Mitigation of Magnetic Flux Density of Underground Power Cable and its Conductor Temperature Based on FEM

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ABSTRACT: This article proposes using a metallic plate to be installed above the underground power cable route to mitigate the maximum cable conductor temperature and the ground surface magnetic flux density surrounding the cable route and underground cable derating factor. The article presents a case study containing a single-circuit 145 kV, three-phase individual cables in flat formation. The impacts of the mitigation plate dimensions such as plate width, thickness, the distance between the underground cables and the plate used in the mitigation, and the plate material are investigated. Three kinds of materials are examined in this article, namely aluminum, steel 100, and steel 500. Moreover, the optimal design dimensions of the metallic plate for the case under study were estimated. It is concluded that the shielding factors of the magnetic flux density and cable core temperature with aluminum are greater than steel 100 and steel 500. In addition, the derating factor, which is the ratio of the current capacity of the underground cable with shielding plate and that without shielding plate at the same cable core temperature, is increased to be 1.28 with the use of shielding Aluminum plate, rather than 1.18 and 1.17 in case of using Steel 500 and Steel 100 shielding plates, respectively. Finally, the proposed algorithm was validated by comparing its results with the experimental measurements obtained by the others, indicating good agreements.

INDEX TERMS: Underground Cables, De-rating Factor, Magnetic flux density, Magnetic shielding factor, Mitigating shielding factor of temperature, Shielding plate

I. INTRODUCTION

Due to the increase in electrical energy demand within urban centers, high voltage underground power cable systems are becoming more used. However, with the continuous rise in the number and relevance of underground cables, there is a higher exposure to the magnetic fields produced by such cables currents, leading to more cases of human electrosensitivity.

Moreover, the exposure to the magnetic field produced by the magnetic flux of underground power cables may increase the many diseases risk for the values of the magnetic field intensity higher than certain threshold levels, capable of inducing harmful currents in the human tissues [1-4].

On the other hand, the increase in cable loadings leads to an increase in the magnetic field, which increases the temperature of the cable components, especially the insulation, causing the cable system failure.

In standards [5, 6], the limits of exposition to magnetic flux are recommended to be between 100 μT and 3 μT. Hence, the design and development of magnetic flux density mitigation procedures significantly necessitate keeping its value under the recommended levels. Many magnetic field shielding techniques have been proposed and optimized, such as the use of metallic plates, raceways, and horizontal and U-reverse magnetic shields [5-9]. Many studies are done on the magnetic field calculations produced by underground power cables (UGCs). Some are based on analytical methods and others on numerical and experimental methods [10-12]. In reference [12], a computational model for determining the magnetic field produced by a practical in-service underground pipe-type cable was formulated. A contribution to evaluating the electromagnetic fields due to (UGCs) is presented in reference [13]. In [14], the FEM is used for predicting magnetic field generated by insulated cable, the currents and losses in the shields.

In reference [15-22], a description of some technical
solutions adopted nowadays to reduce extremely low frequency (ELF) magnetic fields generated by power cables are presented. Then some cases study on power cables is considered. In [8], mitigation of the magnetic field shielding of (UGCs) using hybrid finite-element method is adopted. A comparison between different constitutive materials for magnetic shielding was presented. It was concluded that aluminum shielding is more efficient. In [10], experimental measurements investigate the efficiency of different underground magnetic shielding techniques. Measures are also done for temperature rise around the cable conductors. The experiments were performed on a test site where a real 138 kV underground cable section was built. In [11], the magnetic field mitigation techniques for underground power systems using conductive or ferromagnetic shielding plates were introduced. The power losses due to the conducting set formed by the shielding plate/earth return path and the contribution to the series impedance were considered two new aspects. Results for the magnetic field reduction factor at the soil surface were obtained for different shielding materials, different shielding thickness values, and different frequency values. The installation of such shielding metallic plates near the underground cables affects the thermal performance of the cables. Therefore, a suitable design of the shielding plate should be thermally and magnetically investigated to ensure the correct behavior of its magnetic and temperature mitigation and avoid capacity derating [12].

In this article, to mitigate both the maximum core temperature and the ground surface magnetic flux density, a metallic mitigation plate above the underground cables in the earth is chosen as a proper position. Optimal design dimensions of the mitigation plate, such as the width, the thickness, and the distance between the underground cables and the mitigation plate, are obtained for the case under study. Also, the effects of the dimensions of this mitigation plate are directly buried in the soil, as shown in Fig. 1. Fig. 1 shows the configuration and the meshes of three-phase individual cables in flat formation. In this situation, the finite element method is used to simulate the case under study and investigate the impacts of mitigation plate dimensions on the magnetic flux density, temperature shielding factors, and underground cable derating factors.

