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PASSIVE LOOPS TECHNIQUE FOR ELECTROMAGNETIC FIELDS MITIGATION: APPLICATIONS AND THEORETICAL CONSIDERATIONS.

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ABSTRACT

The paper illustrates the innovative technique of passive loops, used for electromagnetic field shielding of HV and EHV cable lines and adopted to overcome the concern arising whenever an existing or planned underground cable line crosses densely populated areas, where restrictions of the electromagnetic field (EMF) are requested. This method is an alternative to the use of copper plates, but it is as if they have now been made flexible and with a variable thickness. A careful cost-benefit analysis shows that passive loops are a simple and effective solution that can be tuned to achieve the required Shielding Factor (SF), exploiting the technology of low voltage commercial cables.

KEYWORDS

EMF, passive loops, electromagnetic fields, shielding factor, HV cables, EHV cables.

INTRODUCTION

The method, generally used to slightly reduce the electromagnetic field, is to adjust the laying parameters such as interaxial distance between the phases, laying depth and geometry. If a greater reduction of the EMF is requested, a common solution can be the adoption of special shielding apparatus external to the cables such as ferromagnetic raceways, metallic plates and grids of insulated conductors. The installation and the thermal problems linked to the losses are also presented, with a careful analysis in order to properly balance the shielding efficiency to achieve the required field mitigation with negligible impact on the rating.

A new technique ids presented in this paper which uses simple loops of standard LV power cables to mitigate the magnetic field for both cables, joint bays and manholes.
The Shielding Factor (SF) of a given mitigation technique is defined here as the ratio between the magnetic field modulus before and after the adoption of the mitigation measure at 1 metre above ground on the axis of the circuit.

THEORETICAL CONSIDERATIONS

The passive loop is an innovative technique with SF that can reach the value of ten with standard practice. The passive loops are easily placed in the trench together with HV cables, with negligible impact on the installation operations of the main cable circuit: standard practice is to limit the over temperature to a few tenths of a degree centigrade, with a careful choice of the section and of the position of the loops. The first application of passive cables technique has been in Vienna in 2005 to reduce the EMF of the joint chambers of a 5.2 km long 400 kV double circuit [1].

As it is known, the electromagnetic field is directly proportional to the circulating current and to the cable interaxial separation but decreases rapidly with distance.
A general criterion is that symmetric dispositions of the main cables results in a symmetrical arrangement of the passive loops, so that only an even number of cable is presented here. The phase sequence of a single three phase circuit has no influence on the modulus of the resulting magnetic field, but becomes fundamental with two or more circuits laid in parallel.

A careful choice is necessary to select the section and the position of the passive cables: the calculation is not simple and needs dedicated software, which has been developed and tested by the authors. Passive loops can be easily tested in the laboratory: the position of cables can be varied and the total number increased by simply adding more cables. One of the most important aspects is to minimize the resistance and the reactance of the passive system. Low voltage cables are normally installed, due to the very low tension induced into the cables. They are arranged in the trench of the HV cables, either on the surface of the compacted backfill, at the same level or even below the HV cables.

Shielding of cables in flat formation is easier because optimum disposition of passive cables can be in flat formation; for a trefoil arrangement, the passive cables should have a triangular structure. The solutions depend also on the dimensions of the trench and on the acceptable over temperature: high voltage, high current systems are more difficult to shield and require larger passive conductors.
The study considers the optimum disposition of the passive loops around the power cables or the joints, where the position of the passive cables can be, a priori, continuously varied. In order to limit the otherwise enormous number of cases, the investigated area is here limited to the accessible volume of the trench and the distance between adjacent cables is varied in steps of 50 mm or 100 mm, respectively for small and large trench widths. A test on the validity of this simplifying assumption has been done on the joint bay in configuration “E”, shielded with 8 passive copper cables of 240 mm^2.The differences in the computed SF are less than 1% and justify the assumption of the step variation of the position of the cables.
The experience demonstrates that the dispositions of the shielding cables presented here have the property to be “optimum solutions” in a mathematical sense: when one or more cables are slightly displaced from the position of best shielding, there is only a minimal decrease of the SF. Due to this property, the passive cables can be installed with standard care and do not require particular technologies.
The following table 1 reports the main layout schemes for HV and EHV cable trenches and joint bays: the nominal current is 870 A for 150 kV and 1500 A for 380 kV. The ground thermal resistivity is assumed to be 1 K*m/W and the unperturbed

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ambient temperature is 20°C.

