Technical and Economic Feasibility of Passive Shielding Used to Mitigate Power Lines' Magnetic Fields

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Abstract: - This paper targets optimal reduction in overhead power lines' magnetic fields using passive shielding. The combined technical and economic feasibility of using mitigation is assessed. Case studies include different power lines with two different phase arrangements and different configurations. Zone-based mitigation -rather than point-based- is applied by modifying the objective function to be based on a specific geographic domain, at which magnetic field is desired to be minimal. To obtain the feasibility of magnetic field mitigation for a power line, the cost of passive shielding is modeled using four basic cost parameters. Genetic algorithm is used to optimize passive shielding as a multi-objective problem. The problem is made up of two main objective functions: maximization of the magnetic field reduction and minimization of the cost of mitigation. A new Feasibility Index, which assesses the feasibility and effectiveness of mitigation of a line is defined and formulated.

Key-Words: - Passive shielding, Transmission lines, Magnetic fields, Cost-optimization, Genetic Algorithms, Multi-objective optimization.

1 Introduction

The concern from the risk of power lines magnetic fields exposure is encouraging authorities worldwide to develop policies aiming at reducing those fields in residential and/or industrial areas. For example in Europe, magnetic fields have to be less than 100 mT [1], although some European countries have settled more strong limitations: in Italy 3 mT for new lines, and in Switzerland restricted by only 1 mT [2, 3]. Even if the relationship between magnetic fields and certain forms of cancer produces small risk, the risk must be looked at seriously. Because large numbers of people are exposed to EMF, a small risk could add up to a substantial number of additional cancer cases nation-wide. In addition to human hazard, magnetic fields mitigation is very important to decrease electromagnetic interference on electronic and electric apparatus [4].

In [5], about 140 papers are introduced and reviewed to summarize the suitable methods for power-frequency magnetic field mitigation focusing on overhead power lines. Methods found in [6, 8] are based on phase reconfiguration, which proves to be effective yet costly if applied to an existing power line. [9] presents a good optimization method to provide optimum configurations for low magnetic fields with minimum cost considering horizontal, vertical and digging costs. The previous methods used for new design or reconstruction the power line. Other methods using shielding materials require current derating of the mitigated line [10, 11] due to high losses in the shield. In addition, conventional metallic shielding to protect a build or office from power line magnetic fields requires a lot of materials. However, active shielding with conductors provides a high shielding factor [12-14], the cost is very high to be implemented, and if there is a problem in the control unit, the shielding system may become an additional source of the magnetic field. This paper offers an in-depth analysis of mitigation by passive shielding (by loops) in the power line vicinity. No attempts were made to judge whether using mitigation methods are justified not only from a technical perspective but also from an economic one [15-19]. The present work is an attempt to seek this justification by expressing shielding effectiveness quantitatively.

The paper uses the zone mitigation approach and employs genetic algorithms (GA) in optimizing passive shielding using Egyptian transmission lines (500 kV, 220 kV, 66 kV) as a case study, thus the proposed technique can be used for any power line even if the produced magnetic fields from these lines is small. Cost optimization methods are then introduced to the optimization process by modeling the four major cost parameters, namely, cost of shield conductors and their installation (CSC), cost of parasitic power losses (CPL), cost of supporting structures and their installation (CSS), and cost of capacitive compensation (COC). A multi-objective optimization is then applied to assess mitigation effectiveness for all possible power line configurations.

2 Problem Formulation

With passive shields, the original magnetic field induces current in the shield conductors, which in turn generates a linearly polarized magnetic field leading to a reduction in the prevailing field. The optimization problem seeks optimal loop conductors' position as well as the value of compensating capacitors -if any- constrained by practical considerations which include flashover constraints, geometric constraints, the height of the pole, and compensation constraints. These constraints are listed in [16-18]. Another constrained used to limit the shield current to be less than the shield conductor ampacity (1), where I is the induced loop currents and I_{rated} the ampacity of shield conductors. Another constraint used for cost optimization presented by (12).

$$[I] \le I_{rated} \tag{1}$$

Traditional assumptions are adopted [16] [17], namely, that the effect of induced currents into earth is negligible, that each current-carrying conductor is infinitely long and parallel to ground, that the ground wire current effect is negligible, and that the loop length is much longer than its width so they could be considered to have infinite length. The induced current is calculated by

$$[I] = [Z_l]^{-1}[X_{lp}][I_p] \tag{2}$$

, where I_p is the phase currents, Z_l is the loop impedance, and X_{lp} is the mutual loops-phases reactance. Please, refer to [16-19] for more details about this equation.

