Progress In Electromagnetics Research C, Vol. 140, 185-192, 2024

PIER C

(Received 21 November 2023, Accepted 15 January 2024, Scheduled 27 January 2024)

GA Based Optimization Technique for Magnetic Field Attenuation Around High Voltage Overhead Transmission Lines Using Mechanical Rearrangement of Power Conductors

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ABSTRACT: The magnetic field produced by overhead high voltage transmission lines has received extensive attention owing to its possible biological effects on humanity. The scientific community as well as general public are interested in the possible threats that living things may receive from the magnetic field. This research proposes a magnetic field mitigation approach near an overhead transmission line to avoid negative impact on the population around these lines. Apart from altering human brain activity and heart rate, magnetic fields can also lead to diseases like cancer. As a result, many techniques are employed to lessen that magnetic field. To reduce this magnetic field, scientists are looking for transmission line schemes. The suggested study investigates the influence of mechanical rearranging power conductors on magnetic field mitigation using genetic algorithm (GA) which is one of the evolutionary optimization techniques. The proposed GA has the objective to minimize the magnetic field as a fitness function and the location of conductors as genes considering their symmetry. The proposed method is tested using two published study cases of actual overhead transmission lines resulting in 48.4% and 57% reduction in magnetic field for case 1 and case 2, respectively. The contribution of the proposed method is to provide higher mitigation level of the mechanical rearrangement method depending on different sub-conductors spacing for one phase. The proposed mechanical rearrangement increases the geometric mean radius of the inner phase by optimizing its sub-conductors spacing within allowable critical ranges, thus the practical implementation of the proposed method requires a special design of the inner insulators string to support its sub-conductors.

1. INTRODUCTION

The attenuation of magnetic fields is a critical aspect in ensuring the safe and effective operation of overhead power transmission lines. The presence of heightened magnetic fields can lead to power loss and interference with radio signals. High voltage overhead transmission lines (OTLs) are indispensable in the contemporary world for the efficient distribution of electrical energy. However, these lines also generate electromagnetic fields (EMFs) at power frequencies (50/60 Hz), which have been associated with potential health risks in humans. Moreover, the electrical and electronic equipment in the vicinity may be impacted by these EMFs, necessitating the development of strategies to mitigate the magnetic field beneath OTLs. Epidemiological studies have explored the effects of long-term exposure on human health [1]. The findings from these studies suggest that prolonged exposure to electromagnetic fields has been linked to a range of health issues in certain scientific research. These include minor ailments such as headaches, skin rashes, insomnia, reduced learning capacity, and disorientation, as well as more severe conditions like various cancers and neurological disorders including Alzheimer's disease and Amyotrophic Lateral Sclerosis (ALS). The correlation between the levels of magnetic fields and different types of cancer has been estimated [2]. Therefore, it is advisable to minimize unnecessary exposure to electromagnetic radiation wherever possible [3, 4]. A method to derive the analytical formula of the magnetic field produced by any power line has been presented. The development of the presented method was made possible through the representation of the magnetic field vectors with double complex numbers. The derived formulas are accurate at any distance with practical importance, close to or far from the line, whereas the existing formulas in the technical literature were only accurate at far distances from the line. Also, the calculations based on the derived formulas are identical to those of any computer program that takes into account the same assumptions. Various methodologies are employed to calculate and reduce the magnetic field surrounding OTLs. An analytical evaluation of power-line magnetic fields, based on complex vectors, is proposed. The use of complex algebra greatly simplifies analytical calculations, and hence complex conductor arrangements are considered. A general formula for the magnetic-field intensity of any multiphase single-circuit line configuration is obtained. An expression for practical three-phase line configurations is simply derived as a particular case of the general formula. The proposed approach is then extended successfully to double-circuit lines, taking the load differences between circuits into account. Approximate formulas are validated by comparing magnetic flux density values with those computed from the general expressions [5]. The