Configuration	cables interaxis (mm)	laying depth (mm)	trench width (mm)
A) 150 kV trefoil	100	1400	600
B) 150 kV flat formation	100	1400	700
C) 380 kV trefoil	140	1500	700
D) 380 kV flat formation	300	1500	1100
E) 150 kV joint bay	450	1800	2000
F) 380 kV joint bay	700	1900	2000

Table 1: Relevant parameters for the analysed cases

150 KV CABLES AND JOINT BAY

For a 150 kV plant designed for Italy, the design is to install the cable in trefoil condition with configuration "A" with the joint bay in configuration "E".

In order to mitigate the magnetic field, four passive copper cables 0.6/1kV 1x240 mm^2 are installed in the trench as described in figure 1. The EMF is mitigated below 3 µT for any point at 1 meter above ground.

For the joints, a solution with 8 cables, regularly spaced in flat configuration on top of the backfill, shields the EMF below 3 µT for distances greater than 3 meters from the axis of the joint bay. This value of 3 µT is particularly important in Italy, since it is fixed as quality goal by a recent decree of the Prime Minister [2].

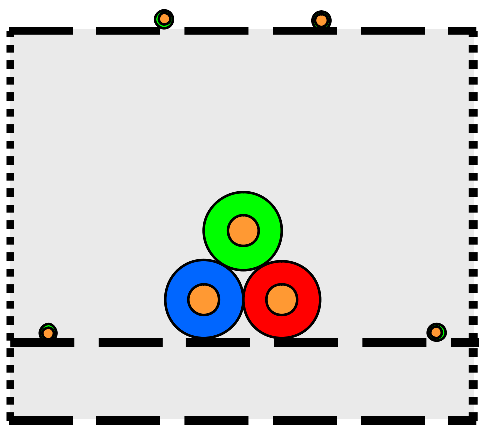

Figure 1: Optimized passive cable arrangement

The maximum overheating is only 0.5 K on the hottest cable, similar values are found for the joints, corresponding to a derating of less than 3 A, that can be considered negligible. These solutions reduce the required clearances between the cable installation corridor and residential properties.

The installation of passive loops is quite easy and cheap when the cables are arranged on a horizontal layer of backfill, normally compacted during the standard laying technique. In figure 1 the dashed lines show the three levels of the trench: on the bottom, at laying depth and on the top of the compacted backfill. The dotted lines represent the positions where the cables can be arranged, before backfilling the trench, with the help of simple supports. In this paper, the union of dashed and dotted lines is named "the perimeter".

In the joint bay the bottom of the trench is quite attractive because of the greater distance from the joint axis: passive cables can conveniently be placed there. The remaining section of the trench has been investigated and gives slightly better solutions, but results in more heating due to the proximity to the power cables.

380 KV JOINT BAY

The simplest way to allocate a single layer of cables is on the top of the compacted backfill: optimum solutions are found installing the cables regularly spaced, starting from the extremities of the trench and gradually adding further cables towards the centre. The cables are arranged in a single layer 400 mm above the joint axis. In the case of two cables, they are at the extremities of the trench; further cables are arranged progressively closer to the trench axis.

Figure 2 is a graphical representation of the optimized disposition of the cables in one layer, up to 16 cables: obviously only one layer is applied at a time.

