Magnetic Field Reduction Measures for Transmission Lines Considering Power Flow Conditions

D. Reichelt, R. Scherer
Nordostschweizerische Kraftwerke, NOK
CH-5400 Baden

R. Bräunlich, Th. Aschwanden
Fachkommission für Hochspannungsfragen, FKH
CH-8044 Zürich

Proceedings of the
1996 IEEE Transmission and Distribution Conference
Los Angeles, September 15-20, 1996
IEEE-Publ. Nr. 96CH35986, pp. 468-492

Magnetic Field Reduction Measures for Transmission Lines Considering Power Flow Conditions

D. Reichelt, Member, IEEE, R. Scherer
Nordostschweizerische Kraftwerke
CH-5400 Baden, Switzerland

R. Bräunlich, Member, IEEE, Th. Aschwanden, Member, IEEE
Fachkommission für Hochspannungsfragen
CH-8044 Zürich, Switzerland

Abstract — **The magnetic field produced by transmission lines may disturb sensitive electronic equipment in the vicinity. For a given tower configuration the power flow conditions of the line determine the magnitude of the emitted magnetic fields. The influence of load, phase angle and direction of the flows on the combined magnetic field of multi-circuit lines is discussed systematically. Besides optimal arrangement of the phase conductors emphasis is given to the grouping of the phase conductors to circuits. Examples of existing power lines and projects show practical applications.**

KEYWORDS

Overhead transmission line, extremely low frequency field ELF, magnetic field, electromagnetic compatibility, low field phase arrangement, power flow

1. INTRODUCTION

The more recent studies and investigations about electric and magnetic fields in the vicinity of power transmission lines were mainly stimulated by public concern and in particular by the controversial debate about the possibility of biological effects of low magnetic fields. In some countries the approval of new transmission line projects as well as upgrading of existing transmission lines requires an environmental impact statement. One important item in such a report is the impact of electromagnetic fields in residential areas. With the present design of transmission lines, the magnetic flux density in the vicinity and even directly under the line (1 m above the ground level) is generally much lower than the internationally recommended exposure limit of 100 μT for low frequency magnetic fields in areas with public access [1].

It is widely recognized that low frequency magnetic fields may disturb technical installations, such as video display units (monitors of computer terminals) even at low field flux densities. In particular, large display units of CAD workstations are very sensitive in this respect. Low level magnetic fields may also affect the operation of sensitive measuring equipment (e.g. electron microscope) or instruments for medical diagnosis (EEG). Power frequency magnetic fields were analysed in a number of publications [2], [3], [4], [5]. Various measures were proposed for the reduction of transmission line magnetic fields [6], [7]. Most of the existing concepts for field reduction of multi-circuit lines are based on a uniform loading of the circuits involved [8]. However, this will not be the case, if the circuits are not operated in parallel. Therefore the simulation of power line magnetic fields has to be based on real operating conditions.

Multi-circuit lines are widespread in the Western European transmission network (UCPTE). Typically, two or more 380 kV or 220 kV circuits, respectively, are on the same tower. In most cases the circuits have independent power flows. The ratio of the individual loads may vary in a wide range. The paper discusses the influence of various power flow conditions (load, phase angle, flow direction) of multi-circuit transmission lines on the magnetic fields in the vicinity of the lines. Besides optimal phase conductor arrangement the grouping of phase conductors to circuits can reduce the combined magnetic field significantly. The case of a project is shown, where the magnetic field was reduced by grouping the phase conductors to an optimal arrangement.

0-7803-3522-8/96 $5.00 © 1996 IEEE

2. LOW FIELD PHASE ARRANGEMENT FOR MULTI-CIRCUIT LINES

2.1 Magnetic field of multi-circuit lines

Power frequency magnetic fields of three phase systems have to be treated as vector phasors, i.e. temporal and spatial sinusoidal varying vectors. In general the vector locus traces an ellipse. In the following the magnetic flux density B (or B-field) will be considered. In the Laplace domain a mono-frequency quasi static field can be described as a complex vector field [5]. Fig. 1 shows the real and imaginary parts, which are space directional vectors with components in the x- and y-axis. B-fields of power lines can be treated as a two-dimensional fields with four components, i.e. real and imaginary parts in both, x- and y-direction. The description of a 3-dimensional field at one point would need 6 components.