2.1 Reduction Factor

The Reduction Factor (RF) is a factor which indicates the reduction in magnetic field after applying passive shielding. The reduction factor may be defined in two ways:-

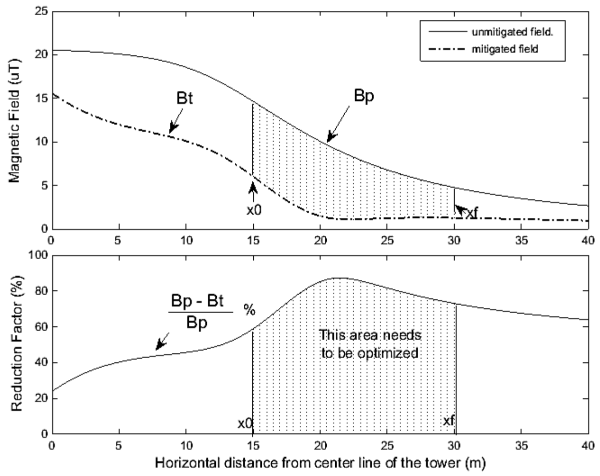


Fig.1 a) magnetic field distribution, b) ERF over the horizontal distance

A) Point Reduction Factor (PRF)

It can be expressed by

$$PRF = \frac{|\overrightarrow{B_p}| - |\overrightarrow{B_t}|}{|\overrightarrow{B_p}|} \tag{3}$$

, where $\overrightarrow{B_p}$, $\overrightarrow{B_t}$ are the magnetic field generated by phase currents, the resultant magnetic field at a specific location, respectively.

B) Extended Reduction Factor (ERF)

It is based on field mitigation over a critical mitigation zone – rather than at a single point - extended from x_0 to x_f [19]. Figure 1 shows an example of applying ERF to optimize magnetic field mitigation. It represents the magnetic field profile at one meter above the earth. Values of x_0 and x_f are selected as in section 3.

$$ERF = \frac{1}{x_f - x_0} \int_{x_0}^{x_f} \frac{|\overrightarrow{B_p}| - |\overrightarrow{B_t}|}{|\overrightarrow{B_p}|} dx \tag{4}$$

2.2 Genetic algorithm parameters

There is no general theory available that would help to tune GA parameters for any problem because it is a heuristic search algorithm. Therefore, any recommendations to implement GA depend on selecting suitable parameters using trial and error. This work is mainly based on MATLAB R2016b version through Global Optimization Toolbox [20]. GA options are still by default except; the population size = 40-60, as this value gives a suitable running time and a high probability of obtaining the optimum results, and Constraint tolerance = 10^{-3}. There are additional recommendations in section 6.

2.2 Mitigation Options

Improving magnetic field mitigation -based on passive shielding- relies on the use of series compensation, and the choice of a practical number of shield conductors: 2, 3 or 4. It is then aiming at a high reduction factor; either PRF or ERF. And then applying cost optimization as discussed in section 5.

3 Case Study

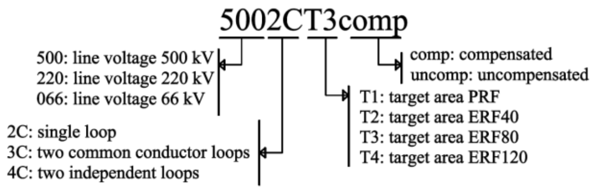
In this section, the study compares the mitigation options which are applied to the Egyptian lines 500 kV, 220 kV, and 66 kV. The first has a flat, single circuit, configuration, the latter two have vertical, and double circuit configurations. Detailed tower and line dimensions are shown in Table I. Magnetic fields computations are made at a height one meter from the ground level at mid-span. Three loop configurations are recognized: (1) Single loop with two conductors (2C), (2) Two common- conductor loops with three conductors (3C), and (3) Two independent loops with four conductors (4C).

Table I Case study power lines parameters

Parameter description		Parameter value		
		Line 1	Line 2	Line 3
Line's voltage level (kV)		500	220	66
Number of circuits/tower		1	2	2
Right-Of-Way (m)		35	25	13
Maximum sag (m)		12	9.5	6
Load current/phase(A)		1000	1000	1000
Minimum phase-to-shield clearance (m)		5.1	3.3	2.3
Coordinate of phase conductors at towers*	a	(-12.0,19.1)	(-5.4,15.7), (5.1,35.1)	(-3.7,11.5), (3.7,17.1)
	b	(0.0,19.1)	(-6.6,24.9), (6.6, 4.9)	(-3.7,14.3), (3.7,14.3)
	c	(12.0,19.1)	(-5.1,35.1), (5.4, 5.7)	(-3.7,17.1), (3.7,11.5)

* Coordinates are referred to the origin which located at the center of the tower and at ground level.

First, the study evaluates the need for compensation. Secondly, the effectiveness of mitigation based on target zone is assessed. The work deals with four scenarios of mitigation target zones relative to the right of way limit (ROW): (1) "T1": is PRF when the target point is located at ROW, (2) "T2": is ERF, when the target zone is over a distance extended from 80% ROW to 120% ROW, (3) "T3": is ERF when the target zone is over a distance extended from 40% ROW to 120% ROW, and (4) "T4": ERF, when the target zone is over a distance extended from 40% ROW to 160% ROW. In view of the large numbers of combinations, the following code is devised to indicate the line voltage, loop configuration, target area, and whether it is compensated or not.



4 Results of Passive Shielding Optimization

First, an optimal setup is sought, to which economic optimization is applied as shown in the following section.