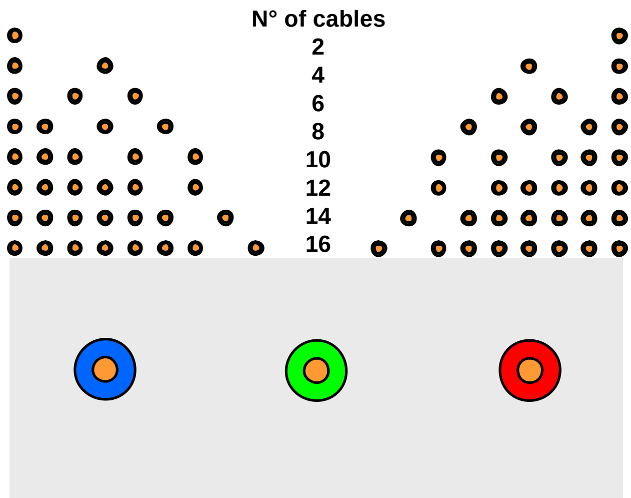

Figure 2 : Optimized disposition of up to 16 cables placed on the top of the backfill of a 380 kV joint bay

Figure 3 reports the SF, as a function of the number of cables, obtained using 240 mm^2 Cu cables with a resistance of 8.13 µ? /m, considering the cables at a mean temperature of 40°C, and with a conductor diameter of 20 mm. Sharing the cables in two layers, below and above the joints, is a good way to increase the SF from 3 to 5, preventing a saturation effect. In figure 3, the lower layer includes 2 cables when the total number is up to 10, and 4 cables for more then 10 cables.

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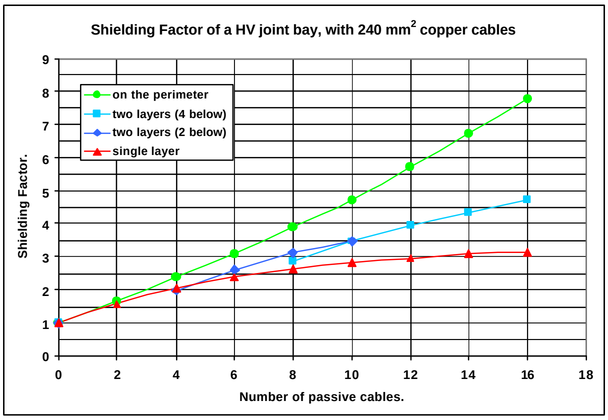

Figure 3: Shielding factors for a 380 kV joint bay

The SF reported in figure 3 are the best values that can be obtained assuming a maximum over temperature of 5 K on the central joint, corresponding to a derating of 3.6%, if the joints are at their maximum allowed temperature.

A very effective shielding solution is to rearrange the cables on the perimeter of the joint bay: figure 4 shows an optimised disposition of the 16 cables.

An even more effective solution has been obtained with 800 mm^2 aluminium cables, again with the 16 cables arranged on the perimeter, as described in figure 4. In this case the SF reaches the significant value of 13, with only 3 K of increment in the central joint temperature. This solution avoids surrounding the joint bay with a large and expensive metallic box.

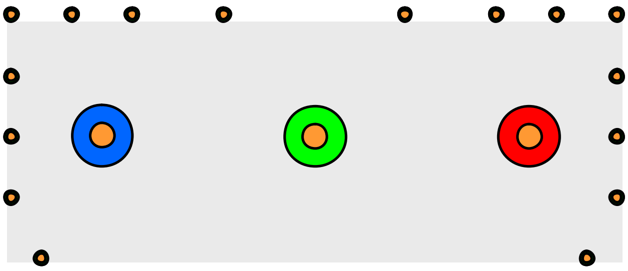

Figure 4 : Optimized disposition of 16 cables on the perimeter of a 380 kV joint bay.

On the hypothesis of putting the 16 passive cables freely around the power cables, the optimum solutions appear like two arcs on both sides of the outer joints, quite resembling the disposition of figure 4, with most of the cables being regularly spaced and with the outer ones a bit further separated. The SF of each solution mainly depends on how close the cables are to the joints; in this case the thermal influence can reach quite high values but the effect on rating can be reduced to a few Amps using sufficiently large sections. As can be seen from the examples, as a general rule, the passive cables are not placed in the central part of the trench.

Specially developed hollow core aluminium cables, with low impedance, installed along the perimeter of the trench of a 380 kV joint-bay have given a SF some 20% higher than the compacted round conductor of the same DC resistance.

