by 50Hz power lines [10]. This must never be exceeded in

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general public exposure. The attention value limit of 10μT is adopted in children's playgrounds, residential buildings, schools where people are staying for 4 hours or more per day. Electric cables in the forthcoming years are expected to achieve a very low magnetic field at their vicinity and are set with an objective limit of 3μT [3].

Most popular methods used to reduce ELF magnetic fields are twisting, active shielding [11], conductor splitting [1] and phase mixing [11]. The disadvantages in introducing twisting of cables is that twisting of the cable gets affected by specific torsion constant, helical length of the cable surges and flexibility of the cable [13][14]. In some specific cases, where twisting is not practically possible to implement, active shielding is preferred which further increases the thickness of the cable which again restrict the flexibility of the cable. One of the most cost effective and efficient methods to reduce the ELF magnetic fields is conductor splitting. In our case study, conductor splitting makes single core single phase cable into a N core single phase cable of the equal dimensions. The current in the derived conductors are also split equally [1]. Phase mixing is basically rearrangement of the phase and neutral conductors in different configurations [11]. Flexibility of the cable doesn't change as there aren't any drastic changes in the arrangement of the core conductors. However, there exists a small increase in its overall dimension. By applying conductor splitting and phase mixing simultaneously the net ELF magnetic field due the single phase electric cable is reduced. It can also be made available for a colossal range of voltages and currents. The aforementioned innovative and simple design is also feasible for electric wiring in commercial, residential and industrial installations.

Magnetic field simulations for the various cable configurations were done using the software called MagNet developed by Infolytica. The model uses the finite element technique [15] for an accurate and quick solution of Maxwell's equations to produce the magnetic field around the current carrying cable. It divides the structure into many smaller triangular elements referred to as the finite element mesh. Input data are the dimensions of the cable, material characteristics, boundary conditions required to observe the field, sources of current or voltage. The simulator generates field solutions and computes the requested quantities. MagNet has been previously used for analysing electromagnetic flux of Permanent Magnet Brushless DC (PMBLDC) motor [16]. Rest of the paper is organized as follows: The formulae used for calculating magnetic fields for the single core and multi core cables are discussed in Section 2. Section 3 presents the simulated and theoretical results and conclusion is drawn in section 4.

## 2.FORMULAE USED TO CALCULATE THE ELF DUE TO THE CABLE

The formulae used to calculate the ELF due to the different configurations of the cables considered are already found in the literature. Magnetic field due to finite length current carrying cable is derived using basic equations from Biot-Savart law. For the case of multiple core cables, the formula used is of magnetic field due to number of conductors, which is explained in the literature as the vector addition of the individual field produced by each conductor present in the cable.

The formulae are based upon the following assumptions [17]:
(i) The earth has no effect on magnetic field produced by the cable, based on the fact that most materials other than ferromagnetic material have a relative magnetic permeability of very close to unity.
(ii) Each cable is considered to be in finite length
(iii) Total magnetic field at any point may be determined by a linear superposition of the magnetic fields produced by all of the currents in the cable system.
(iv) There are no stray currents flowing in the cable sheath/ shields or neutral conductor by source other than the current flowing in cable conductors.

### 2.1 Magnetic field due to single straight finite length current carrying conductor

In the *x*-axis, a thin and straight wire of finite length carrying a current *I* is placed as shown in Fig. 1. Note that we have anticipated that the leads to the ends of the wire create cancelling assistances to the net magnetic field at the point *P* [18] .

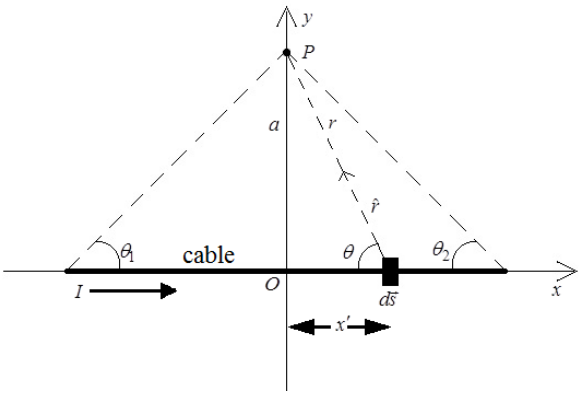



Fig.1 Magnetic field at any point due to current carrying conductor of finite length

The Magnetic field at any point P which is at a distance of $a$ is specified using the formulae given by [18]

$$B = -\frac{\mu_0 I}{4\pi a}\int_{-\theta_1}^{\theta_2} \sin\theta\, d\theta = \frac{\mu_0 I}{4\pi a}(\cos\theta_1 + \cos\theta_2) \quad (1)$$

where $B$ is the magnetic field due to the conductor of finite length, $\mu_0$ is the permeability of free space ($\mu_0$= 4π x $10^{-7}$ $Hm^{-1}$), $I$ is the current in Amperes in the conductor, $a$ is the perpendicular distance between the conductor in m and the observation point $P$ and $\theta_1, \theta_2$ are the angle subtended by the observation point with respect to the ends of the conductor in degree.

