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ASSESSMENT OF THE ELECTRIC AND MAGNETIC FIELD LEVELS IN THE VICINITY OF THE HV OVERHEAD POWER LINES IN BELGIUM

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1. INTRODUCTION

Nowadays there is a growing concern about the health effects on people living in the vicinity of HV power lines. This concern is mainly based on a presumption that the exposure to ELF (extreme low frequency) power frequency fields and more particularly the 50 Hz magnetic field of HV overhead lines (and perhaps underground cables which aren't discussed in the present paper) might cause adverse health effects.
Therefore, on the one hand, international bodies like ICNIRP (International Commission on Non-ionizing Radiation Protection) and the European Council have proposed exposure reference levels not to be exceeded in order to protect the general public and occupational people against ELF electric (E) and magnetic (H) fields.
On the other hand, epidemiological studies dealing mainly with the possible induction of childhood leukaemia make reference to cut off points (i.e. long term mean exposure values) between "exposed" and "unexposed"[1] people which are much lower than the reference levels. Whatever the recommended levels not to be exceeded might be, it is important to know the actual exposure levels due to HV power lines.
Maximum exposure levels in the vicinity of HV power lines are easy to compute on basis of the design parameters. However the very large number of existing layouts and load flow diagrams makes it very difficult to analyse the behaviour of a whole network only by use of models. Therefore very few data are presently available concerning the actual exposure levels, and more particularly the long-term average exposure levels.

In order to quantitatively assess these levels in Belgium a measurement campaign has been performed in the whole country during the winter of 2000 - 2001.
For this measurement campaign all the overhead transmission lines under the responsibility of ELIA, the Belgian Transmission System Operator, have been taken into consideration. This concerns the sub-networks with rated voltages 70, 150, 220 and 400 kV.

Although the main concern was the H-field, measurements of the maximum E-field have also been performed.

[1] "Unexposed" means exposed at levels less than the concerned cut-off point and for which no association with an increased relative risk has been found.

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2. EXPERIMENTAL DESIGN

2.1. Description of the network sample

The total length of the Belgian overhead network is given in column B of Table 1.
The survey was based on a representative sampling of several “lines” in each sub-network.

A	B	C	D	E	F
Rated voltage (kV)	Total length (km)	Number of sampled lines	Total length of sampled lines (km)	Ratio D/B*100 (%)	Ratio nr spans with measurements / total nr of spans (%)
380	883	7	212	24	1
220	267	2	35	13	0.8
150	2005	10	126	8	0.8
70	2455	8	93	4	0.2

Table 1: Characteristics of the Belgian overhead network and sampling data

A line is a portion of the network between two nodes where the characteristics are homogenous (same layout, same number of conductors and same cross section…). It ranges from a few hundred of meters up to several tens of kilometres.
A line can be single as well as double. In that latter case it usually has two different circuits in which the currents are normally independent, though in most cases they are correlated. For some lines, however, (mostly in the 70 kV network) the bus-bars are the same at both extremities and, hence, also the currents in both circuits. These lines can be called “split lines”.

Though the sampling was performed at random, four restrictive conditions have been taken into account:

1) Open space sampling, i.e. a free access to the vicinity of the lines was required: no houses, trees or other obstacles were present in order to avoid the shadow effect for the E-field measurement.
2) Only lines for which metering data (counting) were available have been kept. The reason for making this choice was the necessity to assess the long-term field behaviour and, hence, to know the evolution of the current flowing in the lines for a period of several years[2].
3) By lack of representativeness, too short lines have been excluded for the statistical analysis.
4) Double lines with totally uncorrelated currents in both circuits were also excluded because it would have been too difficult to make afterwards a correlation between fields and currents.

As shown in column E of Table 1, a higher weight has been given in the sampling of the lines with the highest rated voltages, because they are also responsible for the highest field level.