An interesting application is to a 380 kV circuit with cables in trefoil formation (configuration “C”), so that the joint-bay (configuration “F”) can be shielded to the same level of EMF. From figure 3, with 12 copper cables with a section of 240 mm^2, placed on the perimeter of the joint bay, the EMF of all the circuit is mitigated to the same value of 9.1 µT that is emitted by the cables in trefoil formation, assuming installed dimensions according to table 1. The peak value of the EMF of the joint bay without any shielding is 47.3 µT.

400 KV SYSTEM MITIGATED IN VIENNA

For a 400 kV plant in Vienna, completed during 2005, the magnetic field is mitigated below 15 µT at soil level at a rating of 1500 A, as prescribed by the local authority. Two different solutions are applied, for cables and manholes.

For the cables, an intrinsically mitigated solution is used adopting a particular “open trefoil” configuration with an interaxial distance of 270 mm at a laying depth of 2.7 m.

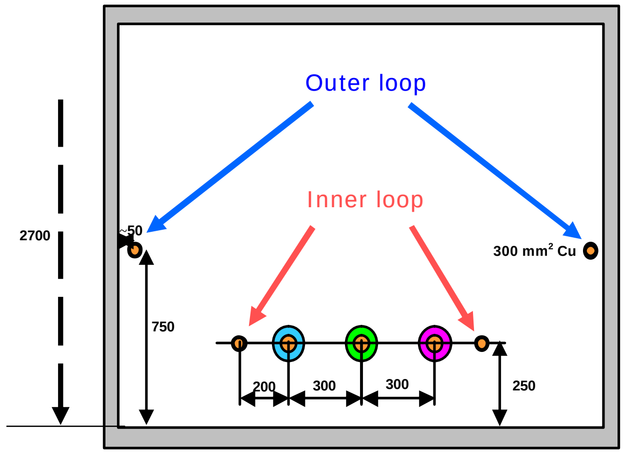

Figure 5: Disposition of the two loops in the manhole

In the manholes, the three joints are arranged in flat configuration with an interaxial distance of 300 mm, at a height of 250 mm from the floor of the chamber (figure 5). In these conditions an electromagnetic field of more than 22 µT is expected at soil level, too high for the requested level of 15 µT, with a required SF of almost two.

The goal is to reduce the electromagnetic field, with the easiest solution and without interfering with the existing project of the civil works. A safety margin was introduced, to consider schematic modeling and installation uncertainties: number of loops, conductor cross section and geometrical arrangement in the joint chamber are key parameters.

For the manholes, where the joints necessarily have a larger separation, two loops of copper cables have been installed, next to the outer joints and on the walls of the chamber, practically halving the EMF at soil level.

The design has been tested at Prysmian Laboratories, for a planar configuration, with the two loops at the same level as the joints (figure 6).

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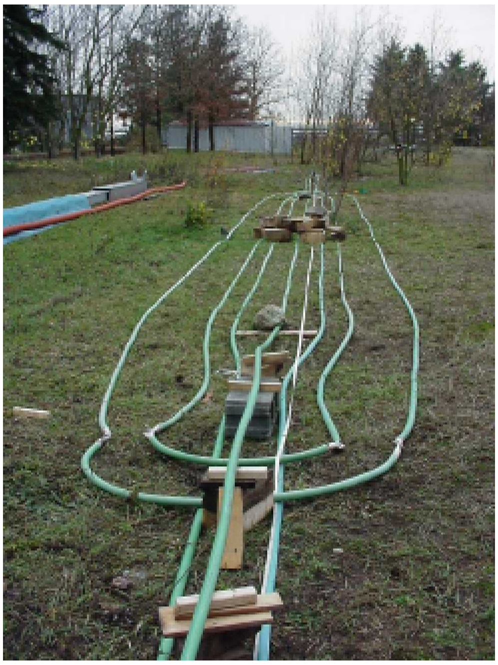

Figure 6: Test of the SF of the passive loops

The optimized solution consists of the two loops of passive cables installed, symmetrically around the joints, but at slightly different levels (figure 7).