Table II Compensation and Reduction Factors for 500 kV Line Based on Target area T2

CASE	Loop Coordinates (m)	CF	RF %
5002CT2uncomp	(-6.8, 18.9), (26.7, 13.6)	0	59.8
5002CT2comp	(-1.3, 24.0), (19.2, 18.16)	0.81	89.7
5003CT2uncomp	(-7.9, 16.0), (-5.1, 19.8) &(26.3, 13.9)	0, 0 & 0	64.3
5003CT2comp	(21.3, 17.6), (-3.9, 22.4) &(17.0, 18.0)	0.23, 0.24 & 0.26	91.8
5004CT2uncomp	(-16.7,17.1), (21.8,14.8) & (5.0, 18.0), (26.8, 14.3)	0 & 0	72.8
5004CT2comp	(15.5, 15.4), (-4.4, 16.5) &(20.2, 17.3), (-1.2, 14.1)	0.8 & 0.75	92.2

4.1 Appling Capacitive Compensation

The effect of series capacitive compensation is studied by applying GA with and without compensation in all cases. Because of a large number of cases, Table II selects a number of them to display loop coordinates, optimal compensation factors (CF), and reduction factor (RF %) for three loop configurations in the case of a 500 kV line with target area T2. The table shows that using capacitive compensation has significant effects on magnetic field mitigation. Compensation appears to be most effective in the case of two conductor configuration.

4.2 Zone-Based Optimization

The reduction factors for the four target areas are calculated in order to assess the effectiveness of mitigation based on the target zone. Fig. 2 displays magnetic field distribution before and after mitigation for the selected cases. As shown in the figure, when traditional PRF is adopted at ROW edge, mitigation effectiveness is worst. The field has a minimum distribution when optimization targets T3 and T4. The target area T3 is chosen to be the most suitable mode to further apply optimization of passive shielding mitigation. This approach has been repeated for all configurations and also for other lines. With transmission lines 500kV, 220kV, and 66kV, the overall field reduction is substantial when the optimization targets the distance extending from 40% ROW to 120% ROW. Figure 3 depicts the optimum position of shield conductors used in double circuit 220 kV line for all configurations and with the T3 target area.

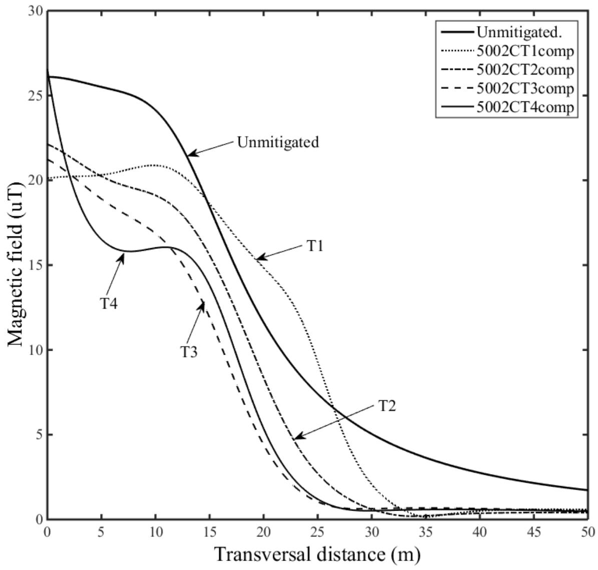


Fig. 2 Magnetic field distribution for single circuit 500kV line for cases of 2C.

5 Economic Considerations

The optimization procedure discussed in the previous sections aims solely at finding optimal coordinates of the shield conductors and the best value of capacitors used for compensation. Full optimization is only attained when one additional aspect is considered, namely, the cost factor. The costs associated with the implementation of passive shielding may fall into CSC, CPL, CSS, and COC. An attempt is made in this work to estimate them. It is noted that it is difficult to find an exact relation between the cost of the model and reduction in magnetic field, but there are approximate ways to find this relation.

5.1 Cost of Shield Conductors and Their Installation

CSC is the most pronounced of all costs, it is mainly proportional to the amount of aluminum and steel for ACSR conductors which are preferred for their high dependability, low economy, and high strength-to-weight ratio. The conductor size influences its electrical resistance (R) and geometric mean radius (GMR); thus it has a great effect on the induced current and in turn on mitigation effectiveness.

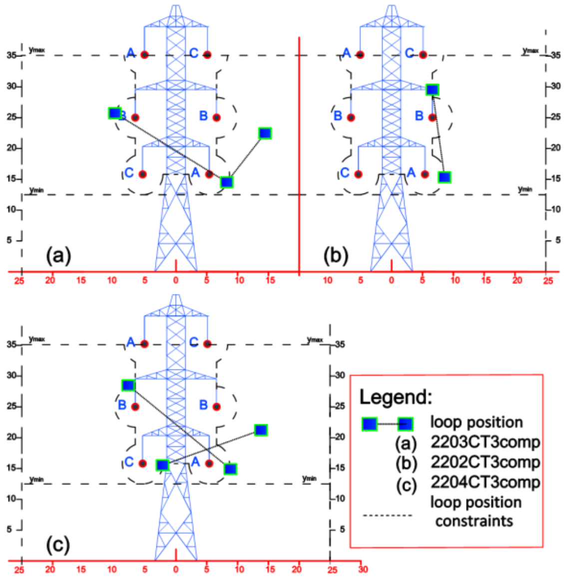


Fig. 3 Location of loops conductors for a) 2203CT3comp, b) 2202CT3comp, and c) 2204CT3comp

The relation between conductor size and its cost is not linear as noticed in the collected data from a number of different ACSR conductor's data [21]. Therefore, the data are used to generate approximate relations between CSC, electrical resistance, and the associated GMR. Meanwhile, the installation cost of shield conductors is nearly proportional to the size of conductors and their length. Most companies, which are specialists in this area usually take the installation cost as a factor based on conductor type and size. This cost factor is about 20% of CSC [22].