In the proposed electro-thermal coupling method, the following procedure is proposed:

(i) The magnetic potential \( M \) is used as a dependent variable to solve the Maxwell–Ampere law [23]:

\[
\nabla \times \mathbf{H} = J \tag{1}
\]

\[
\mathbf{B} = \nabla \times \mathbf{M} \tag{2}
\]

\[
\mathbf{J} = \sigma \mathbf{E} + j \omega \mathbf{D} + \mathbf{J}_e \tag{3}
\]

\[
\mathbf{E} = -j \omega \mathbf{M} \tag{4}
\]

where, \( H \) is the magnetic field strength, (A/m); \( J \) is the vector of the current density, (A/m³); \( B \) is magnetic flux density, (T); \( M \) is the magnetic potential, (Vs/m); \( \sigma \) is conductivity, (S/m); \( E \) is the electric field strength, (V/m); and \( J_e \) is the current density, (A/m³).

(ii) Then, the following heat transfer equations can be applied:

\[
\nabla \cdot q + \rho C_p \frac{\partial T}{\partial t} = Q \tag{5}
\]

\[
q = -\sigma_{th} \nabla T \tag{6}
\]

where, \( \rho \) is the material density, (kg/m³); \( C_p \) is the heat capacity, (J/kg.k); \( q \) is the heat flux density, (W/m³); \( \sigma_{th} \) is the thermal conductivity, (W/m.k); and \( Q \) is the heat dissipated by the cable losses, (W/m).

(iii) Finally, the following electromagnetic heating equation is applied to describe the relationship between the heat generated by the cable losses from one side and the electric field and cable current density from the other side

\[
Q = J.E \tag{7}
\]

The proposed model is divided into two areas; the upper is the air, and the lower is the soil. Both the cable and the metallic sheathing plate are directly buried in the soil, as shown in Fig. 1. Fig. 1 shows the configuration and the meshes of three-phase individual cables in flat formation.

For improving the computation competence of the proposed model, the conductivity of the cable core conductor and its metallic sheath variations with temperature change are considered using the following IEC equation [24]:

\[
\sigma = \frac{1}{\rho_{20}(1+\alpha_{20}(T-20))} \tag{8}
\]

where, \( \rho_{20} \) is the resistivity at temperature 20 °C in (Ω.m) of the conductor or the metallic sheath material of the cable; \( \alpha_{20} \) is the resistance temperature coefficient, (1/°C) and \( T \) is conductor or sheath temperature.
The current carried by the underground cable is considered at balance condition with an angle difference of 120° between each three-phase current and the others. The heat transfer boundary conditions are set at a constant temperature of 35 °C.

To investigate the impacts of design dimensions of the mitigating plate, a mitigating shielding factor \(SF_B\) is considered, which is defined as the ratio between the maximum value of the magnetic flux density without the use of the mitigation shielding plate \(\left( B_{o,\text{max}} \right)\) and its value with the use of the mitigation shielding plate \(\left( B_{M,\text{max}} \right)\) [10, 25]:

\[
SF_B = \frac{B_{o,\text{max}}}{B_{M,\text{max}}}
\]  

Similarly, a mitigating shielding factor of temperature can be defined as given in equation (10).

\[
SF_T = \frac{T_{o,\text{max}}}{T_{M,\text{max}}}
\]

Where \(T_{o,\text{max}}\) is the conductor temperature without the use of the mitigation shielding plate and \(T_{M,\text{max}}\) is its temperature with the use of the mitigation shielding plate. The derating factor [26] is used to estimate the effects of using the mitigating plate. The derating factor in this study means the ratio of the current capacity of the underground cable with the shielding plate and that without the shielding plate at the same core temperature.

### III. CASE UNDER STUDY

The case under study is a typical 145 kV high voltage three-phase underground cable of three individual cables in a flat configuration. Fig. 2 and Table I summarize the construction details of one phase of 145 kV, three-phase cable.