The magnetic field due to single core finite length current carrying cable is shown in Fig. 1. The magnitude of magnetic field at any point $P$ due to current carrying conductor of finite length is given by Eqn. (1). The direction of magnetic field at that particular point can be determined using right hand thumb rule.

**2.2 Magnetic field at any point due to a system of straight finite length current carrying conductors**

Consider two finite length current carrying conductors placed in the *x*-axis. The directions of both currents are into the page. As shown in Fig. 2, the magnetic field lines due to two current carrying conductors are in the yz-plane [18].

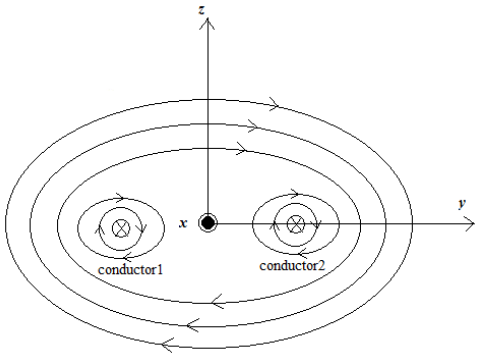



Fig 2 .Magnetic field lines of two conductors carrying current in the same direction

In a system of two current carrying conductors [18], let $\vec{B}_1$ be the magnetic field due to conductor 1 and $\vec{B}_2$ be the magnetic field due to conductor 2 at point P. The superposition of magnetic fields due to two current carrying conductors are shown in Fig. 3.

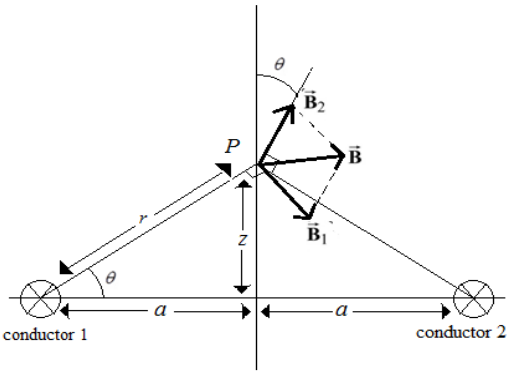



Fig 3 .Magnetic field at any point due to two current carrying conductors

Using Ampere's law, the magnetic field at point P due to each conductor $i$ is given by [18],

$$B_i = \frac{\mu_0 I}{2\pi r} = \frac{\mu_0 I}{2\pi\sqrt{a^2 + z^2}}, i = 1,2 \quad (2)$$

The net magnetic field at point $P$ is given by the algebraic addition of magnetic field due to individual conductor and is given by

$$\vec{B} = \vec{B}_1 + \vec{B}_2 \quad (3)$$

where $\mu_0$ is the permeability of free space ($\mu_0$=4π x $10^{-7}$ $Hm^{-1}$), $I$ is the current flowing through the conductor in A, r is the distance between the point P and the conductor in m, $z$ is the perpendicular distance from the axis of cable and the observation point in m and $a$ is the thickness of insulation in m.

Figure 2 shows the magnetic flux lines around two conductors carrying current in the same direction. Fig. 3 shows the net magnetic field given by the

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equation (2). The net magnetic field due to the conductors may be obtained by vector addition of their individual magnetic fields.

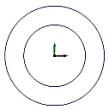
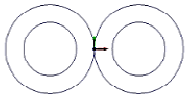
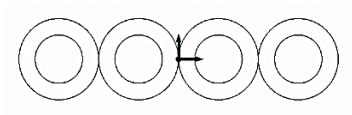
## 3. RESULTS AND DISCUSSIONS

### 3.1 Case Study:

In order to find a low cost solution for sinking the ELF magnetic field at the electric cable vicinity, the above proposed techniques were carried out. Initially on single core 4sq.mm (1Cx4sq.mm) cable, the case study is conducted. The magnetic field at its vicinity is simulated and calculated for a current of 3A. The production of 2sq.mm cables has been commercially stopped, so by conductor splitting 1Cx4sq.mm conductor is replaced by two core 2.5sq.mm (2Cx2.5sq.mm).The current distributes equally in the split conductors as 1.5A. Finally, four core 1sq.mm (4Cx1sq.mm) cables are considered for observing the effect of both conductor splitting and phase mixing. The core conductor size is considered as 1sq.mm , so that the net over all dimension of the cable isn't altered. In the final configuration of 4C x 1sq.mm, phase mixing was implemented and each of the phase conductors carry 1.5A but in phase shift of $180^{o}$.Simulations of the electric cables were done using MagNet 7.1.1 Software.