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analytical calculation of the magnetic-field magnitude in complex arrangements is reduced to basic plane geometry calculations. The magnetic field is analyzed more easily than other approaches, and more compact formalism and the powerful machinery of complex algebra are introduced [6]. In [7], the longitudinal and cross-sectional profiles of electromagnetic fields produced by OHTL estimated using genetic algorithm (GA) are presented. Depending on limited number of field measurements produced by overhead transmission lines, the estimation accuracy is maximized by comparing these measured values with the theoretical ones calculated through the representation of the magnetic field vectors with double complex numbers. The procedure has been validated for different line configurations, and the numerical results obtained show that the proposed procedure considerably improves the theoretical calculation. The advantage of this approach of magnetic field calculation is that the fitness function could be modified to have the objective to mitigate the magnetic field by adjusting both of electrical and mechanical designs of OHTL. [8] proposed the concept of passive loop mitigation of conductors as a technically and economically viable solution to diminish the magnetic field of AC overhead lines. This method, applied to the flat distribution line configuration, is utilized in medium voltage systems. The impact of the passive loop conductor on the reduction of magnetic field intensity is further examined. Passive loops are represented by a loop of conductors positioned so that a voltage is induced due to the sequence of the magnetic flux generated by the phase conductors of a transmission line. This induced voltage, considering the impedance of the loop, results in a current flow within the loop. This current subsequently generates a magnetic field that counteracts the field produced by the phase conductor current of the line. [9– 11] explored the mitigation of a three-phase overhead line magnetic field using a U-shaped grid shield. The U-shaped grid shield comprises wires situated in a vertical plane and two horizontal planes, all connected in parallel. The magnetic field distributions are comparable when the lengths of the arms of the grid and electromagnetic shields are equal. Hence, the grid shield is preferred due to its ease of installation and cost-effectiveness. The use of such a U-shaped grid shield allows for a four-fold reduction in the amount of metal compared to the plane shield. To mitigate the magnetic field strength near overhead transmission lines, both electrical and mechanical methods are employed. Mechanical methods include modifying the positions of conductors to minimize the magnetic field. Transposing overhead power lines is a method to achieve the necessary reductions in electric and magnetic field intensities [12]. However, the optimal solution is constrained by discrete field values, and this technique requires more than one line for verification. Another mechanical technique suitable for a single line involves altering the geometrical characteristics of the line to achieve the lowest possible electric and magnetic field strengths [13]. The aim of [14] was to theoretically examine electromagnetic fields associated with high-voltage transmission lines, calculate their level in OTLs, and estimate the amount of electromagnetic interference. The computation was based on the use of fields and corona effects software (FACE) in computer-aided analysis (CAA). The study recommended maintaining a safe operational distance from high-voltage transmission lines and emphasized that engineers should consider the impact of electromagnetic interference during the design phase of the high-voltage transmission power system to prevent additional costs arising from the effects of electromagnetic interference produced by high-voltage transmission lines. [15] contributed a novel approach to determining the magnetic flux density and electric field strength near high-voltage overhead transmission line. This technique is based on the application of two fully connected feed-forward neural networks, each estimating the magnetic flux density and the electric field strength independently. Performance analysis results indicate that the proposed method can accurately estimate the electric field intensity and magnetic flux density for various configurations of overhead transmission lines. The primary objective of the research led by [16] was to quantify the static electric potential and the static electric and magnetic fields. This included calculating and analyzing the electric and magnetic fields caused by overhead DC high-voltage transmission lines, especially when they were close to the human body. Such an analysis is crucial for understanding the biophysical impacts and ensuring the safety of the public living near overhead transmission line. The basic characteristics of these fields are largely determined by variables such as the transmission voltage, current, and the physical configuration of the conductors in the transmission line. It has been demonstrated that the location beneath the overhead transmission line affects the minimum and maximum exposures to static electric and magnetic fields. This variation is influenced by factors such as the height of the transmission line conductor and the configuration of transmission line conductors. In [17], Kuznetsov et al. presented results of synthesis, theoretical and experimental studies of a robust system of active shielding of the magnetic field generated by overhead power lines with triangular conductor arrangements. The synthesis is based on the solution of a multi-criteria stochastic game, in which the vector payoff is calculated on the basis of the Maxwell equations solutions in a quasi-stationary approximation. The comparison of experimental and calculated results of the magnetic flux density values in the shielding space showed that their spread does not exceed 30%. In [18, 19], Ant Lion Optimization (ALO) is used to determine the best arrangement of overhead transmission line conductors in order to minimize the radiated magnetic and electric fields. Transmission lines with single and double circuits are optimized using the ALO algorithm. A computer code, developed in MATLAB and based on the ALO algorithm, is utilized to determine the conductor line positions that will result in minimized field emissions. Moura et al.'s research focused on using multi-objective optimization approaches to restructure conductors in order to maximize the utilization of OTLs. The objective of the optimization problem is to minimize the resultant ground-level electric and magnetic fields [20]. In the research conducted by [21], optimal phase arrangement techniques were utilized to mitigate the electromagnetic fields generated by overhead transmission lines, with a particular focus on a 3-circuit OTL with a voltage of 230/69 kV. The study presented a mathematical model developed using MATLAB, to demonstrate this approach. Two novel strategies for decreasing electric and magnetic fields are examined in [22]. The first technique entails modifying the position of the center phase to enhance the delta configuration. The second technique investigates the utilization of multiple shielding wires and involves the computation of the currents coursing through these wires. The results of these two methods were subsequently compared with the electric and magnetic fields, as well as the right-of-way values, associated with the prevailing conventional configuration. The research paper [23] presents an innovative approach for estimating uncertainty in the computation of electromagnetic field densities in proximity to overhead transmission lines. An analysis of the findings reveals that the proposed method effectively ascertains the uncertainty in the calculations of electromagnetic field intensities near OTLs. In the current research, the aim is to minimize the resultant magnetic field above ground level for a three-phase transmission line configuration with three cables per phase by repositioning the power conductors. GA is employed to achieve this objective. The positions of the conductors are encoded as genes, and the peak value of the magnetic field over the residential area is used as the fitness function.