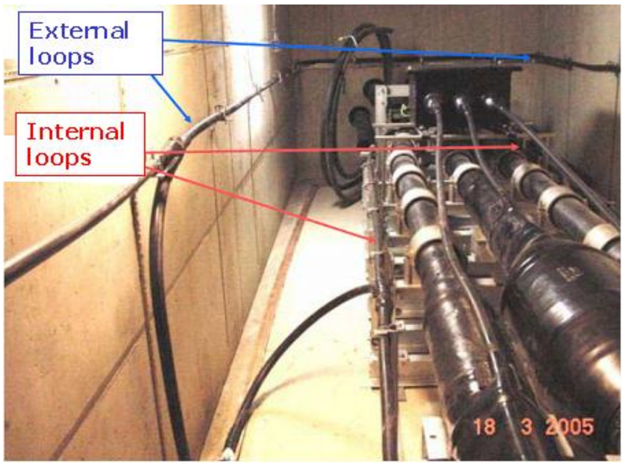

Figure 7: Passive loops installed in the joint chamber

The inner loop is installed beside the external phase of the three 400 kV cables, at the same elevation, with a constant distance of 200 mm.
At the extremities of the manhole, where the cables converge to a triangular arrangement, the loop is closed: the geometry is the same on both sides of the chamber. To realize the inner loop, about 25 m of 0.6/1kV 1x300 mm^2 copper cable has been used, for a joint chamber length of 12 m.

The outer loop is fixed on the walls of the chamber, with a spacer to maintain a separation of 50 mm for air circulation at a constant elevation of 750 mm from the floor. The main purpose of the inner loop is to reduce the modulus of the electromagnetic field, while the outer loop gives a smoother shape. The conductor section of 300 mm^2 is the best solution to achieve the shielding efficiency required with two loops.

Power losses are negligible and do not influence the rating because the cables are installed in air inside the cooled joint chamber. Both the outer and inner loop are grounded: the connections are protected by heat shrinking sheaths.

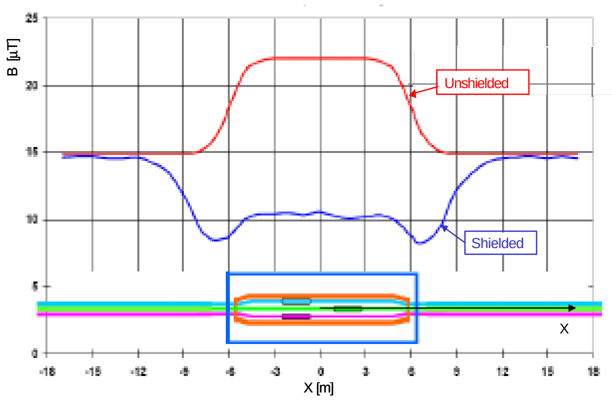

Figure 8: Modulus of the measured magnetic field along the axis of the circuit, across the joint chamber

The measured results are displayed in figure 8, where the field is reported for a nominal current of 1500 A. The peak value of the field along the joint chamber is below 11 µT, with a SF of about two. In the inner loop a current of 337 A was measured, while in the outer it was 86 A. For practical purposes the same cable is installed for both loops, despite the different currents.

345 KV MITIGATED JOINT BAY

For a 345 kV circuit at 60 Hz, designed for the U.S., the requested limit for the EMF is 20 µT, measured at 1 meter above ground, with a current of 1368 A. The limit is exceeded at the joint bay where the interaxial distance has already been reduced to 750 mm and the joints are installed at a depth of 2000 mm. The resulting EMF is about 43 µT, requiring a corresponding required SF of more than two.

The designed solution, reported schematically in figure 9, is to install a layer of four loops of passive cables, placed 400 mm above the joints. The cables, with a section of 300 mm^2, are placed at positions of ±1 m, ±0.9 m, ±0.8 m and ±0.7 m from the joint bay longitudinal axis. The inner loops are 1 m longer and shield the part of the cables where they progressively recover the flat configuration.
The computed over temperature of the central joint is of only 2 K and does not give derating problems.

