DESIGN AND VALIDATION OF POWER-FREQUENCY MAGNETIC FIELD CONDUCTIVE SHIELDING FOR UNDERGROUND CABLES

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INTRODUCTION

In this paper a systematic cost-effective procedure is presented to assist in the optimal 2D design of conductive shielding for underground high voltage power cables. A 2D shape optimization algorithm based on gradient methods is used. It was found, surprisingly, that the optimal shielding shape, for a given weighted combination of magnetic energy and dissipated energy in the shielding material can result in a complex structure, presenting high shielding efficiency. A process of experimental validation at reduced scale was applied and a practical approximation was verified.

BACKGROUND

In latest years, in addition to issues related to environmental impact, a major problem for the installation of new power lines near populated areas seems to be the concern about magnetic fields. The reason behind this concern is twofold, namely, the interference caused on electronic equipment based on electron beams and the suspected biological effects based on a series of epidemiological studies [1]. A proposed solution is to bury the cables; however, this alone just aggravates the problem as the cables will be closer to the surface. The real advantage of the operation is that we can fasten a shielding configuration inside the ground. Distances between cables can be minimized allowing shielding techniques by metallic plates [2], [3]. These techniques are not feasible for power lines.

To solve a shielding problem for underground cables a two dimensional numerical approach is used. This presupposes that to obtain the solution we have some initial knowledge of the shape. Intuitively one often assumes that for a horizontal cable configuration, a flat, rectangular shape (or a wedge shape if the configuration is triangular) located somewhere between the cable system and the affected area. However, with this approach obtaining shielding factors $(B_0/B_{\text{shielded}})$ of more than an order of magnitude is very rare. The procedure presented here based on optimization, allowing arbitrary shape, arbitrary thickness and arbitrary length of the plate (in 2D) with fixed total volume can yield values of shielding factors of two orders of magnitude.

Optimization methods [4] have been used in various areas in power technology and recently in shielding design [5]. These methods can be classified as deterministic, which are gradient based (e.g. finite difference, continuum gradient), or stochastic (e.g. genetic algorithms, particle swarm optimization, simulated annealing). Also combinations of two approaches are possible (e.g. gradient + genetic algorithm). In this work we have used continuum gradient based shape optimization, although its formulation can be complicated, it is very efficient.

CONTINUUM GRADIENT BASED SHAPE OPTIMIZATION

Given a system of three-phase underground power cables as shown in Fig. 1, we optimize the shape of the conducting plate, in order to minimize the magnetic field in the region of interest $\Omega_m$, which is usually just above the ground in the vicinity of the cables.

Fig.1 Geometry for shape optimization design of a shielding structure for a 3-phase system of underground cables.

We assume that the initial shape of the conductor is rectangular $\Omega_c$. During the shape optimization, the total material (area) of the conductor is fixed. As for the objective function for minimization, we choose the sum of the magnetic energy in the region of interest and the dissipated energy in the conductor, with corresponding weighting factors $w_m$ and $w_c$. The conductivity of the shield is $\sigma$ and the vector potential is $A_z$.

$$E = \frac{w_m}{2\mu_0} \int_{\Omega_m} \left| \nabla \times (A_z \hat{z}) \right|^2 d\Omega_m + \frac{w_c}{2} \int_{\Omega_c} |A_z|^2 d\Omega_c, \quad (1)$$
The region of interest has the following dimension: \( \Omega_m \{10\text{mx2m}\} \); the initial shape of the conducting plate is \( \Omega_c \{0.5\text{mx0.077m}\} \), and the distance between the centre of the three phase arrangement and the lower boundary of the region of interest is 0.6m.

As the first attempt, the shapes of the upper and lower boundaries of the conductor are specified by two Fourier series, with the Fourier coefficients as the design parameters. For optimization, we compute the gradient of the objective function with respect to the design parameters. The gradient is computed by combining the solutions of the forward and the adjoint eddy current problems. Thus two function evaluations are required for constructing each gradient, independent of the number of the design parameters. This is the major advantage of such a method over other gradient methods where the gradient is evaluated by finite differencing.

The forward eddy current problem is solved using finite element formulation

\[
-\nabla \cdot \left( \frac{1}{\mu} \nabla A_z \right) + j\omega\sigma A_z = j_z, \quad (2)
\]

The solution of the forward problem, in terms of the magnetic vector potential, is used to construct the source term for the adjoint problem. Both the adjoint and the forward problems have the same linear operator.

\[
L(A^e, \Phi) = \frac{1}{\mu_0} \int_{\Omega_m} \nabla A^e_z \cdot \nabla \Phi_i / \Omega_m + \int_{\Omega_c} A^e_z \cdot \Phi_i / \Omega. \quad (3)
\]

The first variation of the objective function, with respect to the shape of the conductor, is constructed from the solution of both, the forward and the adjoint problems,

\[
\delta E = \int_{\Gamma} \mathbb{R} \left[ \frac{1}{\mu_0} \nabla A_z \cdot \nabla A^e_z - \frac{1}{\mu_c} \nabla A_z \cdot \nabla A^e_z - j\omega\sigma A_z A^e_z \right] + \int_{\Gamma_c} \frac{\omega\sigma}{2} |A_z|^{-1} d\xi d\Gamma, \quad (4)
\]

where \( \Gamma \) represents the boundary of the conductor, and \( \xi \) is the displacement of the boundary. The continuum gradient computed from (4) is verified by comparing with the finite difference gradient. For optimization, we use the MATLAB routine 'FMINCON' which pursues constrained optimization based on sequential quadratic programming method.