2. MAGNETIC FIELD DENSITY CALCULATION

The phasor of the magnetic flux density surrounding a 500 kV transmission line is computed using a method based on the Biot-Savart law. According to this method, the sources of the magnetic field are point current sources located at the center of each equivalent conductor. Under the aforementioned assumption, the vector components of the magnetic flux density phasor at an arbitrary point $P(x;y)$ can be calculated as presented in [15]. For AC overhead high voltage transmission lines, the line currents vary sinusoidally with time at the specified power frequency. Consequently, the induced magnetic field in the area surrounding the power transmission lines also varies at the power frequency. Phase algebra can be utilized to combine numerous components, thereby yielding the amplitude of the required magnetic field (both horizontal and vertical vectors). For a three-phase system, current I can be expressed as follows [22]:

$$[I] = I_{rms}\angle 0^\circ, \quad I_{rms}\angle 120^\circ, \quad I_{rms}\angle -120^\circ \tag{1}$$

For a conductor carrying current I through the point (x_i, y_i), the magnetic flux density could be calculated as follows:

$$(B_x)_P = \sum_{i=1}^{m} \frac{\mu_o \times I_i}{2\pi} \left(\frac{-(y-y_i)}{(x-x_i)^2+(y-y_i)^2} + \frac{(y+y_i+\partial)}{(x-x_i)^2+(y+y_i+\partial)^2} \right) \tag{2}$$

$$(B_y)_P = \sum_{i=1}^{m} \frac{\mu_o \times I_i}{2\pi} \left(\frac{x-x_i}{(x-x_i)^2+(y-y_i)^2} - \frac{x-x_i}{(x-x_i)^2+(y+y_i+\partial)^2} \right) \tag{3}$$

$$\partial = 503\sqrt{\frac{2\rho_g}{f}} \times e^{-i\pi/4} \tag{4}$$

where ρ_g: earth resistivity ($\Omega \cdot$ m), f: frequency(Hz), μ_o: air magnetic reliability, and ∂: complex distance.

So, at an arbitrary point, the value of the magnetic field intensity is defined as the resulting value:

$$B(x,y) = \sqrt{|B_x|^2 + |B_y|^2} \tag{5}$$

3. PROPOSED METHODOLOGY

In the suggested research, the diminution of the magnetic field is formulated as an optimization problem. The repositioning of conductors can lead to alterations in the electromagnetic properties of a transmission line. This is due to the potential influence of conductor positioning on capacitive and inductive effects [22]. As per [24], the rearrangement of conductors can affect the electric and magnetic fields surrounding the conductors. Therefore, one of the considerations in Overhead Transmission Line (OTL) projects is the mitigation of the magnetic field. It is proposed to employ the genetic algorithm (GA) to identify the optimal new positions for the conductors in the transmission system, with the objective of minimizing the magnetic field to the greatest extent possible. The suggested methodology involves only the mechanical rearrangement of power conductors, as the shield wires of type $7/16''$ EHS aluminum material do not impact the calculation of the magnetic field according to [15, 22, 25].