Table III Variations in Shield Current, RF and CSC with Different Sizes of Conductors

CSC %	R (Ω/km)	GMR (mm)	Shield current		RF (%)
			%	A	
100%	0.0514	12.65	58.40	584	73.34
80%	0.0648	11.7443	54.93	549	67.71
60%	0.0865	10.2979	49.36	494	57.77
40%	0.1298	8.1164	39.90	399	42.12

The case of "5002CT3comp" is chosen to explore the relationship between CSC and the effectiveness of mitigation. In view of the results from GA, loop conductors are replaced by other conductors which have different costs. Table III lists the results obtained when other conductors are considered with costs 40%, 60%, 80%, and 100% of the highest conductor cost used in the collected data. The table displays the corresponding resistance and GMR of the conductors, induced current percentage relative to rated line currents, and the resulting RF (see Fig. 4).

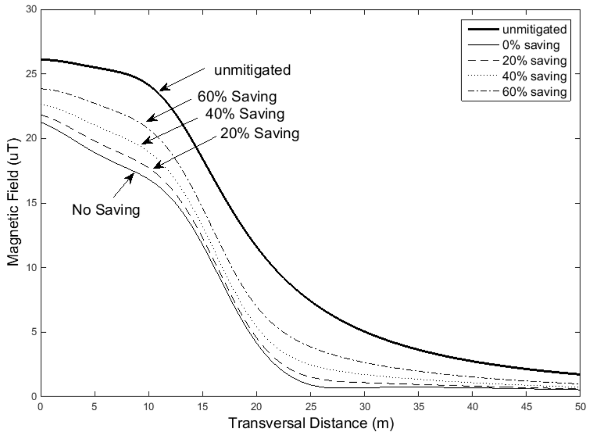


Fig. 4 Mitigated and unmitigated MF distribution for single circuit 500kV line, mitigation is performed by various sizes of conductors.

5.2 Cost of Power Losses

CPL of shield conductors is considered to be equal to the loss in funds due to the reduction in electric energy sold. CPL may be calculated by

$$CPL = \int \alpha P_{loss}(t)dt \tag{5}$$

, where α is the electricity tariff of one kWh. The value of α depends on voltage level as shown in Table IV.

Power losses in shield conductors are not constant over the year due to loading variation in the main phases. The average power loss in shield conductors is calculated using loss factor. Therefore, CPL may be calculated by

$$CPL = KP_{ave} \tag{6}$$

K is the cost of one kW of average losses in the shield conductors over the year.

Table IV Average Electricity Tariff And Loss Factors For Different Voltage Levels, 2015-2016, Egypt

Voltage level (kV)	α ($/kWh)	"Loss factor"	K ($/year/kW)
500	0.027	0.553	186.8
220	0.027	0.32 per circuit	109.8
66	0.036	0.32 per circuit	201.8

5.3 Cost of Supporting Structures and Their Installation

Poles or posts are installed to support the loop conductors. The work is based on steel poles as long poles are required to provide the conductor clearances with the ground. The cost of poles mainly depends on the amount of material used. Most companies and suppliers which are specialists in steel designs, evaluate their products as a cost per unit of mass. All poles mass calculations are based on Egyptian Code of Practice for Steel Construction and Bridges, which in line with most international codes [23].

Every member in a steel construction must be checked for stability and slenderness ratios. The first constraint in designing a cantilever is the slenderness ratio to find the minimum diameter of a tubular section based on unsupported height. The second constraint for design is the ratio between the tubular diameter and minimum thickness. Installation cost depends on the height of poles and their numbers. It is usually in approximate range of 15-30% of the cost of support structures [22]. Therefore, CSS can be evaluated by

$$CSS = K * H^3 \tag{7}$$

, where, the factor K depends on the type of steel (yield stress, density), and H is the height of the pole. Appendix details how to obtain this equation.

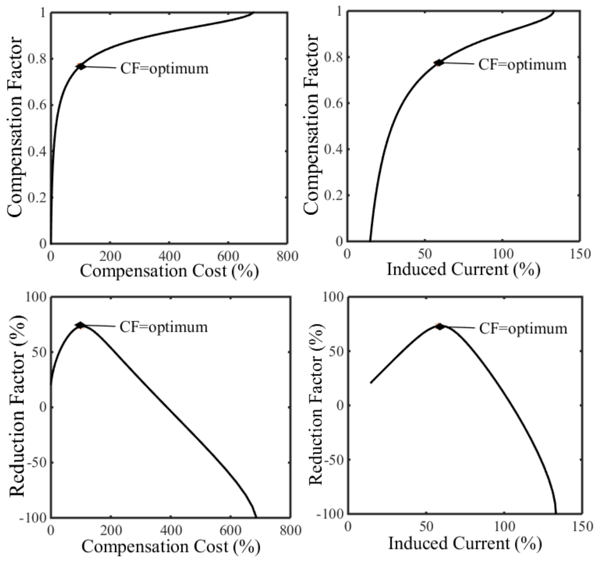


Fig. 4 (a) Relation between CF and COC, (b) Impact of CF on shield current, (c) Impact of shield current on RF, (d) Relation of COC with RF.