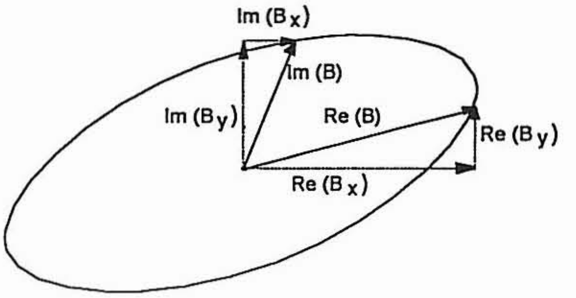

Fig. 1 B-field vector locus of a 3-phase system

The magnitude (RMS-value) of a two-dimensional field has to be calculated as the root mean square of the four components (1). As the space directional vectors are instantaneous values, the factor $1/\sqrt{2}$ is needed to calculate the RMS-value [9A].

$$B_{RMS} = \frac{1}{\sqrt{2}} \cdot \sqrt{\mathrm{Re}(B_x)^2 + \mathrm{Im}(B_x)^2 + \mathrm{Re}(B_y)^2 + \mathrm{Im}(B_y)^2}$$

$\mathrm{Re}(B), \mathrm{Im}(B)$: space directional vectors (peak values) (1)

B_x, B_y: vectors components

With multi circuit lines the combined field is the superposition of the individual fields of the circuits. Since two-dimensional fields are characterized by four components, the superposition is done by adding these components, i.e. adding the space directional vectors of the real and imaginary parts.

$$B_{sum} = B_1 + B_2 = \mathrm{Re}(B_1) + \mathrm{Re}(B_2) + j(\mathrm{Im}(B_1) + \mathrm{Im}(B_2))$$

B_{sum}: vector phasor of the combined field (2)

B_1, B_2: vector phasors of the individual fields

The value of B_{sum} depends on the magnitudes and the phasor angles of the field components of each individual circuit. Thus, the combined magnetic field of a multi-circuit line depends on the current magnitude and the phase angle of each circuit. It must be noted, that the magnitude of the combined field is not equal to the sum of the magnitudes of the individual fields. The magnitude of the combined field may even be lower than the individual field of each circuit.

The vector locus of the combined field of multi-circuit lines with circuits operating at the same frequency is still an ellipse. This was verified by a measurement near a 380 kV line with two circuits. One of the measurement described in section 3.1 was analysed in detail. The space components of the magnetic field were measured during 15 cycles (300 ms at 50 Hz) with a sampling interval of 0.6 ms. Fig. 2 shows the measured locus of the vector phasor. The RMS-value of the measured B-field was 0.941 µT.

Generally, the magnetic field of three-phase power lines declines rapidly with the distance from the line axis, characterized by an inverse power series of the distance. For a symmetrical 3-phase system (no zero sequence component), the magnitude decays with the power of two of the distance and neglectable terms of higher order [10]. If the line consists of more than one 3-phase circuit, the second and even higher order terms can be reduced significantly by optimizing the phase conductor arrangement which is used for low field configurations or higher order phase arrangement [11].

2.2 Criteria for low field phase arrangement

Two general rules can be proposed for a tower design with low magnetic fields.

I. Compact design: The conductors should be arranged as close as possible, since the field far away of overhead lines is proportional to the distance between the phase conductors.