2.2. Electric and magnetic field measurements

For each chosen line, measurements of the E-field[3] and H-field have been performed on three different spans[4] and, for each span, on 8 different positions, i.e (see Figure 1 and Table 2):

1 and 5: under the lowest conductor[5] near the tower
2 and 6: under the lowest conductor where the field is the highest (near mid span)
3 and 7: at a distance of “a” meters at both sides of the axis of the line and at mid span
4 and 8: at a distance of “2a” meters at both sides of the axis of the line and at mid span

In some cases, however, when the line was completely symmetrical or when the accessibility to one

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[2] It can be assumed, by ignoring the change in the conductor height with the load, that the magnetic field at a given location is proportional tot the current flowing in the line

[3] The electric field has only been measured under the line at points 2 and 6 of Figure 1

[4] Contrary to the lines the three different spans cannot be said to have been chosen at random because accessibility was the main concern.

[5] If there are more than one lowest conductors, the most external is chosen

side of the line was too difficult measurements have only been performed at point 1 to 4.

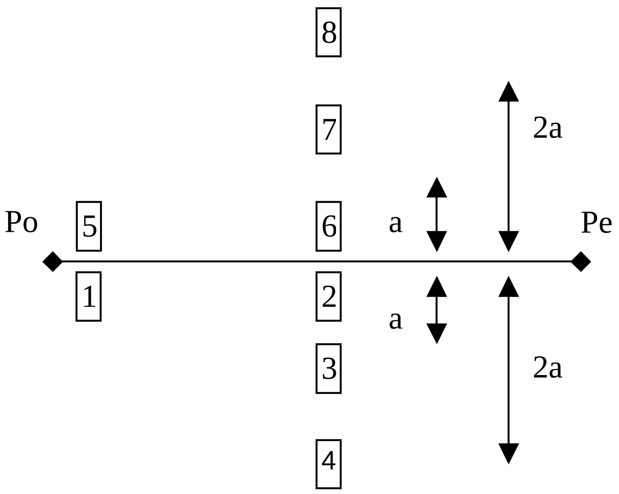

Figure 1: Measurement points on a span between tower Po and Pe

All the measurements have been made at 1.5 m above ground. However, near the tower and under the line (points 1,2,5,6), magnetic field measurements have also been carried out at a height of 3.5 m in order to assess the increase in field levels at the first stage of an hypothetical house built under the line. It has to be highlighted, indeed, that in many European countries, and in Belgium in particular, there are no right of way and anybody may build a house (or any other building) right under a line provided the clearance distances are respected !

kV	a (m)
380	40
220	30
150	25
70	15

Table 2: Lateral measurement distances

3. RESULTS

3.1. Electric field

Figure 2 shows the arithmetic mean and the maximum of all the electric field values recorded under the lines during the measurement campaign.

It must be pointed out that, since the maximum values showed on the graph are those recorded during the measuring campaign, they are not necessary the maximum maximorum of the network.

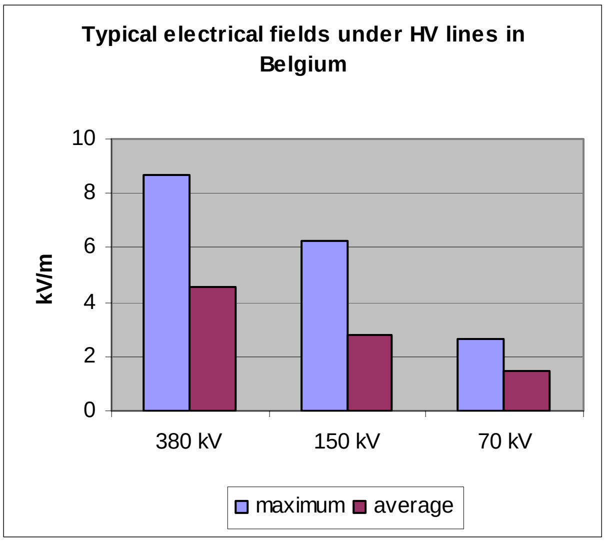

Figure 2: Maximum and average electric field in the Belgian three main HV sub-networks

However they take into account the increased sag due to high load conditions.

On the other hand, as all the measurements have been recorded in open spaces, they are representative for only that part of the network and give average values in excess.