### TABLE I

| Cables Details          | 145 kV |
|------------------------|--------|
| Current rating (A)     | 1114   |
| Maximum allowable temperature | 90 °C  |
| Conductor Material     | Copper (single-core) |
| Conductor Diameter (mm)| 58     |
| conductor shield thickness (mm)| 0.3   |
| Insulation Type and thickness | LPOF, 18 mm |
| insulation screen (mm) | 0.3    |
| Insulation Diameter (mm)| 594.6 |
| Screen Type            | Aluminium |
| Cover Type             | Polystyrene |
| sheath thickness (mm)  | 9.4    |
| Overall Cable Diameter (mm)| 126    |
| Cable interspacing (m) | 0.5    |
| Soil thermal conductivity (W/m. °C) | 1 |
| laying depth (m)       | 1.8    |

Three different materials of the metallic shielding plate are investigated. These materials are aluminum, steel 100 and steel 500. The magnetic relative permeability and conductivity of these materials are given in Table II.

### TABLE II

| Metallic shielding plate material | Conductivity (σ) (Sm⁻¹) | Permeability (µ) |
|-----------------------------------|--------------------------|------------------|
| Aluminium                         | 3.5×10⁷                   | 1                |
| Ferromagnetic Steel 100           | 10²                      | 100              |
| Ferromagnetic Steel 500           | 10²                      | 500              |
IV. RESULTS AND DISCUSSION

The simulation using the suggested electromagnetic-thermal technique of underground power cables provides an effective tool to recognize the impact of mitigation plates on the power cables’ magnetic flux density and their cores temperatures.

A. Without mitigation plate

Fig. 3(a) shows the contour of the normal magnetic flux density, $B$ ($\mu$T) and Fig. 3(b) illustrates the temperature distribution in ($^\circ$C) within and around the underground cable under study. The cable is loaded by 1114 A and its surrounding soil conductivity is 1 (W/m.$^\circ$C).

As shown in Fig. 3, an increase of flux density around the cable leads to a temperature increase of the cable core and the soil surrounding it. It can be shown clearly in Fig. 4, presenting the normal magnetic flux density along a distance around the center cable at various heights above the ground surface. It is noticed that the values of the normal magnetic flux density and the temperature decrease with increasing height above the ground surface. Also, the normal magnetic flux density values are more significant than the target value (3 $\mu$T), which is required to be achieved to protect against possible long-term effects associated with exposure in residential areas [7].

![Fig. 3 Contours of (a) normal magnetic flux density and (b) the cable temperature without mitigation plate](image)

B. Impacts of shielding strip dimensions on UGC Magnetic Flux Density and its Core Temperature

i) Thickness of the mitigation plate impact

The impact of the mitigation plate shield thickness on the magnetic flux density shielding factor and temperature shielding factor is illustrated in Figs. 5 (a) and (b). Cable phases are installed in a flat arrangement, as shown in Fig. 1(a), and the shield is installed on the top surface of the cable duct. It is noticed that an increase of the magnetic plate thickness increases the shielding factor of both normal magnetic flux density and maximum temperature in all used materials of the mitigation plate. Still, the best mitigation results are obtained when the aluminum plate is used.

Regarding the temperature shielding factor given in Fig. 5(b), it is easy to observe that it is enormously increased until the thickness of 0.013 mm. Then, the thickness of the Ferromagnetic shields steel 500 shields has higher values of temperature shielding factor. Furthermore, the temperature...
shielding factor of the Ferromagnetic shields steel100 is higher than its value for aluminum at 0.02 mm thickness. Finally, from Figs 5 (a) and (b), it is concluded that the optimal thickness is 0.029 mm regardless the mitigation plate material. This finding is in agreement with the results obtained by [26].

**ii) Width of shielding strip impact**

Fig. 6(a) shows the variation of normal magnetic flux density shielding factor $SF_B$ with the increase in the magnetic plate width. From this figure, the $SF_B$ is improved with the width increase, achieving a maximum at 4 m in aluminum shields. In comparison, it is improved to lower values and satisfies its maximum value at 3 m and stays constant in Ferromagnetic shields steel 100 and 500 shields. This behavior is exceptionally related to other parameters, such as the distance between the cable and the plate, cable current, and the cable phases arrangement.

Fig. 6(b) gives the variation of the temperature shielding factor with the increase in the magnetic plate width. As it is observed from this figure $SF_T$ increases rapidly with the aluminum plate width increase. The rate of $SF_T$ increases with the plate width increase for Ferromagnetic shields steel 500 and100 is lower than aluminum plate, while $SF_T$ of both steel 500 and100 are very close. These calculations are done when the shield is resting on the top surface of the cable duct. Again, this characteristic depends on other parameters, such as the distance between the cable and the plate, cable current and the cable phases arrangement.