GA is a sophisticated tool designed to identify the optimal solution for an optimization problem. The objective of this study is to compute the suitable geometric configuration of the conductor to minimize the magnetic field it generates. The decision variables in this optimization problem are the power conductor's horizontal (x_i) and vertical (y_i) coordinates. These coordinates form ordered pairs that define the positions of the conductors. The magnetic field can then be calculated based on the geometric arrangement of the conductor. Geometric constraints are imposed to prevent cable overlap and ensure adherence to safety distances and physical limitations such as spacer dampers and tower sizes. These constraints comprise minimum and maximum horizontal and vertical limits ($x_{\min}$, $x_{\max}$, $y_{\min}$, $y_{\max}$), minimum and maximum distances between conductors in the same bundle ($d_{\min}$, $d_{\max}$), and the minimum average distance between conductors of different phases ($D_{\min}$). Thus, the optimization problem can be formulated as follows.

3.1. Constraints

$$x_{\min} \le x_i \le x_{\max}, \; i = 1, 2, 3, \ldots, m \tag{6}$$

$$y_{\min} \le y_i \le y_{\max}, \; i = 1, 2, 3, \ldots, m \tag{7}$$

$$d_{\min} \le \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \le d_{\max}, \; i = 1, 2, 3, \ldots, m \tag{8}$$

$\forall i$ and j of same bundle

$$\sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \ge D_{\min} \; i = 1, 2, 3, \ldots, m \tag{9}$$

$\forall i$ and j of different phases.

TABLE 1. Cases studies data.

Original configurations	Case 1	Case 2
current (kA)	2.820	1.15
Phase conductor diameter (mm)	46.2	30.6
Peak Magnetic Field density	65.14 (μT)	24 (A/m)
Average Magnetic Field	21.74 (μT)	10.3865 (A/m)
Phase A conductor positions (m)	(−10.4785, 16.5320)	(−14.1, 22)
	(−10.2500, 16.7590)	(−13.65, 22)
	(−10.0215, 16.5320)	(−13.2, 22)
Phase B conductor's positions (m)	(−0.2285, 16.5320)	(−0.45, 24.35)
	(0.0000, 16.7590)	(0.0000, 24.35)
	(0.2285, 16.5320)	(0.45,24.35)
Phase C conductor's positions (m)	(10.0215, 16.5320)	(13.2,22)
	(10.2500, 16.7590)	(13.65, 22)
	(10.4785, 16.5320)	(14.1, 22)

TABLE 2. Proposed GA parameters.

GA parameters	Value of attributes
Genes number	$N = 18$
Number of Chromosomes	$M = 100$
Probability of crossover	$Cp = 0.6$
Probability of Mutation	$Mp = 0.01$
Function Tolerance	1e-10

3.2. Fitness Function

The objective function is to attenuate the maximum value of the magnetic field, calculated at a height of 1 meter above ground level.

4. SIMULATION, RESULTS AND DISCUSSIONS

This paper demonstrates the proposed optimization procedure with two cases studies [20, 22] involving typical transmission line with three conductors per phase. In this paper, the horizontal boundaries, defined as ($x_{\min}$ and $x_{\max}$), are determined by the x-positions of the furthest left and right conductors in the original configuration of the OTL, respectively. The highest conductor height of the original OTL is the maximum vertical limit ($y_{\max}$), and the lowest vertical limit ($y_{\min}$) is 10 meters. The $d_{\min}$ and $d_{\max}$ values indicate that the lowest and maximum distances that can exist between conductors within the same bundle are 0.169 and 2.0 meters, respectively. There is a minimum distance of 3.5 meters ($D_{\min}$) between conductors of different phases according to IEC71 standards[26] and calculation in [27].

4.1. Case Studies

Table 1 presents the data set for the proposed case studies including the original geometric configuration of the conductors and the maximum values of Magnetic Field Magnitude.

Table 2 presents the suggested GA parameters. The proposed method considers 18 genes (N) indicating the (x, y) positions of power conductors

4.2. Results

Table 3 shows the optimized OTL configuration and magnetic field for the proposed method in which the power conductors are rearranged as in the proposed method in [20].

Figures 1(a) and 1(b) show the configurations and corresponding field values of the original OTL, the proposed optimization method, and that of published literatures. The proposed method could be implemented practically by modifying the inner insulators string to be longer by about 1 meter in order to support the sub-conductors of this phase.