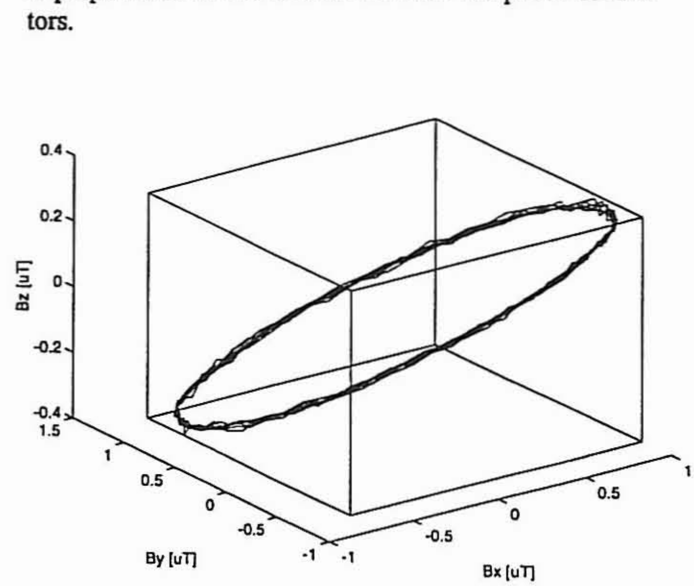

Fig. 2 Vector locus (measured), $B_{RMS} = 0.941$ µT

II. Phase arrangement: For multi-circuit lines the phases should be arranged in such a configuration that the superposition of the individual fields produces a minimum combined field. In a first step, the center point of all currents having the same phase must be determined. (The center point would correspond to the center of gravity if the currents were replaced by masses.) Then the conductors have to be arranged in such a manner, that the center points of all phases will be as close as possible. Referring to [10] it can be shown that the second-order term of the B-field series expansion will vanish completely, if the center points of all groups of currents having the same phase angle coincide. Thus the far field will depend on the distance as $1/d^3$. Fig. 3 shows an optimal phase arrangement of two 380 kV circuits.

The described method gives the basis for the geometrical optimization of the tower design. It is based on given currents for each circuit and on equal phase angles of all circuits. However, in the realistic operation conditions of power lines, the circuits will normally have currents of different magnitude and different phase angles. The operating conditions have a strong influence on the combined magnetic field, which will be discussed systematically in the following chapter.

Taking unequal loads of the individual circuits of multi-circuit lines into account, a further criterion for the reduction of the magnetic fields has to be considered. The phase conductors can be grouped in different ways to 3-phase circuits. Section 4.2 shows a practical application.

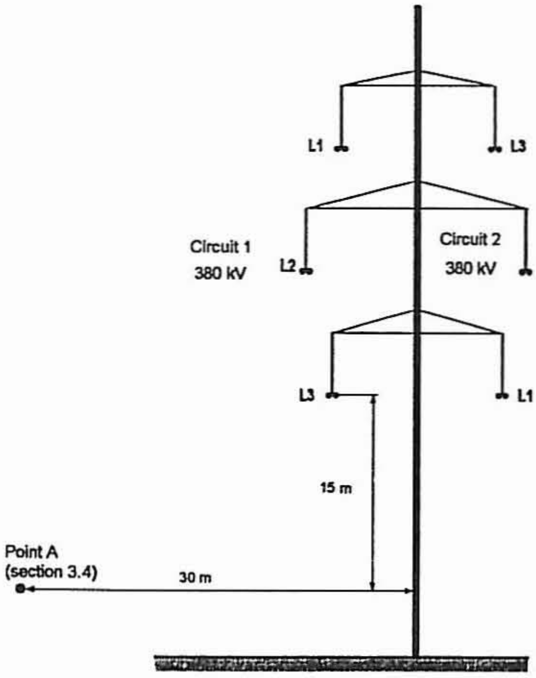

Fig. 3 Tower with optimal phase arrangement

3. INFLUENCE OF OPERATING CONDITIONS

3.1 Time-varying power flow

The varying power flows of multi-circuit lines produce varying magnetic fields, too. The example of a real case will illustrate this context. An overhead transmission line with two 380 kV circuits crosses an industrial area. Monitor disturbances were reported from a building with offices located exactly under the line. The monitor disturbances could be observed at certain times of the day, only. The magnetic fields were measured on both sides at 20 m from the line axis (measurement A and measurement B, respectively), 1 m above the ground level. Fig. 4 summarizes 96 measurements taken in 24 hours. Most of the measured values were 1.5 μT or below. However, at certain times field magnitudes between 1.5 μT and 2 μT were measured. In this range of field magnitudes, monitor disturbances were observed. The variation of the field values was caused by the varying power flows on the line. As the circuits were not operated in parallel, different magnetic fields were measured on each side of the line.