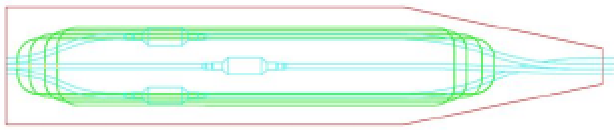

Figure 9: Passive loops disposition in the joint bay

Figure 10 shows the EMF across the joint bay, with indication of the values without mitigation devices and shielded below the requested limit of 20 µT with 8 passive cables.
The circuit has been successfully installed during 2006.
At 50 Hz the SF and the corresponding over temperature would be slightly less than they are at 60 Hz.

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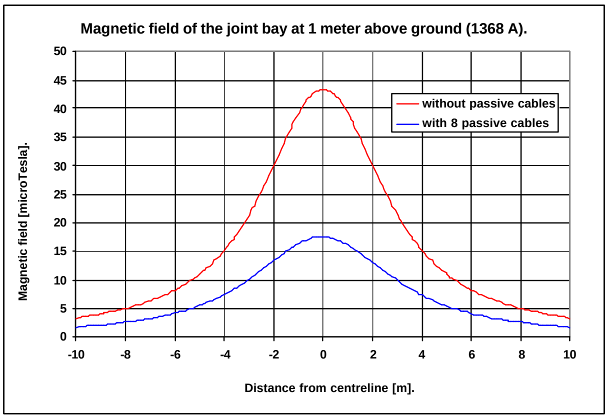

Figure 10: Computed EMF with passive loops

COMPARISON OF COPPER AND ALUMINIUM CONDUCTORS

The solution for the best type of cable is an important aspect, either for the performance or for the economical point of view. The graph of figure 11 compares the SF attainable with copper and aluminium conductors of the same section and diameter, in the case of 380 kV joint bay, where the power cables are arranged as in configuration "F". The shielding construction is composed of 16 cables arranged on the perimeter of the trench. Copper cables show a shielding factor 10% higher than aluminium cables at constant section, due to the much lower resistivity.

Comparing the data at constant resistance, aluminium has a shielding factor 20% higher, due to lower inductance. Similar results can be obtained with different cable arrangement and geometrical solutions.

Low voltage aluminium cables are light, easy to handle and do not have corrosion problems like directly buried unprotected plates. At present, aluminium cables offer a cost competitive solution, according to Cu/Al metal price ratio [3].

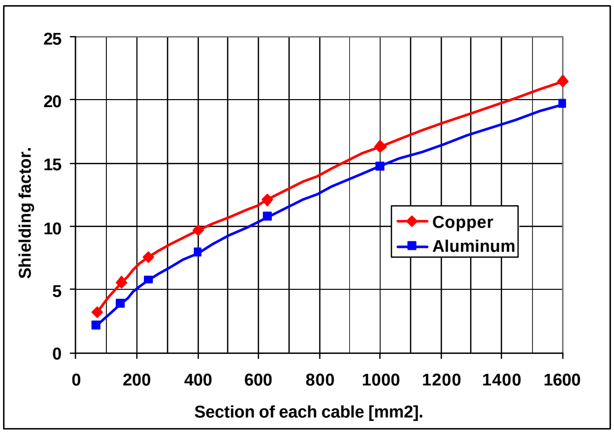

Figure 11: Shielding factor for 380 kV joint bay with 16 cables of different conductor section

It is obvious that, for optimized solutions, the SF is an increasing function of the conductor section and of the total number of cables. From figure 3, the SF with 20 cables, which have a total section of 4800 mm^2, reaches the value of about 10. With 16 cables of 300 mm^2, the SF is only 8.5 and reduces to 3 with 4 cables of 1200 mm^2. The criterion is that, at constant section, the larger the number of cables, the greater the SF is. In fact, for conductor sections larger than approximately 100 mm^2, the induced current is limited by the inductance of the cable and the resistance substantially determines the value of the losses and the corresponding thermal heating on the power cables.