5.4 Cost of Compensation

Shield loops are compensated using capacitors with a fixed value according to the optimum compensation factors resulted from the optimization procedure. Cost of Compensation (COC), in this work, is based on a number of capacitors connected together to construct a capacitor bank. In reality, COC does not exceed 5% of the total implementation cost, which justifies the simple assumptions shown below.

The bank consists of a number of sets (n) connected in series, each set consists of a number of capacitor units (m) connected in parallel to withstand the shield current. Equation (8) is used to evaluate COC, where C_{unit} is the cost of capacitor unit.

$$COC = nmC_{unit} \tag{8}$$

The case "5002CT3comp" is chosen to illustrate the relation between COC and the effectiveness of the mitigation. With the same previous results obtained through GA, and without changing in conductor size or its coordinate, CF is varied from zero to one. Compensation factor's impact on associated COC is plotted in Fig. 4a, where COC is relative to the cost at optimum CF (0.77). The relation of shield current to CF is displayed in Fig. 4b. The plotted shield current is relative to the rated current in phase conductors. Fig. 4c shows the effect of the induced current on the RF. Thus the impact of CF on COC is displayed in Fig. 4d. Changing the CF has not only affected the induced current amplitude but also it changes the current phase angle, which in turn changes the phase angle of the magnetic field produced by loops. RF increases from 34% (at CF=0) towards its maximum value of 73.3% (at CF= 0.77) and then it decreases at high CF till it reaches -106% (At CF=1). This means that high compensation factors have a high amplitude of induced current and less favorable angle for magnetic field mitigation.

5.5 Cost of Mitigation by Passive Shielding

Economic evaluation is done by using "the minimum revenue-requirements method" [24]. The cost is calculated by the equivalent capitalized cost formula. In this formula, all the operating and maintenance costs are translated into equivalent investment costs. The equivalent capitalized cost (ECC) is calculated in [25] without optimization.

$$ECC = CSC + CSS + COC + \frac{CPL}{r} \tag{9}$$

, where r is annual fixed charge rate.

6 Cost-based Optimization

Optimization may now be based on the relevance of magnetic field mitigation within a targeted area. Cost optimization will minimize the cost while seeking an "acceptable" reduction in magnetic field, as demonstrated by the following results.

The objective is to increase the mitigation performance (RF) and reduce the total cost. In the objective function, the reduction factor is weighed by w_1 and the reduction in total cost by w_2. The approach, which considers the relative importance of mitigation, is expressed by (10). Note in (10) that RF (%) and ECC (%) have the same units.

$$\text{Maximize} \quad F_1 = \frac{w_1 RF + w_2(1 - ECC)}{w_1 + w_2} \tag{10}$$

, where the fitness function F1 is made up of two components, one relates to the targeted reduction factor and the other relates to the reduction in total cost (ECC). To find the relation between the RF and optimal total cost, GA is applied with varying values of weight factors (w_1 , w_2). For each weight, there is an optimal solution at which the field is mitigated by a certain RF with the minimal applicable cost.

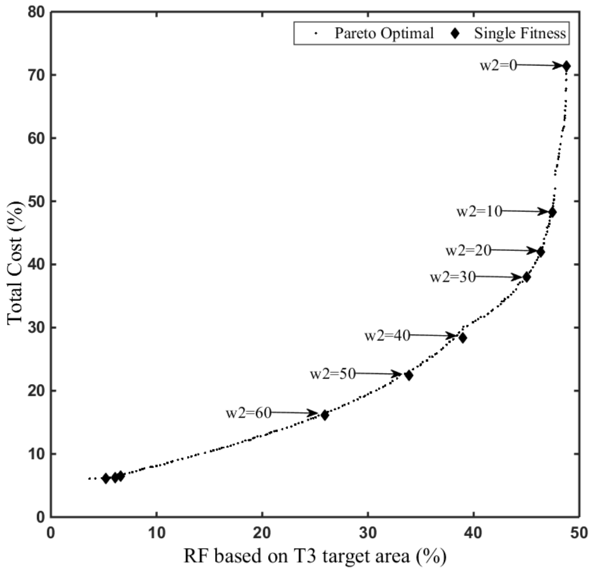


Fig. 5 Pareto optimal and a number of cases with different weight factors for 2Cconfiguration for 220kV line.