3.2 Uneven load of the circuits

The current magnitude and the proportion of the individual circuit currents have a significant influence on the magnetic field emission. In an optimized low field arrangement the reduction of the magnetic field will be lowered if the currents of each circuit are not equal. As an example the combined magnetic fields of a 2-circuit line with an optimized phase conductor arrangement (fig. 3) were simulated for three different load conditions. The currents of circuit 2 were modified according to table 1. Case 1 is the reference case with even load. Case 3 has the maximum uneven load. Although the total load of case 3 is half of case 1, the maximum combined field of case 3 is about 85 % of case 1.

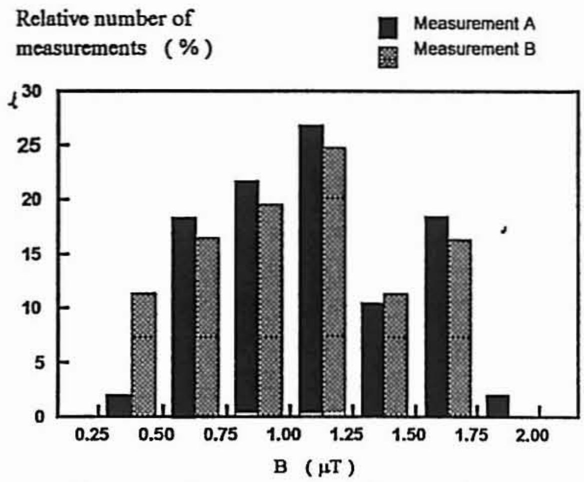

Fig. 4 24-hour measurement of the magnetic field

Table 1 Unidirectional operation with load variations

	Current of circuit 1	Current of circuit 2
Case 1	1000 A	1000 A
Case 2	1000 A	500 A
Case 3	1000 A	0 A

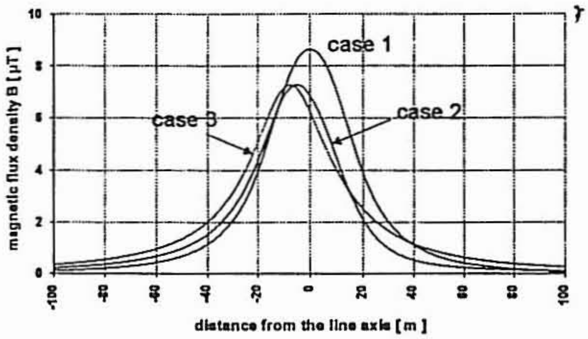

Fig. 5 Magnetic field for different loads

In many cases the combined magnetic field may be higher for unequal currents, especially at a certain distance from the line axis. Fig. 5 shows the profiles perpendicular to the line axis of the combined fields. In the range between -10 m and -100 m from the line axis the combined field of case 3 is higher than the field of case 1, even though the total sum of the currents of case 3 was half as high as in case 1.

3.3 Reverse power flows

The individual power flows of multi-circuit transmission lines may have opposite directions. Typically, this is the case if circuits belonging to different grids are on the same tower, i. e. mixed lines with 380 kV and 220 kV circuits or lines with transmission and sub-transmission circuits.

In order to analyse the reduction of the magnetic field two cases with reverse power flows were simulated using the same line configuration as in chapter 3.2. The current of circuit 2 had the same magnitude but reverse direction (table 2). Fig. 6 shows the combined fields for the cases 4 and 5.

Table 2 Reverse power flow on circuit 2

	Current of circuit 1	Current of circuit 2
Case 4	1000 A	−1000 A
Case 5	1000 A	−500 A

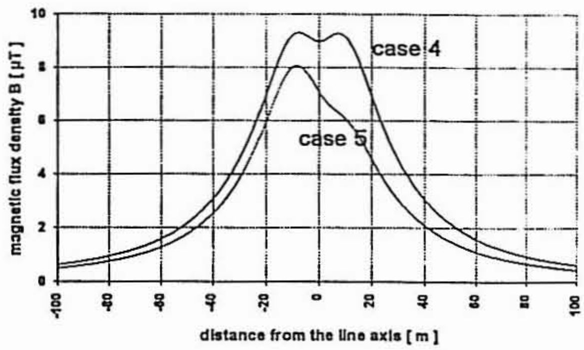

Fig. 6 Magnetic fields for reverse power flow

Comparing case 4 to case 1 and case 5 to case 2, respectively, the combined field is higher for reverse power flows. The difference becomes significant at a certain distance from the power line, typically 20 m and more. In table 3 the field magnitudes of all 5 cases are compared at a point at -30 m from the line axis.