Table 1 gives Magnetic field of the cable for different configurations of conductors inside the cable at 5cm from the axis. Magnetic field of 1Cx4sq.mm, 2Cx2.5sq.mm and 4Cx1sq.mm current carrying finite length cable at a point 5cm from the axis is shown in figures 4 - 6. The magnetic flux lines due to current in 1Cx4sq.mm cable is presented in Figure 7.It is well recognized that the magnetic field around a straight current carrying conductor forms circular concentric field lines [19]. It is found that the cancellation of magnetic flux lines are negligible because, the phase and neutral conductor(s) are considered to be kept away from each other. Figure 8 shows the magnetic flux lines due to 2Cx2.5sq.mm cable. There was no appreciable reduction of magnetic field observed because there was no cancellation of magnetic flux lines in single phase system. In the 4Cx1sq.mm as shown in Fig. 9, the consequence of conductor splitting and phase mixing leads to cancellation of magnetic fields. Field cancellations occur because of the conductors carrying current in opposite directions. Tables 2 - 4 gives Magnetic field due to 1C x 4sq.mm, 2C x 2.5sq.mm and 4C x 1sq.mm cable at various point of observation ranging from 2 to 30cm. Figure 10 shows the magnetic field of the electric cable with different configurations of conductors at the vicinity. The magnetic field is plotted in logarithmic scale as it diverges from $10^{-2}$ to $10^{2}$ μT for observation points fluctuating from 2 to 30cm. The simulations were carried out demonstrating the magnetic field and magnetic flux lines for several configurations of conductors from the cable axis at 5cm.

Table 1. Magnetic field observed at 5cm from the axis of the cable

| Configuration of conductor inside cable | Conductor dimension | Magnetic Field (μT) | |
|---|---|---|---|
| | | Simulated | Calculated |
|  | 1Cx4sq.mm | 8.917 | 11.985 |
|  | 2Cx2.5sq.mm | 10.400 | 12.000 |
|  | 4Cx1sq.mm | 1.000 | 1.670 |

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From Table 1 it can be observed that the magnetic field can be reduced by replacing single core conventional cables by four core conductor split and phase mixed cables. The reduced magnetic field is observed to be well under the ICNIRP attention limit of 10µT. The magnetic field also lies well below the objective limit of 3µT at vicinity of the cable.

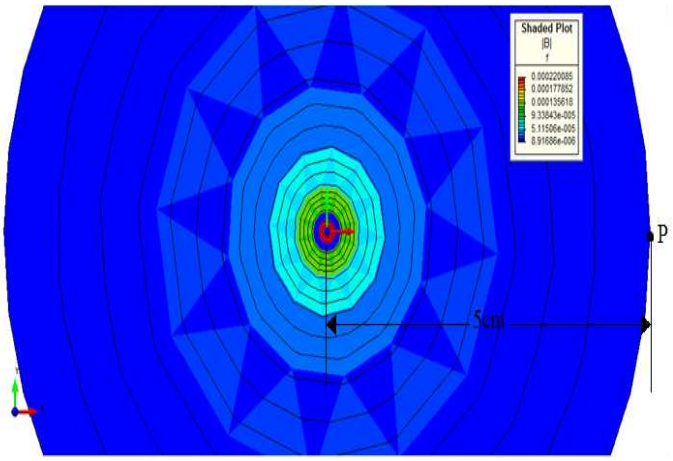



Fig. 4 Magnetic field due to 1Cx4sq.mm cable using MagNet Software.