Electric field limits	
Location	Field value
inhabited areas	5 kV/m
road crossings	7 kV/m
elsewhere	10 kV/m

Table 3: Belgian regulation on the electric field

The reason for that is the existence in Belgium of a regulation specifying he maximum values of the electric field under overhead lines. These values, given in Table 3, were published in 1987 well before the ICNIRP (1998) and European (1999) recommendations. Although slightly different from those international reference levels, they are in good agreement with them.

Taking into account this regulation, the design parameters of the lines (clearance) depend on the presence or not of roads or houses, and hence, the field values vary accordingly. The recorded E-fields are conform to the Belgian regulation and the ICNIRP guidelines respectively.

It is important to note that E-field measurements are very difficult to perform because many objects (operator, tripod …) and climatic parameters are liable to perturb the field. By comparing the results obtained by different teams using calibrated equipment and the same protocol, we discover systematic differences as high as 40 % and were obliged to discard some of the measurements. Therefore, the results presented in Figure 2 are in fact only representative of the north part of the country. This is also the reason why the results for the 220 kV network, located in the south part of the country are not shown on Figure 2.

3.2. Magnetic field

As already stated in the introduction, one of the main objectives of the measurement campaign was to get statistical data representative for assessing the B-field exposure levels of whole the Belgian network. Therefore a statistical methodology has been developed. The main idea behind this methodology was to develop a statistical representative distribution for estimating the space and time depended variation of the H-field at a given position with respect to the typical span profile of each sub-network (380-220-150-70 kV).

This statistical distribution has then been used for deriving the main statistics of interest (mean, percentiles, confidence limits…).

This distribution is based on two distributions considered as independent *:*
the aggregated distribution of the current load $\boldsymbol{I}$ *in the different lines and the statistical distribution of the standardised magnetic field* $\boldsymbol{H_{st} = H/I}$

The statistical analysis of the time dependency of the H-field for a given line can indeed be assumed to be completely known when that of the current is known.

3.2.1. <u>Correlation between the H-field and the current load</u>

In order to correlate the H-field strength with the current load, this latter was recorded each time a selected line was sampled. Moreover, the power flow of each sampled line has been recorded during one year at a sampling rate of 15 minutes. In this way it was possible to calculate the field levels for different load conditions and, in particular, to assess the long-term average exposure levels.

Irrespectively of the clearance distances that change with the load conditions[6], it can be assumed that the field levels are proportional to the current load of the line. This is true for a single as well as for a split line, however it isn't true for a double line where each circuit contributes individually to the resultant of the H-field at a given point.

However, for performing general calculations on the long-term behaviour of the fields it has also been assumed that each circuit of a double line influences only the field levels on the corresponding side of the line. This assumption, although physically not correct, leads to acceptable statistical results when the currents in both circuits are sufficiently correlated.

Taking this assumption into account it was possible, for each H-field (µT)[7] measurement to calculate the "standardised field" H_{st} (µT/kA) which is equal to the quotient of H by the line current I (kA) measured at the same time. This standardised field is independent of the time: it depends only, for a given line, on the variations in the space from one span to the other and, for a given sub-network, from one line to the other. It depends, of course also on the measurement uncertainty.

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[6] This variation of the clearance has been taken into account in the calculations

[7] The magnetic field, represented by the letter H, is expressed in A/m; however, as usually, we give the results in terms of the induction field (B-field) magnitude in µT, with the equivalence in air of 1 µT for 0.8 A/m

3.2.2. Application of the statistical methodology

The current load of a specific line fluctuates with daily, weekly and yearly periodicities that are highly different from one line to the other. It has been observed, however, that the general evolution of the load flow distribution of a given line from one year to the other was relatively stationary and could be neglected.

Due to the very high dispersion that exists between the load factors of the different lines and, in order to enhance the aggregate distribution of the currents over the entire sub-networks, data recorded on additional circuits have been pooled to those referring to the measurement campaign.

Figure 3 shows an example of the load distributions of the 16 lines that have been used for assessing the current distribution of the 380 kV network.

This graph shows a very high variability in the magnitude of the maximum currents and in the load factors.

The aggregate distribution $F_I(i)$ has been derived from the individual distributions $F_{Ij}(i)$ by applying the following formula:

$$F_I(i) = \sum_{j=1}^{L} F_{I_j}(i).P(L_j)$$

where $P(L_j)$ is the probability associated to line j. and L is equal to 16. This probability is proportional to the length of the line. However for double lines, due to the high correlation that exist between both circuits, this length has been divided by 2.