As a rule of thumb, with a constant section of 4800 mm^2, the SF is only 20% greater than with 240 mm^2 cables, using the same number of cables arranged on the perimeter. Figure 11 demonstrates that with a large number of cables it is convenient to increase the section of each conductor to have a better SF. In the case of few cables larger sections have the main effect of reducing the over temperature, but with negligible effect on the SF.

COMPARISON OF CABLES AND PLATES

In flat configuration, with the same total section of copper and the same distance from the cables, the copper plate has a better shielding effect, but passive cables can be placed with a great freedom and can reach a much better overall performance

For example, figure 12 reports of the magnetic field at 1 meter above ground with cables in configuration "B", where the trench width has been enlarged to 1 meter.

The dashed part of the line, for a distance smaller than 150 mm from the cable axis, represents the area where the overheating due the induced losses is too high to be accepted. Otherwise, the plane containing the passive cables can be closer, because the cables are mainly placed on the sides of the trench, the losses are limited and the SF can increase.

An even more effective solution can be achieved with the same 12 cables placed on the perimeter of the joint bay, with an arrangement similar to the one reported in figure 4. The magnetic field is mitigated below 3 µT with an over temperature of only 0.7 K on the hottest power cable.

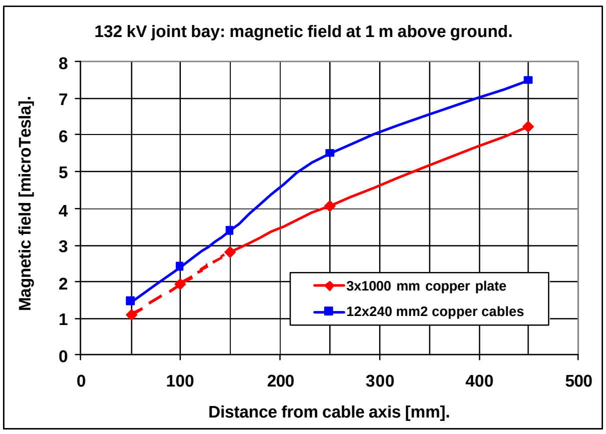

Figure 12: Magnetic field at 1 m above ground, for a 150 kV joint bay in various shielded configurations

TREFOIL AND FLAT ARRANGEMENT

A comparison is given here between 150 kV cable circuit in trefoil formation (configuration "A") and flat touching laying (configuration "B"), to minimize the EMF. Trefoil configuration is a good solution because, as it is it is known from basic formulae, the EMF is √2 times less than the one emitted by the same cables in flat touching formation [4]. Cables in flat formation are easily shielded with one or two layers of passive cables, but only up to a limited SF. The trefoil configuration probably offers the easiest solution, with minimum use of passive cables.

NOTE

Low voltage cables, up to 1 kV, and Medium voltage cables, up to 30 kV, are generally constituted by three single core cables twisted together. The EMF generated by these cables depends on the laying pitch of the cores and decays exponentially with distance from the cable axis. For distances greater than the laying pitch, the EMF generated becomes negligible. This is the reason why, associated with the lower current load of these cables, no practical EMF mitigation measures are necessary.

CONCLUSIONS

This paper shows that the application of loops of passive cables can be the best solution to mitigate the magnetic field produced by HV and EHV power cables. The simple installation technique described here offers good solutions to shield the EMF either emitted by the cables and in particular by the joint bay where other mitigation measures may be difficult or not practical. The solution can be tuned to reach the requested value of magnetic field by simply changing the conductor and / or the number of cables. The current carrying capacity derating of the power circuit is limited to a few degrees centigrade and can be further reduced by simply increasing the section of the passive conductors. The effectiveness of aluminium cables is illustrated in detail, showing how to obtain the same performance as for copper conductors, with a cheaper material thus giving a cost effective solution. Passive cables have superior shielding performance, perfect resistance to corrosion effects and easier installation than metallic plates. According to the authors, the passive loop technique is the best solution to mitigate the magnetic field of the joint bay. A careful analysis shows that passive loops are a simple and effective solution to achieve the required field mitigation through a careful design of the loops, exploiting the technology of low voltage commercial cables.

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