The magnetic field of the obtained curves is calculated at 1 m above ground surface and for the crosswise profile in the range from −80 m to 80 m, with increments of 1 m. The results show that the impact of power conductor rearranging is high on the magnetic field mitigation, and the magnetic field is minimized by about 48.4% and 57% of the original configuration in case 1 and case 2, respectively. In Fig. 2(a), the results of case 1's proposed configuration is compared to the results of [20]. Also Fig. 2(b) shows the result of proposed configuration in case 2 compared to the results of [22]. The proposed optimization case has better patterns than that of the mitigated pattern obtained in [20, 22].

TABLE 3. Results of proposed method.

Proposed configuration	Case 1	Case 2
Peak Magnetic Field	33.59 (µT)	10.28 (A/m)
Average Magnetic Field	9.38 (µT)	3.9716 (A/m)
Phase A conductor positions (m)	(−4.3050, 16.6902)	(−5.7230, 24.35)
	(−4.1088, 16.5111)	(−5.4944, 24.35)
	(−4.0994, 16.6902)	(−5.1990, 24.35)
Phase B conductor's positions (m)	(−0.7202, 16.6245)	(−0.4480, 24.35)
	(0.0000, 15.9483)	(0.0000, 24.35)
	(0.7202, 16.6245)	(0.4480, 24.35)
Phase C conductor's positions (m)	(4.3050, 16.6902)	(5.1990, 24.35)
	(4.1088, 16.5111)	(5.4944, 24.35)
	(4.0994, 16.6902)	(5.7230, 24.35)

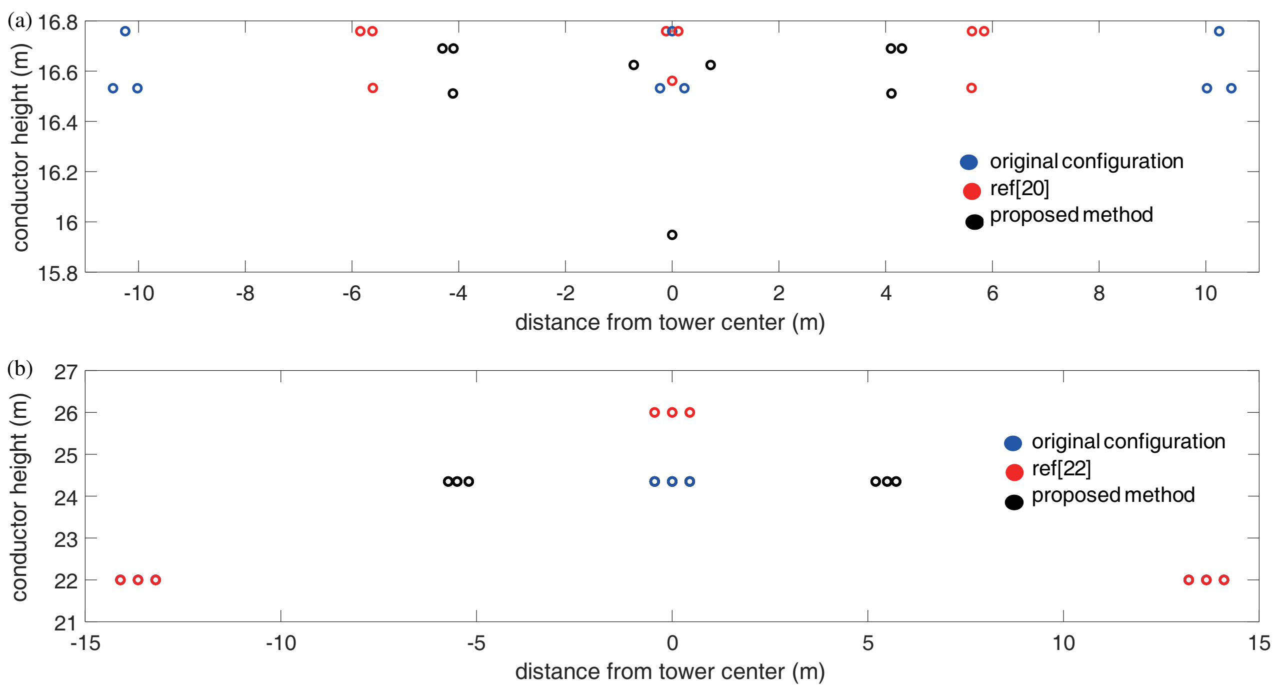

FIGURE 1. OTL configurations. (a) Case 1 layout. (b) Case 2 layout.