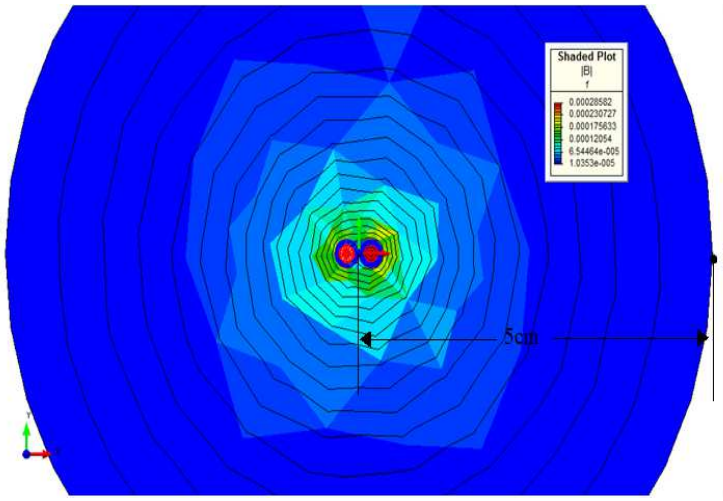



Fig.5 Magnetic field due to 2Cx2.5sq.mm cable using MagNet Software

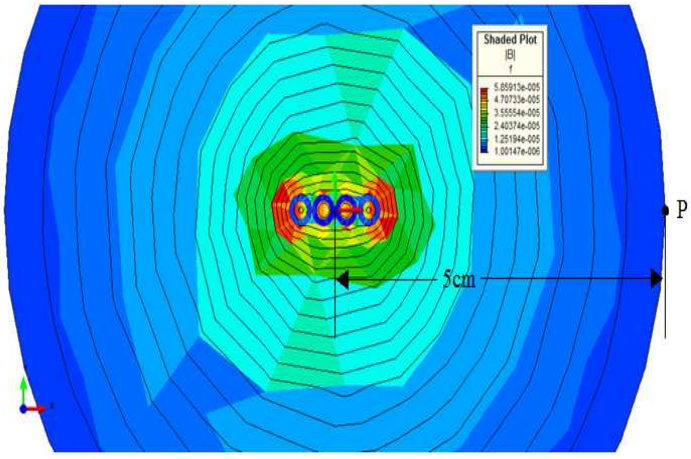



Fig.6 Magnetic field due to 4Cx1sq.mm cable using MagNet Software

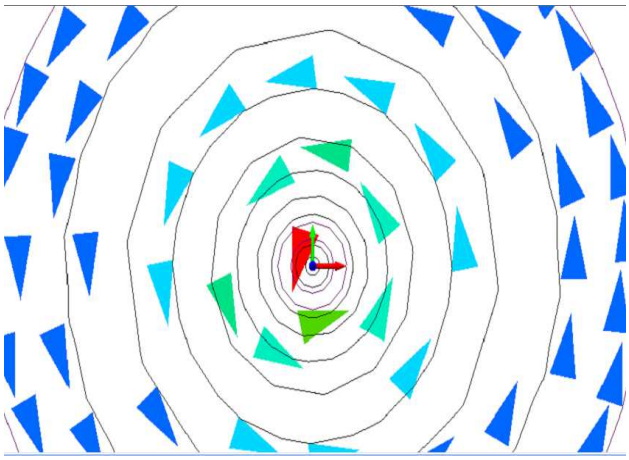


Fig.7 Magnetic flux lines around 1Cx4sq.mm cable using MagNet Software

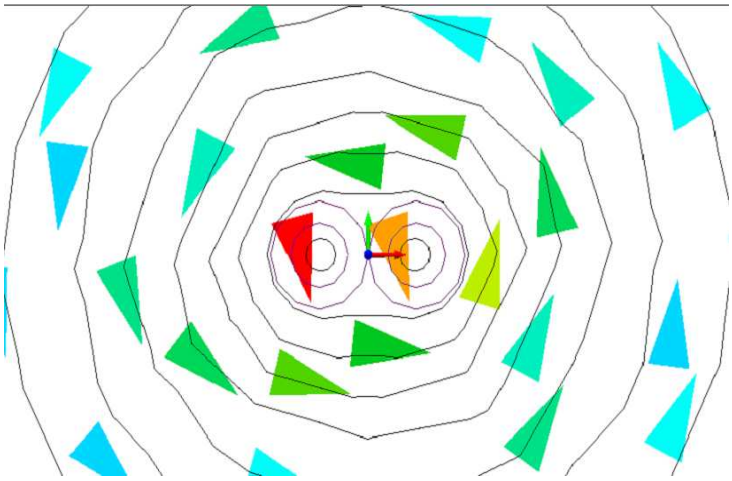


Fig.8 Magnetic flux lines around 2Cx2.5sq.mm cable using MagNet Software

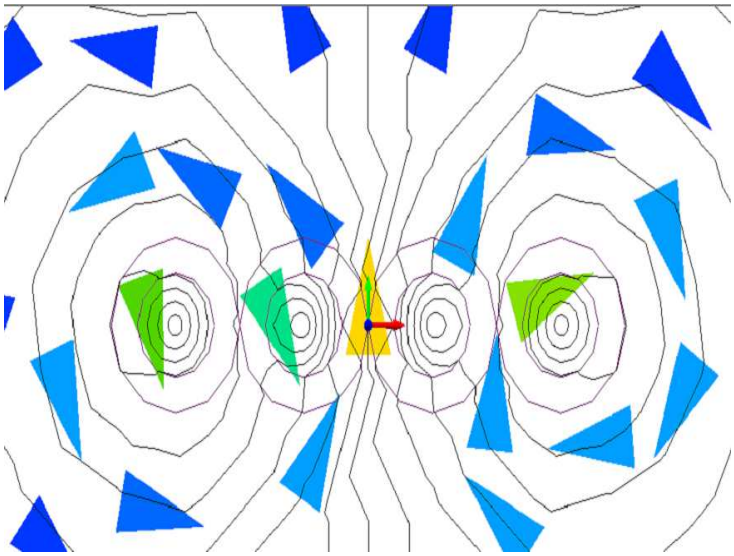


Fig.9 Magnetic flux lines around 4Cx1sq.mm cable using MagNet Software

Table 2. Magnetic field due to 1Cx4sq.mm cable configuration at various point of observation

| Point f observation (cm) | Magnetic Field for various cable | |
|---|---|---|
| | 1Cx4sq.mm | |
| | Simulated | Calculated |
| 2 | 11.350 | 29.994 |
| 5 | 8.917 | 11.985 |
| 10 | 4.598 | 5.970 |
| 15 | 3.059 | 3.956 |
| 20 | 2.293 | 2.942 |
| 30 | 1.545 | 1.916 |

Table 3. Magnetic field due to 2Cx2.5sq.mm cable configuration at various point of observation

| Point f observation (cm) | Magnetic Field for various cable | |
|---|---|---|
| | 2Cx2.5sq.mm | |
| | Simulated | Calculated |
| 2 | 28.969 | 30.200 |
| 5 | 10.353 | 12.010 |
| 10 | 5.152 | 6.002 |
| 15 | 3.429 | 4.000 |
| 20 | 2.577 | 3.000 |
| 30 | 1.688 | 2.000 |

Table 4. Magnetic field due to 4Cx1sq.mm cable configuration at various point of observation

| Point f observation (cm) | Magnetic Field for various cable | |
|---|---|---|
| | 4Cx1sq.mm | |
| | Simulated | Calculated |
| 2 | 9.606 | 10.904 |
| 5 | 1.001 | 1.669 |