Multi-objective optimization uses an array of objective functions and because of this fact, there is more than one solution. MATLAB's global optimization toolbox provides the function "gamultiobj" to optimize (10) based on GA, where the solution is then characterized by Pareto optimality. Recommendations for parameter settings is that "ParetoFraction" = 0.7, "UseParallel" = true, "MigrationInterval"=10 and "PopulationSize" = 500. For more details please go to [20].

$$\text{Maximize} \quad F_2 = [RF, 1 - ECC] \tag{11}$$

The algorithm is driven to select the value of shield conductor's GMR and CSC, while setting R_{min} and R_{max} to be the minimum and maximum resistances, respectively. In this work, the range of selection is based on the data collected to find relations between CSC, R, and GMR.

$$R_{\min} \leq R \leq R_{\max} \quad (12)$$

6.1 Case study

Cost-based optimization is applied to optimize passive shielding by finding the location of each conductor, compensation factor of each loop, and the optimum resistance which reflects the conductor size. Multi-objective optimization is applied to each line for all configurations with target T3 and series compensation. Different weight factors are selected to verify the accuracy of the RF-Cost relationship obtained from Pareto and to detect the effect of relative weights on each cost element. Selected weight w_2 values are 0, 10, 20… and 90%.

Table V Variations in RF, CSC, CPL, COC, And Total Cost with Different w2 for 220 kV Line (all costs referred to the costs of 2203CT3comp)

W2 %	ERF %	CSC	CPL	CSS	COC	Total cost %
		%				
0	48.77	66.67	58.44	87.40	31.39	71.44
10	47.43	42.56	102.69	33.89	33.21	48.32
20	46.35	41.66	70.20	33.46	27.17	41.92
30	45.00	39.05	56.87	32.09	23.67	37.97
40	38.94	54.05	24.34	11.44	18.23	28.36
50	33.91	41.10	18.00	11.00	13.66	22.45

6.2 Results of Cost-based Optimization

As an example, the mitigation on 220 kV line is considered. The optimum relation between RF and ECC of 2C configuration is displayed in Fig.5. The figure shows the Pareto optimal and single fitness of the ten points. In the figure, optimal points of single fitness are located on the Pareto optimality. Discontinuities are caused by nonlinear constraints used in optimization. The case of 220 kV line, using 3C configuration and cost weight of 0%, has maximum cost $113,070. All costs of 220 kV line are referred to the costs of this case.

Table V shows the effect of weight factors on RF and also on the cost of each element. Fig. 5 indicates that applying cost optimization on passive shielding is very important even if RF is much desired, that is noted in the first two points in the table, RF has a slight decrease (1.34%) unlike total cost, which decreases by 23.12%. This observation is noted also in other configurations.

Fig. 6 combines the three RF-cost relations of 220 kV line for the three configurations. It is noted that 4C configuration is favored for RF to be more than 86.96%. Between RF of 23.13% and 86.96% 3C configuration is preferred. The 2C configuration seems not to be suitable for mitigating magnetic fields in 220 kV power lines.

Studying the cases of 500 kV and 66 kV lines followed the same sequence as discussed above with 220 kV. In 500 kV lines it is noted that 4C configuration is favored for RF to be more than 60%. For RF less than 60% the 2C configuration shows the best characteristic. In 66 kV lines, 2C configuration has the lowest cost for RF less than 69.07%, while the 3C configuration shows the best characteristic for RF in the range of 69.07% up to 90.5%. The 4C configuration is to be used for RF in the range of 90.5% up to 92.28%.

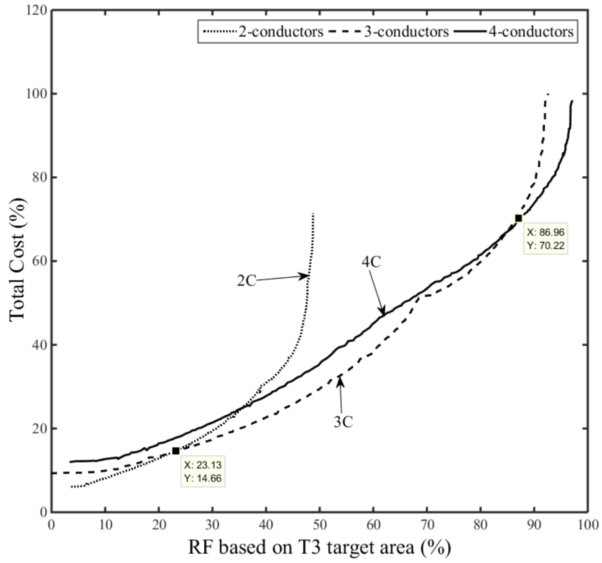


Fig. 6 Optimal relation between the RF and total cost of passive shielding for the three configurations for 220kV line.