TABLE 4. Summary of results of all configurations case 1.

Configuration	Peak Magnetic Field		Avg. Magnetic Field (µT)		% reduction	
	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2
Original	65.14 (µT)	24 (A/m)	21.74 (µT)	10.3865 (A/m)		
Ref. [20, 22]	43.26 (µT)	23.6 (A/m)	12.57 (µT)	10.3344 (A/m)	33.6	1.67
Proposed Method	33.59 (µT)	10.28 (A/m)	9.38 (µT)	3.9716 (A/m)	48.4	57

4.3. Discussion

Table 4 summarize the results of the discussed configurations in the present paper. Results show that the proposed configuration mitigates the magnetic field either as peak value or average value. The proposed configuration corresponding to that introduced by [20, 22] has better results. Also the effect of new arrangement on electric field is considered, and the results demonstrate about 46% and 59% reduction in the maximum electric field in case 1 and case 2, respectively, as shown in Fig. 3.

Finally, the proposed method should be compared to other mitigation techniques such as self-electric compensation [28] and passive and active loops [29, 30]. All of these references and the proposed paper are based on GA with the same objec-

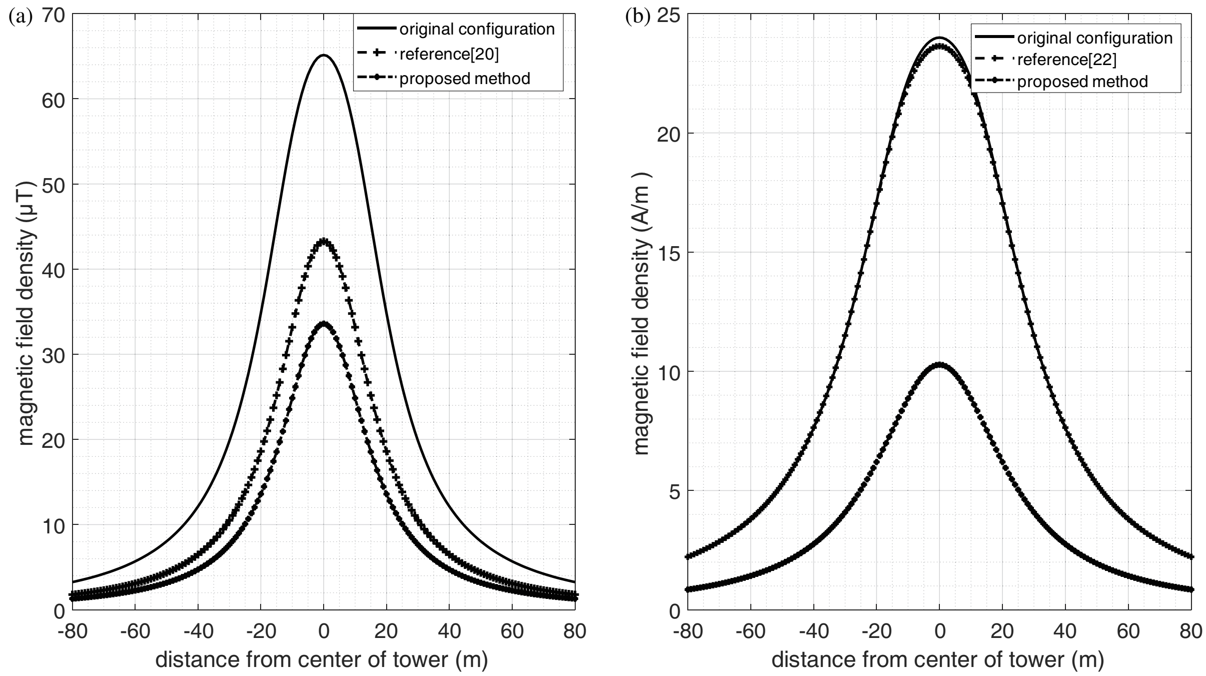

FIGURE 2. Magnetic field patterns for proposed optimization, (a) case 1 compared to Ref. [20], (b) case 2 compared to Ref. [22].

