ALP-1995-102

Report

ISRN KTH/ALP/PR--95/102--SE

Reduction of Magnetic Fields from Electric Power and Installation Lines

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March 1995

Abstract. Two methods of reducing the magnetic fields around electric power transmission lines and installation lines are discussed, splitting of conductors, and twisting. Essential design parameters are derived and it is shown that the division of each conductor into two, all arranged symmetrically around a common center, makes the field decay as the inverse cube of the distance, as compared to the inverse square for an ordinary line. Twisting of telephone cables has long been practised to reduce crosstalk. Here it is shown that twisting of cables and installation lines also results in a drastic reduction of the external magnetic field.

Introduction

During the last years there has been much concern whether magnetic fields from power lines, or maybe rather the induced electric field due to the time-variation of those magnetic fields, could be a health risk. In this paper we will only discuss general methods to arrange the conductors in such a way that the surrounding magnetic fields will become highly reduced. In the power industry several computer studies on magnetic fields from special conductor configurations have certainly been made and documented in internal reports, but we think a general analysis has not been presented.

As well known, the magnetic field around a long straight conductor forms circular concentric field lines, figure 1a. If the current in the conductor is I , the magnetic field strength B (flux density), according to Ampère's law, becomes $B = \mu_0 I / (2\pi r)$, and varies consequently with distance as $1/r$.

The field from two conductors, with a separation, a , carrying the same current in opposite directions, has also circular field lines, figure 1b. *The essential parameter*, that determines the strength of the field, is a/r^2 (see Appendix). If a could be reduced to zero the magnetic field would disappear! Therefore, a general principle to reduce the magnetic field is to *keep the distances between the conductors as small as practicable*.

I. Field reduction by division of conductors

Figure 2a shows in cross-section a three-phase power line with the phase conductors R , S , and T , perpendicular to the plane of the paper, and arranged as a triangle with equal sides around a center C . We presume that the sum of the instantaneous currents is always zero, *i.e.* that no current returns through the ground. This is the normal way of operation. The magnetic field at a point F_1 is composed of contributions from the

currents I_R , I_S , and I_T , and can easily be calculated. We assume for simplicity the instantaneous phase being such that the current in R is at maximum, and that it is returned by two equal currents in S and T , $i_S = i_T = -i_R/2$. In the field point F_1 the field components B_R (directed upwards), and $B_S + B_T$ (which give components downwards) are added. B_R dominates since the distance $R-F_1$ is shorter than $S-F_1$ and $T-F_1$. The resultant B_{F1} will be *upwards*. An analogous discussion applied to the field point F_2 shows that also the resultant B_{F2} will be directed *upwards*.

Now assume that the whole system of conductors is rotated 180° around C . The resultants at F_1 and F_2 will now be directed *downwards*. If the two current systems are added, the resultants at F_1 and F_2 will to a large extent cancel, figure 2b. Each phase-conductor is now replaced by a *phase-pair*. This results in a large reduction of the magnetic field, which, at large distance appears to decay as $1/r^3$ instead of like $1/r^2$ for the original three-phase line.

Substitute conductors

In order to simplify the analysis we return to the three-conductor system, figure 2a, and replace it with a two-conductor system, where the currents I_S and I_T are substituted by a hypotetic sum current $I_{ST} = I_S + I_T$, located at a somewhat greater distance, $x+b$, from F_1 than I_S and I_T . The location of this conductor can in principle easily be calculated. It will not be fixed, but depends on the position of the field point. When the field point moves towards infinity, b approaches $a/2$.

The general solution

Figure 3 shows a generalised three-phase-line, where each phase conductor is divided into two conductors, each carrying half the phase current, and being located diametrically opposite to the center C . They form *three phase-pairs*. The magnetic field in a field point, F , due to the current in one phase-pair, e.g. $R-R$, can be shown to be the same as if the sum current in $R-R$ would flow in a hypotetic conductor R' , located near the center C . In the same way the conductors $S-S$ and $T-T$ can be replaced by hypotetic conductors S' and T' . The point is that the three hypotetic substitute conductors become located *much closer to the center C* than the real conductors. Their locations depend on the distance to the fieldpoint, F , and they approach the center when F is moved away. The result can be described in terms of a *new essential parameter*, a' , representing the distance of the substitute conductors from C . a' is much smaller than the original parameter a , which means that the field in the point F is very much reduced. It also appears that the field strength will go down much faster with the distance, namely as a/r^3 , which can be seen as a consequence of the substitute conductors approaching each others (See Appendix).