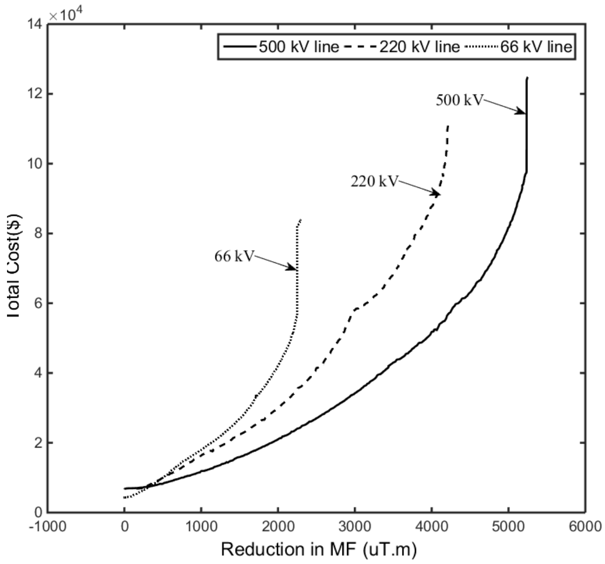


Fig. 7 Relation between reduction in MF (μT.m) and optimum cost ($) of passive shielding to mitigate MF produced from 500kV, 220kV and 66kV

7 Feasibility Index

The best RF-Cost relation of each line is the envelope created by its respective three configurations. These envelopes are plotted in Fig. 7 after adjusting the bases of coordinates to conduct a fair comparison among the mitigation performances by: 1) the costs may now be expressed in absolute money rather than being referred to the maximum cost of each individual line, 2) the MF exposure is expressed in µT.m rather than in relative values. The parameter δ (µT.m) is the total reduction in MF over a distance extended from the tower to infinity and it is calculated by

$$\delta = \int_0^\infty [|\overrightarrow{B_s}| - |\overrightarrow{B_p}|]dx \quad (\mu T.m) \qquad (13)$$

Accordingly, Fig. 7 shows the mitigation performance of each line. Each point on the curves represents the optimal total cost to mitigate magnetic field with a certain value of RF. The passive shielding appears to have the lowest cost for 500 kV line, indicating that passive shielding has the highest "feasibility" if used with that line.

This work defines the feasibility index (FI), which assesses the effectiveness of magnetic field mitigation, as **the integrated reduction in the magnetic field relative to total cost over all possible shielding configurations**. This index can be numerically expressed as

$$FI = \frac{1}{\delta_f - \delta_0} \int_{\delta_0}^{\delta_f} \frac{\delta}{Cost(\delta)} d\delta \quad (\mu T.m/\$1000) \qquad (14)$$

The 500 kV line has the highest FI of 7.79 µT.m/$1000, followed by the 220 kV line with an FI of 5.68 µT.m/$1000, and finally, the 66kV line has the lowest FI of 4.83 µT.m/$1000.

8 Conclusions

Although the Egyptian power lines have been selected as a case study, the work provides a generic (general) procedure to optimize passive shielding throughout all possible mitigation scenarios for any transmission line. The procedure is practical, realistic and accounts for economic considerations.

Zone-based mitigation ensures an improvement over the traditional point-based mitigation. With transmission lines 500kV, 220kV, and 66kV, the overall field reduction is significant when optimization is applied over a distance extending from 40% to 120% ROW. To further improve the mitigation performance, capacitive compensation is used.

Cost modeling of passive shielding is considered, which accounts for four cost components, namely, cost of shield conductors, cost of power losses, cost of support structures, and cost of capacitive compensation.

Comparing the results of different configurations yielded the following:

1) The 3-conductor, 2-conductor, and 4-conductor configurations are not preferred to mitigate magnetic fields produced from 500 kV, 220 kV, and 66 kV lines, respectively. The recommendations to select the optimal configuration is discussed in section 6.2.
2) An optimal RF-Cost relation for each line is developed as the envelope of that relation for the three conductor configurations. With the same procedure, the optimal RF-Cost relation can easily obtained.

A "Feasibility index" (FI), which assesses the relative effectiveness of magnetic field mitigation is defined. It is seen that –in the case studies of this work not a general note- the 500 kV line has the highest field mitigation feasibility.

Appendix

The minimum diameter of the pole may be calculated by

$$\lambda = \frac{K.L}{r}$$

Where, λ is slenderness ratio, maximum value is 180 for compression members. K is the bucking length factor, equal to 2 for cantilever members. L is pole height (unsupported length) in meter. R is the radius of gyration, If tubular section is used then r=0.35D, where D is the outer diameter (m)

The ratio between maximum width and thickness is limited by

$$\frac{D}{T} \leq \frac{165}{F_y}$$

, where: T is the thickness of material used to form the pole and F_y is nominal value of Yield stress equal to 2.4 t/cm^2 for thickness less than 40mm with St 37 "grade of steel".

From the previous equations we can deduce

$D \geq k_1 * H$ & $T \geq k_2 * D$

Cross section area (A) $= \frac{\pi}{4}(D^2 - (D - 2T)^2) \geq k_3 * D^2$

amount of material $= \rho * A * H$, But D depends on H, then $= k_4 * H^3$

But the pole cost depends on material amount and the installation cost is considered to be psroportional to the poles mass. Then (7) can be obtained.

References:

[1] European Commission, Council recommendation of 12 July 1999 on the limitation of exposure of the general public to electromagnetic fields (0 Hz to 300 GHz). *The Council of the European Union*, 1999.

[2] Rianne Stam, Comparison of International Policies on Electromagnetic Fields (Power Frequency and Radiofrequency Fields), *Laboratory for Radiation Research, National Institute for Public Health and the Environment, the Netherlands,* May 2011.

[3] California EMF Program, An Evaluation of the possible risks from electric and magnetic fields (EMFs) from power lines, internal wiring, Electrical occupations, and Applications, *California EMF Risk Evaluation*, Jun. 2002.