**iii) Distance between cables and shielding strip impact**

The calculations are done to obtain $SF_B$ values with the space variation between cables and plate proved that, as given in Fig. 7 (a), its maximum value is obtained when the shield is resting on the top surface of the cable duct. The influence of plates completely disappears at 1.7 m separation. Thus, aluminum shields proved their efficiency, whatever the space between the cable phases and plate.

Fig. 7(b) illustrates the variation of temperature shielding factor with the increase in the space variation between cables and plate. As given in Fig 7(a), its maximum value is obtained when the shield is resting on the top surface of the cable duct. The influence of plates completely disappears at 1.7 m separation.
factor with the increase in the distance between cables and shielding strip. It is noticed that increasing the distance between cables and shielding strip decreases the shielding factor of maximum temperature. Figs 7 (a) and (b) conclude that the optimal distance between cables and shielding strip is 0.1 m regardless of the mitigation plate material. This finding is in agreement with the results reported by [27]. Therefore, one aspect that can help to make decisions in the plate's design is the temperature rise of the shield.

![Graph showing magnetic flux density and temperature shielding factors](image)

Fig. 7 Effect of distance between cables and shielding strip on (a) the normal magnetic flux density shielding factor $SF_B$, (b) shielding strip on the temperature shielding factor $SF_T$.

**C. Magnetic flux density, and temperature within and around the underground cables with optimal dimension of different mitigation plate materials**

In this article the conductive aluminum and Ferromagnetic Steel 100 and 500 are analyzed as shielding plates. This work investigated the impacts of the different shielding materials on the cable core temperature and its surrounding flux density, delving deeper into the influential factors such as the plate width, its thickness, and the space between the shielding plate and the cable route.

Figs. 8, 9 and 10 show the contour of the normal magnetic flux density, $B$ (µT) and temperature, $T$ (°C) within and around the underground cables with Aluminum, Ferromagnetic steel 100 and Ferromagnetic steel 500 mitigation plates with the use of optimal dimensions of different mitigation plate materials. From these Figs it is noticed that aluminum has the best performance as shielding plates. As it is observed in Figs 8 (b), 9 (b) and 10 (b) the temperature of the cable and its surrounding soil has lower value in aluminum shielding if it is compared in shielding by Steel 100 and Steel 500.

![Contour plots](image)

Fig. 8 Contour of (a) normal magnetic Flux density ($B$) and (b) Temperature in case of optimum dimensions of shielding strip of Aluminum mitigation plate.
Similar observations were noticed in the case of magnetic flux density as given in Figs 8 (a), 9 (a), and 10 (a). Again, these results strongly indicate that aluminum is the best material to work as shielding around underground power cables.

**D. Comparison of shielding strip materials with the use of optimal dimensions of different mitigation plate materials**

Fig. 11 shows the distribution of normal magnetic flux density and temperature at the ground surface with various kinds of optimal dimensions of shielding strip material. It is noticed that the Aluminum material gives more mitigation than the two other materials. Furthermore, it is observed that aluminum shielding plates are almost the best choice, even when using higher spaces between the shielding plates and cables. It is also noticed that due to eddy losses of steel 100 and steel 500, the overheating of the area surrounding the cable route and cable conductor may happen. However, this conclusion may be influenced by other parameters [28].

![Fig. 9 Contour of (a) normal magnetic flux density (B) and (b) Temperature in case of optimum dimensions of shielding strip of Ferromagnetic Steel 100 mitigation plate](image)

![Fig. 10 Contour of (a) normal magnetic flux density (B) and (b) Temperature in case of optimum dimensions of shielding strip of Ferromagnetic Steel 500 mitigation plate](image)

![Fig. 11 Impact of using optimal dimensions of different mitigation plate materials on (a) Normal magnetic flux density distributions shielding plate at the ground surface, (b) Temperature at the ground surface](image)
Fig. 12 gives the distribution of normal magnetic flux density and temperature at various heights above the ground surface with various kinds of optimal dimensions of shielding strip materials. Again, it is noticed that the Aluminum material gives more mitigation than the two other materials.

**Table III**

| Type          | \( T_{\text{max}} \) of air °C | \( T_{\text{max}} \) of cable °C | \( B_{\text{max}} \) of air µT | \( B_{\text{max}} \) of cable µT |
|---------------|---------------------------------|-----------------------------------|--------------------------------|---------------------------------|
| Without       | 37.934                          | 90                               | 31.147                         | 7678.3                          |
| Aluminum      | 36.819                          | 68.293                           | 0.3815                         | 7814.7                          |
| Steel 100     | 37.283                          | 74.51                            | 0.55367                        | 39100                           |
| Steel 500     | 37.266                          | 78.835                           | 0.58509                        | 46747                           |

Table III summarizes the impacts of different shielding materials on the cable conductor temperature, air above the earth surface of the cable route, cable flux density and air flux density above the earth surface of the cable route when the optimal design dimensions are used.