We have limited the analysis to the perpendicular (azimuthal) component of the magnetic field. This is the dominating component as soon as r is a few times larger than a . The z -component is zero, and the r -component decays faster with distance than the azimuthal component. Our analysis has been confined to a special phase angle. Other phase angles would give slightly different magnetic fields, but of the same order

of magnitude. We can therefore claim the analysis to be valid in general. This is also confirmed by computer calculations for different angular positions of the conductors, and for different electric phase angles.

Figure 4 shows the calculated field strength as a function of the horizontal distance from the power line, for the original single conductor three-phase line (upper curve), and for the line with divided phase conductors (lower curve).

Summary

A powerful method to reduce the magnetic fields from a three-phase line consists in splitting each phase conductor into two conductors, which form a *phase-pair*. It is essential that all the phase-pairs have a common center, and that the two conductors in each phase-pair are equidistant from the center. On the contrary, the angles between the planes of the phase-pairs need not to be equal, and the distance between the conductors in the different phase-pairs may be different. For one of the phase-pairs the distance may even be zero, *i.e.* its conductors can be replaced by one conductor in the center, carrying the whole current of that phase. This design has been described elsewhere [1].

Figure 5 shows examples of existing types of power lines, where a division of the currents can easily be applied. Similar arrangements are recently described in a review article by Perry [2].

The method of splitting the conductors is not limited to three-phase lines, but can equally well be applied to single phase and dc-lines, cables, domestic power supply installations, and signal cables. The division of each conductor is not limited to 2 conductors; further division into 3, 4, etc. wires, located concentrically around a center, will reduce the field strength still more.

In the special case of a two-conductor line, with one of the conductors placed in the center, while the other is divided into an infinite number of symmetrically located phase-pairs, the line is transformed into a coaxial cable, which, as well known, has no external field.

II. Reduction of Magnetic Fields by Twisting of Cables

Introduction

In telephone cables, twisted, balanced, unshielded conductor pairs have been used since long ago. By twisting (with different pitches for different lines) the inductive coupling is almost eliminated, and by careful balancing (electrostatic symmetry relative to earth) the capacitive coupling to the surrounding is cancelled. In this way, without shielding the conductors, it has been possible to attain the very high attenuation of cross-coupling, of 80 dB or more, which is necessary. Balancing and twisting are in principle useful independent of frequency.

In early electric power installations twisted conductors were commonly used. Nowadays twisting is used in cable manufacturing as a method to keep the conductors together, and to make the cable flexible. However it seems not well known that twisting is an excellent method of reducing the external magnetic field.

The magnetic field close to a twisted line

Figure 6 shows in principle the character of the magnetic field from a twisted conductor pair, A. The field has in reality a complicated three-dimensional, screw-shaped structure. In telephone cables the object is to reduce the coupling between two pairs of conductors located close together, e.g. A and C. For simplicity we assume that C is untwisted. Close to the twisted pair, where $c < b$, the magnetic field from A is essentially transverse. The reduction of the coupling is achieved because the voltage induced in C changes sign twice for each turn, and these signals cancel each others, except maybe from one half turn, at most. *The essential parameter*, controlling the coupling between the lines, will be the ratio b/l , where l is the length of the line. The number of turns per unit length, $n = 1/b$. If both lines are twisted, the difference in number of turns is the important parameter, and it will become particularly high if the lines are twisted in opposite directions.

The distant field from a twisted line

At greater distance from the twisted line, A in figure 6, e.g. at the point F, the field will no longer remain essentially radial, but will close due to *axial* components. This will result in a rapid reduction of the field strength with increasing distance. *The essential parameter*, which determines the field strength will then be b/r .

Figure 7 shows the calculated field strength from a long, twisted line with center-to-center distance 4 mm, and current 10 Amp (typical data for a power supply installation). It is obvious that the field drops very rapidly when the distance, r , exceeds the length of one turn, b .

It is obvious that twisting is equally efficient to reduce the field from three-phase cables, and that it can be combined with splitting of the conductors to achieve further field reduction.

Another consequence of the rapid decay of the field is that, if A is carrying a signal, the leakage of that signal will decay very rapidly with the distance, and conversely that a twisted line is very insensitive to magnetic disturbances.

The reduction of the external magnetic field of a twisted line is also likely to have other consequences, such as reduced inductance and reduced characteristic impedance of the line, regarded as transmission line. At high frequencies, when electromagnetic radiation becomes important, the radiation is likely to become strongly reduced due to destructive interference, and one might expect that the corresponding attenuation of the signal on the line due to radiative losses should become less for the twisted line than for an untwisted.