[4] European Commission, Report on the implementation of the Council Recommendation on the limitation of exposure of the general public to electromagnetic fields (0 Hz to 300 GHz) (1999/519/EC) in the EU Member States, *Commission staff working paper*, 2008.

[5] CIGRE Working Group C4.204. Mitigation techniques of power frequency magnetic fields originated from electric power systems, *CIGRE*, February 2009.

[6] H. M. Ismail, Effect of Tower Displacement of Parallel Transmission Lines on the Magnetic Field Distribution, in *IEEE Transactions on Power Delivery*, Oct. 2008, vol. 23, no. 4, pp. 1705-1712.

[7] H. A. Kalhor and M. R. Zanoubi, Mitigation of Power Frequency Fields by Proper Choice of Line Configuration and Shielding, *Electromagnetics*, Feb. 2007, vol. 25, no. 3, pp. 231-243.

[8] Juan Carlos, P. Cruz-Romero, L. S. Iribarnegaray, and J. M. Román, Magnetic field shielding optimization in underground power cable duct banks, *Electric Power Systems Research*, 2014, vol. 114, pp. 21-27

[9] Víctor J. Hernández Jiménez, Edgardo D. Castronuovo, Ismael Sánchez Rodríguez-Morcillo, Optimal statistical calculation of underground cable bundles positions for time-varying currents, *In International Journal of Electrical Power & Energy Systems*, 2018, Vol 95, pp. 26-35.

[10] R. G. Olsen and P. Moreno, "Some observations about shielding extremely low-frequency magnetic fields by finite width shields, in *IEEE Transactions on Electromagnetic Compatibility*, Aug 1996, vol. 38, no. 3, pp. 460-468.

[11] Alexandru M, Fartinescu CG, Popescu CL, Popescu MO., Shielding of magnetic field produced by energized cables. *In Advanced Topics in Electrical Engineering (ATEE), 2017 10th International Symposium, IEEE*, pp. 378-381.

[12] Ayman Aboud, Hussein Anis , Mitigation of Power Lines-Produced Magnetic Fields by Optimized Active Shielding", *Environmental Science and Technology, American Science Press, Houston*, Texas, USA, Jun. 2012, vol. 2, pp. 178-184,.

[13] S. Barsali, R. Giglioli, D. Poli, Active shielding of overhead line magnetic field: Design and applications", *Electric Power Systems Research*, 2014, vol. 110, pp 55-63.

[14] Del Pino Lopez, Juan Carlos, Luca Giaccone, Aldo Canova, and Pedro Cruz Romero., Ga-based active loop optimization for magnetic field mitigation of MV/LV substations, *IEEE Latin America Transactions, 2014, Vol* 12, no. 6, pp. 1055-1061.

[15] Bignucolo, F.; Coppo, M.; Savio, A.; Turri, R. Use of Rod Compactors for High Voltage Overhead Power Lines Magnetic Field Mitigation, *Energies* 2017, Vol 10, No 9, 1381.

[16] P. Cruz, C. Izquierdo and M. Burgos, Optimum passive shields for mitigation of power lines magnetic field, in *IEEE Transactions on Power Delivery*, Oct. 2003, vol. 18, no. 4, pp. 1357-1362.

[17] P. C. Romero, J. R. Santos, J. C. del Pino Lopez, A. Jaen de la V. , and J. L. M. Ramos, A comparative analysis of passive loop-based magnetic field mitigation of overhead lines, *IEEE Transactions on Power Delivery*, Jul. 2007, vol. 22, no. 3, pp. 1773-1781.

[18] J. C. López, and P. C. Romero, The Effectiveness of Compensated Passive Loops for Mitigating Underground Power Cable Magnetic Fields, *IEEE Transaction on Power Delivery*, Apr. 2011, vol. 26, no. 2, pp. 674-683.

[19] Ayman Aboud and Hussein Anis, Zone-Specific Magnetic Field Mitigation Using Evolutionary Computation," *International Journal of Innovation in electrical power systems (IJIEPS)*, Jan. 2012, Vol. 4, No. 1, PP. 1-15.

[20] MATLAB Help, MATLB R2015b, Math Works Inc., 2015. Online, 2017, https://nl.mathworks.com/help/gads/genetic-algorithm-options.html?s_tid=srchtitle

[21] General Cable Company, *Utility Cable Products List Price Adjustement*, July 2014.

[22] Juho Yli-Hannuksela, Olavi Maknin, *The Transmission Line Cost Calculation*, University of Applied Science, Finland, 2011.

[23] Housing and Building National Research Center, *Egyptian Code of Practice for Steel Construction and bridges*, Ministry of Housing, Utilities and Urban Development, 1st ed., Ministerial Decree No. 279.

[24] Harry G. Stoll, *Economic evaluation in Least-Cost Electric Utility Planning*, 1st ed., J Wiley & Sons, New York.

[25] R. A. Walling, J. J. Paserba, and C. W. Burns Series-capacitor compensated shield scheme for enhanced mitigation of transmission line magnetic fields, *IEEE Transactions Power Delivery*, Jun. 1993, vol. 8, no. 1, pp. 461–469.