Table 3 Combined magnetic fields at -30 m from the line axis

	Currents	B_{res}
Case 1	1000 A / 1000 A	2.06 µT
Case 2	1000 A / 500 A	2.53 µT
Case 3	1000 A / 0 A	3.14 µT
Case 4	1000 A / -1000 A	4.59 µT
Case 5	1000 A / -500 A	3.84 µT

3.4 Phase angles

The currents of two circuits usually have different phase angles, caused by different power factors on each circuit. The difference of the phase angles has a certain influence on the combined magnetic field. The phase angle between the two circuits was varied from 0° to 360°, i.e. by variation of the power factors. The simulation is based on the tower configuration of fig. 3. Fig. 7 shows the combined B-field calculated for the point A. It should be mentioned, that at phase angles $90° < \varphi < 270°$ the real power flow of the two circuits would be reverse (see section 3.3). For the simulations, the currents of the circuits were kept constant.

The influence of the phase angles on the combined B-field becomes more complex if more than two circuits are on the

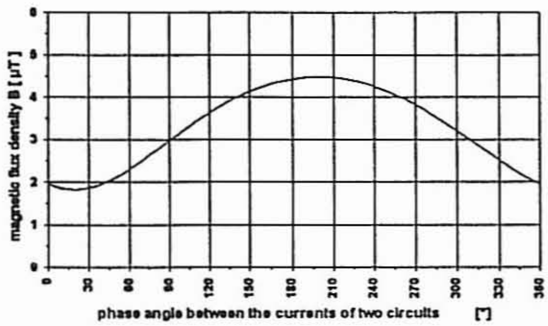

Fig.7 Magnetic field for varying phase angle difference
2 circuits, 1000 A each, configuration see fig. 3

same tower. As an example a line with three circuits (fig. 9) was used. The combined magnetic field at the observation point is shown in fig. 8. Parameters for the calculation were the difference of the phase angles between circuit 1 and circuit 2 (φ_{12}) and between circuit 1 and circuit 3 (φ_{13}), respectively.

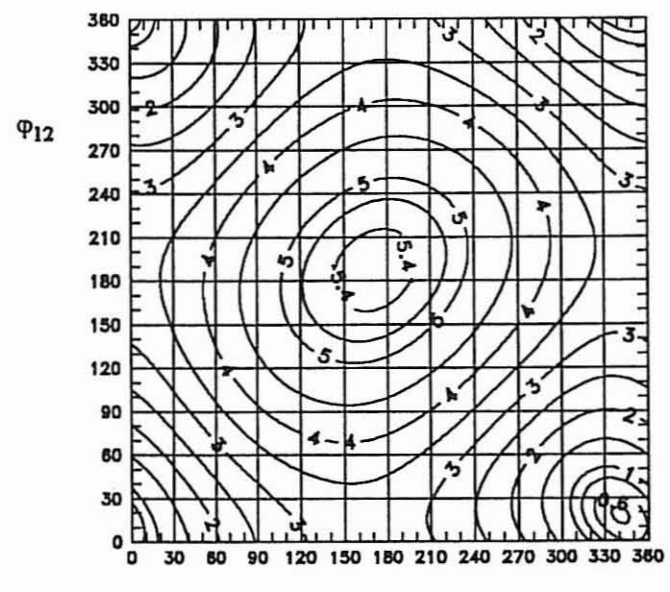

Fig. 8 Magnetic field of three circuits with varying phase angles (values in µT)

φ_{12}: phase angle difference of circuit 1 and 2
φ_{13}: phase angle difference of circuit 1 and 3
Circuit 1,2: 1000 A, circuit 3: 500 A

4. EXAMPLES OF PRACTICAL APPLICATIONS

4.1 Optimal phase arrangement for an existing line

An office building having many PC and CAD work stations is located only 17 meters from the line axis of a 220/380 kV-transmission line (fig. 9). The monitors with the smallest distance to the line are about 8 meters below the lowest tower arm and 10 meters from the nearest conductor.