In the statistical analysis, the current distribution is supposed to be perfectly known as its uncertainty is considered to be small with respect to that of the magnetic field.

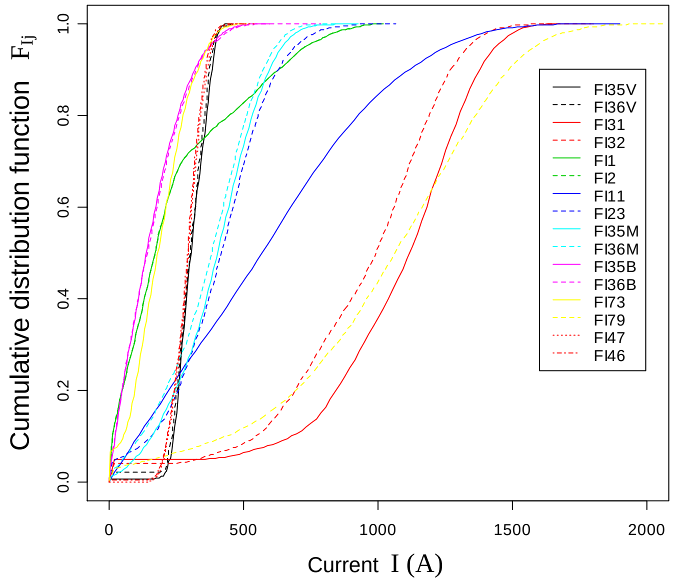


Figure 3: Load distribution of the 16 lines used for calculating the current distribution of the 380 kV network

Two methods were proposed to derive a spatial distribution for the standardised magnetic induction field H_{st} from the available data. The first method assumes a normal probability distribution for H_{st}, which looks to be a quite realistic approximation taking into account the observed data. The second approach is based on a distribution free assumption on the statistical distribution of H_{st} but estimates it non parametrically from the data. This second solution is more difficult to implement and must be seen as a way to assess the validity of the first, and easier, approach. The quality of the H_{st} distribution depends on the representativeness and the size of the available data sample.

As already stated before, the space-time distribution of the H-field has been developed under the quite realistic and convenient hypothesis that the statistical distribution of the standardised fields was independent of the currents. This hypothesis has been validated for the 380 kV network and, to a lesser extend, for the 150 kV and the 70 kV networks for which lines with high mean currents show usually smaller standardised field than lines with smaller loads. However the assumption of independency has been kept because it leads to calculated fields values slightly in excess and thus more conservative.

The space-time distribution of the H-field has then been calculated from the current distribution I and the standardised magnetic field distribution H_{st} by straightforward numerical integration formula. From this distribution it was possible to derive several parameters of interest: such as the overall mean H-field of a sub-network and/or the 95th percentile H-field value giving the ***level of magnetic field that is not expected to be exceeded over the whole sub-network with a probability of 95 %, whatever the load might be.***

Mainly because of the limited knowledge on the standardised H-field (H_{st}) distribution, the statistics derived from the global H-field distribution are not exact estimators of the population parameters, which have to be estimated within some confidence limits. These limits were derived using a simulation method called *bootstrap* which draws randomly new data samples from the original observed one and evaluates the impact of this “resampling” on the variability of the parameters of interest.

3.2.3. Statistical results

Table 4 shows the mean, the standard deviation, the 95 percentile value (including 0.95 confidence limits[8]) at different positions (cf Figure 1) of the 380 kV network.

	H-field (µT) [confidence limits]		
Position	Mean	Standard deviation	95 percentile
H1	[1.4 - 2.1]	[1.3 - 1.9]	[4.2 - 6.0]
H2	[2.1 - 3.2]	[1.9 - 2.7]	[6.2 - 9.0]
H3	[0.8 - 1.3]	[0.8 - 1.2]	[2.4 - 3.7]
H4	[0.3 - 0.7]	[0.3 - 0.7]	[1.0 - 2.2]

Table 4: Mean, Standard deviation and 95 percentile in the Belgian 380 kV network
(Hx for position x as detailed in Figure 1)

The standard deviation (SD) is not to be confused with the confidence limits: the first gives an idea of the field dispersion in the time and in the space (which is very important), whereas the confidence limits depend on the data sampling and could be reduced by performing more measurements.