| 10 | 0.406 | 0.415 |
| 15 | 0.209 | 0.184 |
| 20 | 0.098 | 0.104 |
| 30 | 0.037 | 0.046 |

The magnitude of magnetic field in $\mu T$ for different cable configurations from different points of observations is shown in Fig. 10.

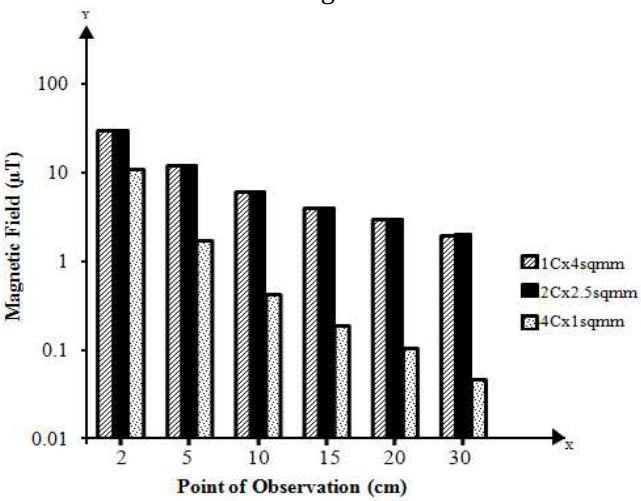



Fig.10 Magnetic field at the vicinity of the electric cable with different configurations of conductors

## 4. CONCLUSION

The results and tabulations presented in this paper shows magnitude of ELF magnetic field varies when the conductor configuration within a particular cable is changed. In addition, if the observation point is increased, the magnitude of magnetic field gets decreased when conductor splitting and phase mixing were implemented in the cable design. These solutions bring about an effective change in reducing the magnetic to be under attention limit of exposure. The theoretical and simulation results also show that, the magnitude of magnetic field can be kept under the objective limit by implementing these methods. Hence, conductor splitting and phase mixing have been proved to be a low cost, and an easy solution in order to reduce the magnetic field from single phase electric cables. Also the scope for development in this solution lies in the different combinations of conductor splitting and mixing. Similar solutions

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can also be found out for three phase cables by analyzing the various possibilities of conductor splitting and phase mixing.

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