After complaints about monitor disturbances, magnetic field measurements at several monitor locations showed that the equipment disturbance level of about 1.5 µT was slightly exceeded even for the most distant monitors.

In order to avoid high expenses regarding individual shielding of the monitors, field calculations were performed to clarify whether any phase change at the three-circuit-line would cause a sufficient reduction of the magnetic field. The result was that the combined magnetic field of the transmission line could be reduced by means of a simple phase change in the lowest circuit. This phase change was tested then and measurements confirmed the results of the calculations: reduction from 2.25 µT to 0.5 µT (mean values). The change of the outer phases to the optimal arrangement was performed at low cost. Fig. 9 shows the original and the optimized phase conductor arrangement.

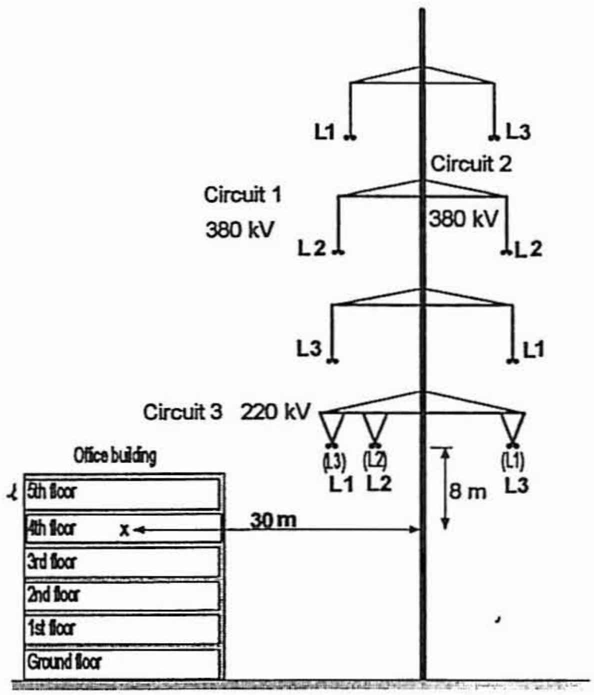

Fig. 9 Office building near transmission line

(L1),(L2),(L3)	original phase conductors of circuit 3
L1, L2, L3	optimized arrangement for circuit 3
X	measurement point (desk top monitor)

The magnetic field emission of the transmission line could be minimized without any visible change at the equipment with the effect that the monitor disturbances disappeared. In the case of a single monitor of course, it would be more cost effective to shield the equipment itself than to take measures at the field source.

This case illustrates how the magnetic field emission of an existing line was reduced. The design of the tower could not be changed. Thus the number of possible variants was limited due to the installed insulators for 380 kV and 220 kV, respectively. The calculations were based on currents representing normal operating conditions. The new arrangement had a significantly reduced combined magnetic field which was verified by measurements.

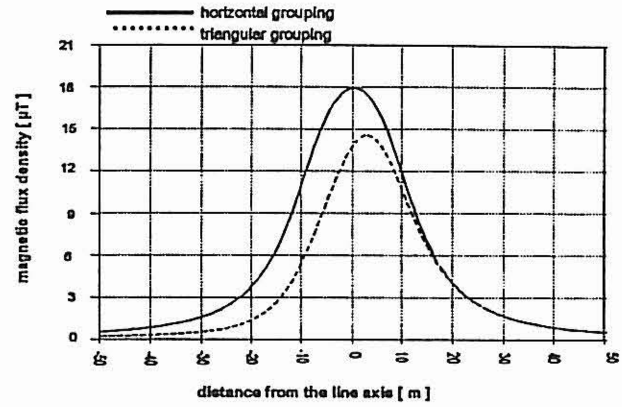

Fig. 11 Magnetic fields for different variants of grouping

4.2 Phase optimization for a 220 kV line project

For the project of a new 220 kV line simulations were performed to determine a low-field phase arrangement. The optimization of the phase arrangement according to the rules described in section 2.2 led to the configuration of the phase conductors as shown in fig. 10. Besides the optimization of the phase conductor arrangement, different possibilities to group the circuits may be used to minimize the magnetic field considering power flow conditions.