References

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Appendix

Estimate of the spatial variation of the magnetic field

The magnetic field from a long, straight conductor forms, as well known, circular concentric field lines. The field strength, $B = \mu_0 I / (2\pi r)$, decays as $1/r$.

As discussed above the field from the three-phase line, figure 1a, can, for a particular phase angle be estimated as the sum of the fields from two conductors. On the x-axis the field has only y-components, and can be expressed as the sum of two geometric series:

$$\begin{aligned} B_1 &= \frac{\mu_0 i}{2\pi(x-a)} - \frac{\mu_0 i}{2\pi(x+b)} \\ B_1 &= \frac{\mu_0 i}{2\pi x} \left(1 + \frac{a}{x} + \frac{a^2}{x^2} + \frac{a^3}{x^3} + \frac{a^4}{x^4} \dots - \left(1 - \frac{b}{x} + \frac{b^2}{x^2} - \frac{b^3}{x^3} + \frac{b^4}{x^4} \dots \right) \right) \\ B_1 &= \frac{\mu_0 i}{2\pi x} \left(\frac{a+b}{x} + \frac{a^2-b^2}{x^2} + \frac{a^3+b^3}{x^3} + \frac{a^4-b^4}{x^4} \dots \right) \end{aligned}$$

We find that the field from the three-phase line in first approximation varies as

$$(a+b)/x^2,$$

where x stands for the distance, r .

For the second three-phase line, which is turned 180 degrees, we find by analogy:

$$B_2 = \frac{\mu_0 i}{2\pi x} \left(-\frac{a+b}{x} + \frac{a^2-b^2}{x^2} - \frac{a^3+b^3}{x^3} + \frac{a^4-b^4}{x^4} \dots \right)$$

For the superposed sum-field we obtain:

$$B_1 + B_2 = \frac{\mu_0 2i}{2\pi x} \left(\frac{a^2-b^2}{x^2} + \frac{a^4-b^4}{x^4} \dots \right)$$

We conclude that the sum field in first approximation varies as

$$(a^2 - b^2)/x^3.$$

The ratio between this field and the field from the original three-phase line defines the *reduction factor*

$$\frac{B_1 + B_2}{2B_1} \approx \frac{a-b}{x} = \frac{a}{2x}$$

Acknowledgement

The author wants to thank Drs. Rolf Johansson, Björn Bonnevier and Bertil Wilner, M Sc, at the Royal Institute of Technology, and Sture Stéen, M Sc, Elsäkerhetsverket, Hässleholm, for many stimulating discussions.

The author is also greatly indebted to Professor Carl-Gunne Fälthammar for support and permission to use the computer facilities at the Alfvén Laboratory.

Figure 1

Figure 2

Figure 3

Figure 4.

Magnetic field strength as a function of the horizontal distance from the center, C , for the three-conductor three-phase line of figure 2a, and, below, for the six-conductor line of figure 2b.

The distance of the conductors from their center, C , is $a = 5$ m, and the transferred current is 1000 Amp.

The height of the line is taken as low as 10 m to mainly take into account the lowest parts of the power line. Variations in the near field region depend on the actual mounting of the conductors.

The properties of the ground (conductivity and permittivity) has not been taken into account.

Note that the field in the far region decays as $1/r^2$ for the single three-phase line, but as $1/r^3$ for the line with split conductors!

Figure 5.

Examples of power lines where magnetic field reduction is obtained by suitable connection of the conductors.

Figure 6

Sketch of the magnetic field from a twisted line, A. The field has everywhere a complicated, three-dimensional, screw-shaped structure.

C is another, here untwisted, line, located in the *mainly transverse-field* close to A.

F is a point in the *distant field*, where the field drops rapidly with distance because field lines are closed due to *axial components*.

Figure 7.

Calculated magnetic field strength from a twisted line, A. (Point F in figure 6), as a function of the distance, r , for different twists, 2-40 turns/meter, as well as untwisted.

The conductors have the center to center distance 4 mm and carry the current 10 Amps, as in a typical installation line.

The calculation is done by integrating Biot-Savarts law along two helices.

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Key words: Magnetic field, Electric power line, Electric cables. Electric transmission lines.

After finishing this report, the author has learned about the work of Pettersson [5,7], and Zaffanella [6], treating the same topic in a different manner, but arriving at similar results.

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