### CHOICE OF WEIGHTING FACTORS AND OPTIMAL SHAPES

We performed optimization with different sets of weighting factors in the objective function. The optimal shape of the conductor (aluminium) depends on these weighting factors.

As an example, we show results for \( w_m = 1 \) and \( w_c = 0.01 \). Fig. 2 shows the decreasing of total energy (the value of the objective function) during the process of optimization. A hypothetical value for the currents \( (10^6\text{A}\text{[rms]/phase]} \) was assumed, with the understanding that the field scales linearly with the amplitude of the source current. A more realistic value \((100 \text{A})\) will be considered in the next section. Note that along the x-axis we plot the number of function evaluations. The total energy for the optimal shape is about 50 times smaller than that for the initial rectangular shape.

**Fig. 2** The decrease of total energy in the process of optimization.

The optimal shape of the conductive shield is shown in Fig. 3; the color map indicates the amplitude of the eddy current density induced in the conductor. Such current distribution achieves the best shielding effect.

**Fig. 3** The optimal shape of the conducting shield, together with the induced eddy current distribution in it.

Another example is given for: \( w_m = 1 \) and \( w_c = 0.0001 \). In this case a more complex shape arises as shown in Fig. 4. The large variation in thickness of this structure is remarkable.

### CONTINUOUS THICKNESS APPROXIMATION

The shape in Fig. 4 is extremely difficult to implement. However a practical design is possible to obtain if we make an approximation of it. We have considered as a
characterizing value, the thickness in the neighborhood of the zone with higher eddy currents.

Coincidentally, it has a similar value to the skin depth for aluminum ($\delta \approx 1.16$ cm at 50 Hz), and we extended this thickness along the shielding structure. We also assumed a polygonal shape as this is possible to obtain by bending an aluminum plate. The approximation is justified since we are interested in measuring the field relatively far from the sources.

As we can observe, the distribution of currents in Figs 4 and 5 are very similar; therefore we can use a shield of polygonal shape to validate the model.

**SMALL SCALE EXPERIMENTS AND VALIDATION**

It is always desirable to validate by experiment a model obtained by numerical computation. However, in the case of underground cables this seems to be costly and cumbersome procedure. To ease this operation we have developed a small-scale model based on a scaling principle, which states that if the geometrical dimensions of the underground line and the shield are reduced by a scaling factor $k<1$, the magnetic field in the scaled interest area is scaled by the same factor provided the source current amplitude is reduced by a factor $k^2$ and the frequency of the system is increased by a factor $(1/k)^2$. Based on this principle, small-scale 3D low-cost experiments can be performed in the lab.

A scaled model six times smaller was built, which implies that the model must operate at a frequency of $50 \times (6)^2 = 1.8$ kHz. A source of such frequency was used consisting of a signal generator and an amplifier. However we can only obtain a current of 0.6 A which produces a very small density of magnetic flux that is difficult to measure with our instruments. Consequently we must make two more considerations, firstly, many turns will be added to the coils such that relatively high fields can be generated (Fig. 6), and secondly, the three sources RST (at 1.8 kHz) will be replaced with only one source (generator, phase shifter and amplifier).

Three approximations were considered with various degrees of simplification (Fig 7).

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**Fig. 4** Optimal shielding shape for the case with $w_m = 1$ and $w_c = 0.0001$.

**Fig. 5** Continuous-thickness approximation for the shielding shape of Fig. 4.

**Fig. 6** Replacement of a three-phase system by two dipoles (a); and finally by only one source (b).

**Fig. 7** Various practical approximations for the optimal shape of Fig 4.
The Shape (c) was implemented and experimentally tested at small scale. A frequency of 1.8 kHz was used which was obtained by a wave generator and an amplifier (Fig.8).

**Fig. 8** Experimental implementation of shape (c) scaled six times.

The thickness along the shape was constant (2mm) and the rms field values (in microtesla) were taken by a 3-coil flux density meter (ML-1 from Enviromentor AB).

**Table 1. Shielding behavior of shape (c)**

<table>
<thead>
<tr>
<th>Y(m) Vertical distance</th>
<th>Prediction of S.F from the Exp. model(**)</th>
<th>S.F (*) (Numerical) Trapezoidal</th>
<th>S.F (Numerical) Optimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.32</td>
<td>23.38</td>
<td>26.17</td>
<td>25.67</td>
</tr>
<tr>
<td>0.44</td>
<td>26.75</td>
<td>36.32</td>
<td>13.58</td>
</tr>
<tr>
<td>0.56</td>
<td>25.00</td>
<td>37.43</td>
<td>31.06</td>
</tr>
<tr>
<td>0.68</td>
<td>21.20</td>
<td>36.10</td>
<td>92.89</td>
</tr>
<tr>
<td>0.80</td>
<td>19.75</td>
<td>34.78</td>
<td>110.96</td>
</tr>
<tr>
<td>0.92</td>
<td>21.00</td>
<td>34.40</td>
<td>127.73</td>
</tr>
</tbody>
</table>

(* ) S.F means Shielding Factor, which is defined as:
S.F = B₀ [no shield] / B [with shield].

(**) The prediction was made using the Scaling Rulers.
The green-colored numbers mean that they belong to the region of interest.

**CONCLUSIONS**

The procedure presented here shows that, given a system of underground cables, it is possible to obtain relatively high field mitigation in a region of interest by obtaining a mathematical solution to an optimization problem. First assuming arbitrary thickness of a conductive shield, and then, from the results, building an approximation of a homogeneous thickness. Even though some resulting shapes can be very difficult to implement, simplified structures are not; and they can still provide cost-effective field mitigation.

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**REFERENCES**