Principally the phase conductors can be grouped in two ways to three-phase circuits, either horizontally or in a triangular configuration (fig. 10). The electric field would be equal for both variants, as well as the magnetic field if both circuits were loaded equally. The latter will not be the case, as the lines will not be operated in parallel. In real operation the two circuits will have different flows. In order to model the uneven power flows, the magnetic field calculations were based on currents of 500 A for one circuit and 1000 A for the other circuit. As it cannot be predicted which circuit will be higher loaded, the worst case had to be taken into account for the simulation of the magnetic fields. Fig. 10 shows the worst case for both variants of grouping. In fig. 11 the combined fields are compared.

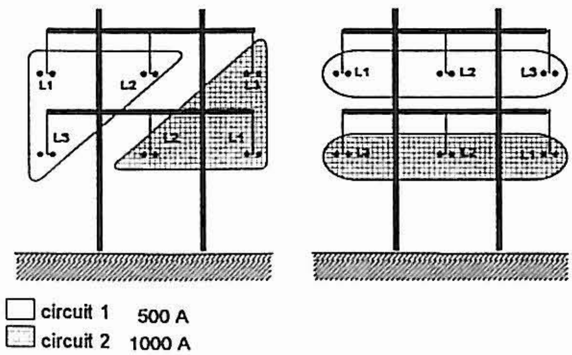

Fig. 10 Possible grouping of the phase conductors

For unequal operating conditions the combined magnetic field of the triangular grouping of the phases will be significantly lower than for the horizontal grouping.

In principle the described method could be applied for other tower configurations. It has to be mentioned that for towers with three crossarms and a vertical arrangement of the conductors as shown in fig. 3 the situation becomes more complex. The combined field of lines on high towers might be reduced using a triangular grouping of the phases. However, for low towers the situation is different. Here, the vertical grouping, as used by conventional arrangements, will have a lower combined field than the triangular grouping. As lines on low towers produce high magnetic fields on the ground level, the vertical grouping should be applied.

5. CONCLUSIONS

Using real operating conditions like typical mean loads as a basis for magnetic field simulations, an optimized arrangement and grouping of phase conductors will reduce the magnetic field emission in the vicinity of power lines. As the power flow conditions may vary independently for each circuit, the minimum magnetic field emission cannot be guaranteed for all operating conditions. Standard operating conditions have to be evaluated for a realistic simulation. The aim is to cover the majority of the possible operating conditions, preferably these with high magnetic field impact.

Already during the design phase, field simulations will help to find an optimized conductor arrangement and routing of the transmission line to make sure that the field emission will be minimized. Additionally any limits of exposure (e.g. IRPA guidelines [1]) will be strictly respected. For upgrade projects the comparison between the field emission of the actual and the planned line situations is very helpful in the project argumentation.

6. REFERENCES

[1] International Radiation Protection Association: "Interim Guidelines on Limits of Exposure to 50/60 Hz Electric and Magnetic Fields." Health Physics, Vol 58, 1990, pp 113-122.

[2] Olsen R. G. , Wong P. S. "Characteristics of low frequency electric and magnetic fields in the vicinity of electric power lines" IEEE Transactions on Power Delivery, Vol. 7, No. 4, October 1992, pp 2046 - 2055

[3] Dawalibi F., Selby A. "Electromagnetic fields of energized conductors" IEEE Transactions on Power Delivery, Vol. 8, No. 3, July 1993, pp. 1275 - 1284

[4] Sarma Maruvada P. "Characterization of power frequency magnetic fields in different environments" IEEE Transactions on Power Delivery, Vol. 8, No. 2, April 1993, pp. 598 - 605

[5] Deno D.W. "Transmission line Fields" IEEE Transactions on Power Apparatus and Systems, Vol. PAS-95/5, September/October 1976, pp 1600-1611.