**E. De-rating factors**

Once a shielding plate is installed on the cable route, where the cable is placed in a specific configuration, more cable current capacity can be obtained due to the decrease in cable core temperature as given in table III. In this table, it is observed that the core temperature is reduced from 90 °C without the use of shielding plate to 68.293 °C when Aluminum plate is used, 74.51 with the use of Steel 100 plate, and 78.835 °C in case of using Steel 500 plate. Therefore, it leads to better utilization of cable core area, and consequently, the economics of cable installations increase. So it is of interest to define and calculate the derating factor (DF) when different materials are used as shielding plates.

\[
DF_{\text{of shielding plate}} = \frac{\text{Cable current without the use of shielding plate}}{\text{Cable current with the use of shielding plate}} \tag{11}
\]

Table IV gives the cable under study de-rating factor when different shielding materials are used. As it is noticed the
shielding by aluminum increases the cable capacity by 28%, while Ferromagnetic Steel 100 improves the capacity of the cable by 17% and Steel 500 increases the cable capacity by 18% respectively.

### TABLE IV
**DE-RATING FACTOR WITH THE USE OF SHIELDING PLATES**

| Shielding material | Without | Aluminium shielding | Steel 100 shielding | Steel 500 shielding |
|--------------------|---------|---------------------|---------------------|---------------------|
| Load current       | 1114 A  | 1422 A              | 1303.5 A            | 1314.5 A            |
| DF                 | 1       | 1.28                | 1.17                | 1.18                |

### E. Validation

Two shielding models presented in [10], namely, reference line "RL" and open shielding "H" were simulated by the use of the proposed method to validate the proposed algorithm presented in this work. The aim is to compare the experimental measurements with the simulation results. The details of the two models are given in [10]. The underground cable system is composed of three individual 138 kV cables of a typical arrangement. The simulated loading current is 830 A and 630 A, respectively. The soil thermal resistivity is taken as 1 k/m.W.

### TABLE V
**COMPARISON BETWEEN EXPERIMENTAL AND SIMULATION RESULTS**

| Loading current | 630A | 830A |
|-----------------|------|------|
| $T_{core}$ °C and $S_{FB}$ | $T_{core}$ (RL) | $T_{core}$ (H) | $S_{FB}$ (RL) | $T_{core}$ (H) | $S_{FB}$ |
| Experimental [10] | 33.04 | 35.2 | 3.75 | 40.8 | 40 | 3.62 |
| Simulation | 31.08 | 35.46 | 3.56 | 37.73 | 45.34 | 3.56 |

The comparison between the experimental results given in reference [10] and the simulation results for the core temperature, $T_{core}$, and magnetic field Shielding Factor, $S_{FB}$, for both reference line, RL, and open shielding layer, H, at 630A and 830A are tabulated in Table V. It is clear that there is a good agreement between both the experimental and the simulation results.

On the other hand, the comparison between of the magnetic flux density in experimental measurements done by [10] and simulated results when the cable is loaded by (a) 840 A and (b) 630 A.

![Fig. 13 The magnetic flux density of experimental measurements done by (a) 840 A and (b) 630 A](image)

### IV. CONCLUSIONS

The proposed article algorithm, which based on the finite element method, shows that the shielding factor of the magnetic flux density increases with the increase of the thickness and width of the mitigation plate. On the other hand, it decreases as the distance between the underground cables and the mitigation plate increases. For the case under study, with the mitigation plate's optimal dimensions, the magnetic flux density shielding factor and the temperature shielding factor reach 0.8 and 0.9, respectively. Also, the derating factor, which is defined in this study as the ratio of the current capacity of the underground cable with shielding plate and that without shielding plate at the same core temperature, is increased to be 1.28 with the use of shielding Aluminum plate, 1.18 and 1.17 in case of using Steel 500 and Steel 100 shielding plates, respectively. By comparing the materials of the shielding plate, it is clear that the shielding factor of the magnetic flux density with aluminum is greater than that of both steel 100 and steel 500. Also, the shielding factor of the temperature with aluminum is greater than that of both steel 100 and steel 500. The algorithm is validated by comparing its results with the experimental measurements obtained by the others and proved good agreements.

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