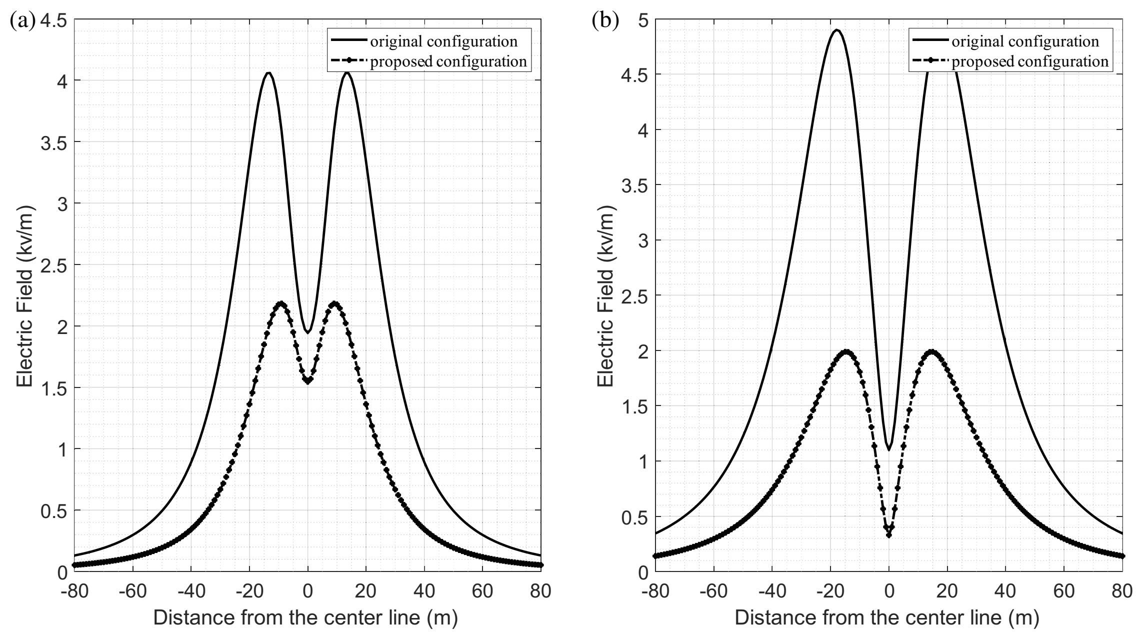

FIGURE 3. Electric field due to new arrangement. (a) Case 1. (b) Case 2.

tive function (minimization of the magnetic field due to electrical line); however, the difference lies on the encoding genes corresponding to the mitigation method. The advantage of the proposed method compared to that of these methods is the low implementation cost since no additional system is added. In [28], the mitigation requires injecting unbalanced currents in the transmission line by means of active circuits consisting of inverters and reactive elements. However in [29, 30], the magnetic field mitigation is implemented by either passive or active loops which require additional installation. Moreover, the proposed method has the advantage of that the magnetic field mitigation is valid at both sides of the line in contrary to the suggested references, which only mitigate the field at one side of the line.

5. CONCLUSION AND FUTURE WORK

This study presents an optimization investigation with the aim of reconfiguring conductors to minimize the resultant magnetic field at ground level. Two cases studies involving an actual

OTL demonstrated that conductor repositioning could potentially reduce the magnetic field by 48.4% and 57% in case 1 and case 2, respectively. These results highlight the effectiveness and practicality of this approach. By employing the Genetic Algorithm Optimization technique, we were able to determine the optimal arrangement of transmission line conductors. Bundled conductors were also considered. The importance of generating a symmetrical solution for the OTL during the evolutionary optimization process is emphasized. This strategy aids in identifying geometric configurations that are more feasible for implementation. The advantage of this method lies in enhancing applicability by improving the mechanical stability of the structure through the exploitation of symmetry. Moreover, the establishment of symmetry simplifies the construction of structural elements, such as spacer dampers, thereby increasing efficiency. This strategy is a significant contribution of this work, demonstrating its potential to considerably impact the field. In the future, the impact of mechanical rearrangement on magnetic field mitigation could be obtained by electrical compensation, causing an imbalance in the phase currents with an equivalent impact. The Genetic Algorithm could also be used to find the optimal current imbalance to achieve this objective. This imbalance is inserted in the transmission system either by active or passive elements, such as a floating circuit.

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