[6] Steward J. R., Dale S. J., Klein K. W. "Magnetic field reduction using high phase order lines" IEEE Transactions on Power Delivery, Vol 8. No. 2, April 1993, pp. 628 - 636

[7] Jonsson U., Larsson A., Sjödin J-O."Optimized reduction of the magnetic field near Swedish 400 kV lines by advanced control of shield wire currents. Test results and economic evaluation" IEEE Transactions on Power Delivery, Vol. 9, No. 2, April 1994, pp. 961 - 967

[8] Tsanakas D., Tsalemis D., Agoris D., Vojazakis J. "Optimum arrangement of the phase conductors of overhead transmission lines for the magnetic field minimization" Paper No. 36-101, Cigré Session, Paris, 1994

[9] "A Protocol for Spot Measurements of Residential Power Frequency Magnetic Fields" A Report of the IEEE Magnetic Fields Task Force, IEEE Transactions on Power Delivery, Vol 8. No. 3 July 1993, pp 1386-1394

[9A] Correction to [9], IEEE Transactions on Power Delivery, Vol 9. No. 1, January 1994, p. 606

[10] Kaune W.T., Zaffanella L.E., "Analysis of magnetic fields produced far from electric power lines", IEEE Transactions on Power Delivery, Vol 7/4, October 1992, pp 2082-2091.

[11] Olsen R.G., James D.C., Chartier V.L. "Performance of reduced magnetic fields power line , theory and measurements on operating lines", IEEE Summer meeting 1992, paper 458-0 PWRD

[12] Vinh T., Jones T. L., Shih C. H. "Magnetic fields near overhead distribution lines - measurements and estimating technique" IEEE Transactions on Power Delivery, Vol 6. No. 2 April 1991, p 912.

7. BIOGRAPHY

Dieter Reichelt was born on November 10, 1961. He received the M.S. and Ph.D. degrees in Electrical Engineering from the Swiss Institute of Technology (ETH), Zurich, Switzerland, in 1986 and 1990, respectively. From 1986 to 1990 he worked as a research assistant at the high voltage and power systems laboratory of the ETH. After two years as a senior researcher and private practice as a specialist consulting engineer he joined the Nordost-schweizerische Kraftwerke (NOK), Switzerland, in 1992. His area of work includes EM-fields, electromagnetic transients, expert systems applications, network analysis and power system protection. Besides, he is active as a lecturer at the ETH since 1995. From 1991 to 1995 he was a lecturer at the engineering college Biel, Switzerland. Dr. Reichelt is a member of IEEE, CIGRE and SEV/ETG.

Rudolf Scherer was born in Baden, Switzerland, on October 31, 1946. He received his M.S. degree in Electrical Engineering from the Federal Institute of Technology (ETH), Zurich, Switzerland, in 1975. Having been with the manufacturing industry and a consulting engineering company for 14 years, he joined Nordost-schweizerische Kraftwerke (NOK), Switzerland, in 1989. His area of work includes HV cable technique, environmental compatibility of HV cables and overhead lines, electromagnetic fields and corona effects. R. Scherer is a member of CIGRE SC 21.

Reinhold Bräunlich was born in Bochum, Germany, on February 21, 1957. He received the Dipl-Ing. degree in electrical engineering from the Swiss Federal Institute of Technology (ETH), Zürich, in 1982. After a short period with BBC Brown Boveri & Cie. as a development engineer he joined the high voltage engineering research group at the ETH Zürich in 1983. Since 1991 he is with the Fachkommission für Hochspannungsfragen in Zürich, where he is working in the field of on site high voltage testing. In 1993 he received his Dr. degree from ETH Zürich. He is a member of IEEE and the Swiss Electrotechnical Association (SEV) and therein a member of the Power Society (ETG).

Thomas H. Aschwanden (M '85) received his Dipl. Ing. and Ph.D degree in electrical engineering from the Swiss Institute of Technology (ETH) in 1978 and 1985. Dr. Aschwanden joined the Weber Research Institute, Polytechnic University of New York, in 1985 and has worked there as a research associate in the field of electrophysics and pulsed power technology. In 1987 he became senior assistant at the high voltage engineering group of the ETH. Since 1990 he is head of the high voltage research commission (FKH) of the Swiss power utilities and industry. The research activities of Dr. Aschwanden include electrophysics, high voltage measurement and testing, electromagnetic compatibility, pulsed power, dielectric materials and insulation technology, lightning protection, diagnosis and on-site testing of high voltage apparatus and systems. He is a member of IEEE, CIGRE and the Swiss Electrotechnical Association (SEV).