Figure 4**Figure 4** gives a plot of the corresponding field profiles for the points H2, H3 and H4 (and their symmetrical H6, H7, H8), without the SD and the confidence limits but with two additional curves: one curve (max) gives the maximum possible magnetic field, not derived from the measurement campaign but calculated taking into account the minimum allowed clearance and the maximum rated current of 2.2 kA; the other curve (rated) is simply the product of the mean value of the standardised field H_{st} by the rated current. In other word it shows the profile of the space-averaged field for the maximum rated current.

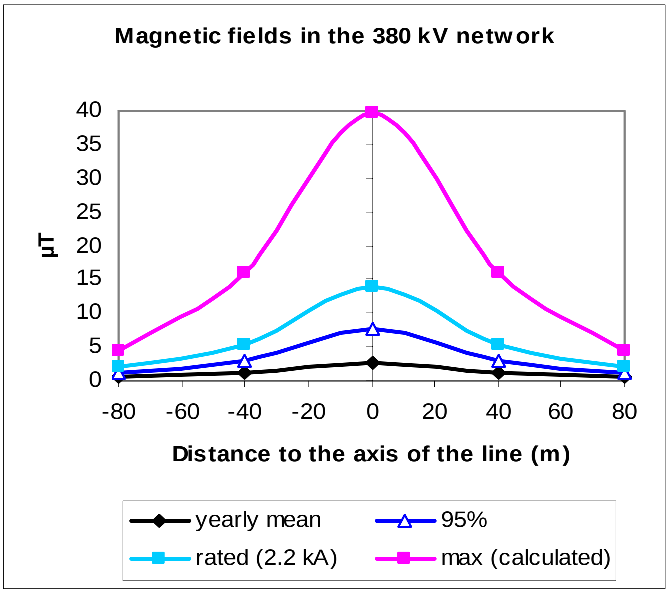


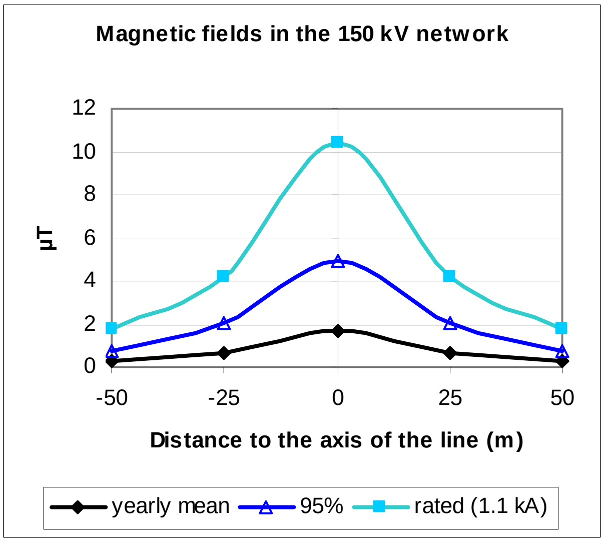
Figure 4: Statistical and maximum values of the magnetic field in the 380 kV network
(dots are measured positions)

Figure 5 and Figure 6 show the same data for respectively the 150 kV and the 70 kV sub-networks but without the calculated maximum field. The rated current used on these plots has been chosen arbitrary and correspond only to the lines with the highest ampacity. It is not representative for the majority of

[8] Conservative estimations

the lines, mainly for the 70 kV network which is the oldest one.

Data for the 220 kV are not shown because they are not considered as sufficiently representative.



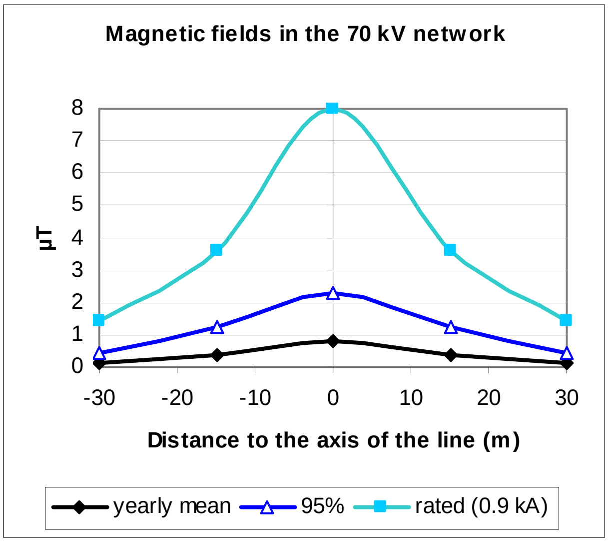


Figure 5: statistical values of the magnetic field in the Belgian 150 kV network

Figure 6: statistical values of the magnetic field in the Belgian 70 kV network

<u>Note</u>: for all the curves presented in Figure 4Figure 4 to Figure 6, the measurement points shown at 0 m are in fact not on the axis of the line but on an abscissa located under the lowest conductor (merge of point 2 and 6 in Figure 1)

The important difference that exists between mean values and maximum values (mainly in the 380 kV network) is due to two parameters: firstly, the *load factor* of the lines and secondly the average *clearance distance* under the lines. The load factor, defined as the ratio obtained by dividing the annual load current by the annual maximum current; has to take into account the N-1 law, i.e. the possibility of the network to continue working correctly in the absence of one of its elements. This explains why the annual maximum currents are usually much lower than the rated currents. On the other hand, a detailed analysis of the distribution of the minimum clearance distance in the 380 kV network has shown that the average distance was about twice the minimum allowed value of 9.5 m used for calculating the maximum field.

It has to be pointed out also that the results showed on the different curves are rather conservative because, as already explained, all the measurements have been performed in areas where there were few or no houses and hence where the clearance distances were the smallest. On the other hands, the plots are made for measurements near mid span where, at least under the line (H2) the field levels are the highest.

3.2.4. <u>Miscellaneous results</u>

1) The comparison of the measurements performed under the line at the two different heights above ground shows that measurements at 3.5 m result in a mean field increase of about 20 % for all the networks except for the 380 kV network where the increase is only about 11 %.

2) The mean ratio H2/H1 between field measurements recorded under the line near mid-span and near the tower is close to 2 for the 70 and the 150 kV networks and is worth about 1.65 for the 380 kV network.

3.2.5. <u>Exposure assessment</u>

On basis of these statistical results it is possible to calculate for each sub-network an average width of the corridors in which a given value of the magnetic field is exceeded. For instance, in the 380 kV network the average width of the corridor in which the long term mean value of 0.4 µT is exceeded is about 170 m, whereas the average width of the corridor in which the value of 0.4 µT is only exceeded in 5 % of the cases is about 280 m[9].

No detailed calculations have been performed yet for assessing the exposure level of the population in Belgium. However, on basis of the corridor widths and on GIS data, the Belgian population living near HV lines in corridors where the annual mean level is higher than the cut off point of 0.4 µT used in epidemiological studies has been evaluated to be of about 1 % of the total population (which amounts 10 millions inhabitants spread on a territory of about 30.000 km^2).

4. CONCLUSIONS

The present measurement campaign makes it possible to perform H-field exposure assessments in the vicinity of the HV overhead network in Belgium. However, larger samples sizes would still enhance the estimation confidence.

In contrast to numerous other studies the H-field estimation is based on the actual current loads in the network. It highlights, among other things, the importance of specifying some kind of measurement protocol, describing how field measurements have to be performed and how exposure limits have to be defined.

It is absolutely not equivalent to speak about a maximum field level, an average field level or a level not to be exceeded during a given time. In this respect, the example of the 380 kV network where there is more than a factor 10 between maximum values and mean values is particularly relevant. Knowing that epidemiological studies are based on long term exposure, if reference levels lower than the ICNIRP (1998) values were proposed by international bodies, they should also be given in terms of long term average values such as the yearly average or the yearly based 95 percentiles described in the present report.

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9 ± confidence limits