An evaluation of magnetically induced current density in human's body, based on measurements conducted in a High Voltage Center of 150/20kV

A.A.P.Paraskevopoulos, P.D.Bourkas,.C.G.Karagiannopoulos

Abstract- **In this paper the magnetic induction measurements recorded in a high voltage center are presented and an evaluation regarding magnetically induced current density is provided. Those measurements were carried out in various positions into the high voltage center and the implications of these results are also discussed. The total of all recorded measurements indicate that magnetic field values and the calculated current density are lower than the internationally accepted reference limits.**

I. INTRODUCTION

Human cells are known to degenerate when exposed to temperatures over 42 ºC and to ionizing radiation. It should be noted, however, that effects (mostly thermal) are also caused by non-ionizing radiation. For this reason, the World Health Organization (WHO) has adopted reference limits concerning human exposure to electric and magnetic fields. These limits vary according to the electric and magnetic field frequencies. For frequencies of 50 and 60 Hz employed in energy networks, the limits are: *E= 10kV/m, B= 500μT for professional personnel, E= 5kV/m, B= 100μT for the general population* [1, 2].Moreover for direct established health effects, WHO has adopted some basic restrictions depending upon the frequency of the field. For low frequencies (up to 10MHz), basic restrictions are provided on current density J. Especially in the range of 4Hz to 1kHz, the limits are:
J= 10mA/m^2 for professional personnel, J= 2mA/m^2 for general population
The limits designation was undertaken by the International Radiation Protection Association (IRPA), along with the International Commission of Non-Ionizing Radiation Protection (ICNIRP) who dealt especially with the non-ionizing radiation limits. The WHO recommends the reference limits set by IRPA and ICNIRP [3] to the international community and these reference limits have already been adopted by several states, including Greece [4]. The reference limits for professional personnel differ from those for the general population, since the professional is exposed under known conditions and being aware of potential risk takes appropriate precautions [1].

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A. A. P. Paraskevopoulos is with the National Technical University of Athens, 9 Heroon Polytechniou str, 15780, Zografou, Athens, Greece (corresponding author to provide phone: +302107721628; fax: +302107722581; e-mail: apostolisparaskevopoulos@hotmail.com).
P. D. Bourkas, is with the National Technical University of Athens (e-mail: pbourkas@central.ntua.gr).
C. G. Karagiannopoulos is with the National Technical University of Athens (e-mail: ckarag@central.ntua.gr).

Possible effects can appear in locations where electromagnetic field values are greater than the safety limits. However, in the electric power transmission and distribution networks, the magnetic induction and electrical strength values recorded near locations accessible to the public are lower than safety limits [5, 6, 7, 8].
This paper includes magnetic field measurements in various positions of a high voltage center (*H.V.C*) of 150/20kV. The H.V.C belongs to the electrical power transmission network of Athens-Greece.
The results are compared to internationally accepted limits. Furthermore a current density calculation in case of a human's presence is provided, following by drawing conclusions.

II. MEASUREMENT PROCEDURE

Magnetic induction B measurements were taken with an instrument capable for operation in an area of 4mG–120G (0,4μT-12mT) and for frequencies of 40–800Hz. The instrument in question is isotropic [5, 9] with three sensors, one for each of the orthogonal axes x, y, z (see Fig. 1). The three sensor practice, is the preferred instrumentation method, because most fields that are encountered have a linear polarization vector whose direction is unknown, or the polarization is elliptical. Therefore, field determination could be done by measuring the three orthogonal components. The recorded reading is an rms value. Each of the x, y, z sensors measures a B_x, B_y, B_z value, while the final reading of the instrument derives from the relation [5]:

$$B = \sqrt{B_x{}^2 + B_y{}^2 + B_z{}^2} \qquad (1)$$

The instrument was calibrated in order to take readings every 5sec. Calibration of static magnetic fields was performed with standard, commercially available permanent magnets of known strength.[5] The relative position of the instrument with respect to the ground was approximately 1.5m, in compliance with specifications [4,10,11].
The values recorded were the highest the instrument registered each time for a certain position. Essentially, measurements were recorded according to the general arrangement (layout) illustrated in Fig. 2.

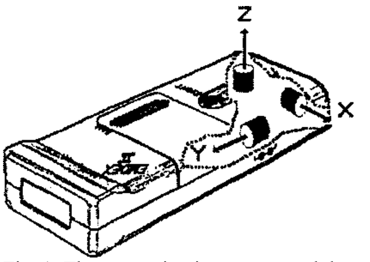

Fig. 1: The measuring instrument and the arrangement of the 3 magnetic field sensors. This instrument is suitable for magnetic induction 4mG-120G (0,4μT-12mT) and for frequencies 40-800Hz.

This figure shows 150kV cubicles (A), 150/20 kV transformers area (B), 20kV cubicles (C), other locations (D)and the area surrounding the substation (E). Under the label (D), areas without power system components (e. g without transformers, cables, busbars etc) as the stairwells and the groundfloor, are considered. .
The measurement performance demonstrated that H.V.C rooms are magnetically inhomogeneous and they have a variety of magnetic induction values depending on instruments position. Otherwise, only one reading would sufficiently describe every area. Hence an area was divided into smaller sections and thus more than one measurement was taken.
If, for instance, the measurements taken in one area are more or less the same regardless of the position of the instrument, then that area is considered a single one (magnetically homogenous area), is not divided into subsections and only one measurement is recorded. On the other hand, if in that same area changing the instrument's position has a significant interference on the measurements, which now vary (magnetically inhomogeneous area), then the area is divided into subsections and separate measurements are recorded.

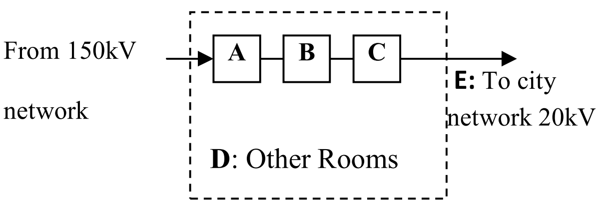

Fig. 2: Substations layout referred to the examined H.V.Cs'. (A) 150kV Cells, (B) Transformers 150/20kV, (C) 20kV Cells, (D) Other rooms, (E) Area surrounding the substation

The number of subsections depends on the magnetic induction "sources", located in a room, (viz electrical equipments like cables, switchboards, busbars, transformers). For example, area A can be divided into two sections: the cables section and the switchboard cubicles section. Furthermore, measurements can be recorded at a variety of distances in every subsection. In this way a large number of measurements can be taken for a specific section.

The criteria by which a position was selected for measurement in a subsection were its accessibility and its relative closeness to electrical equipments (e.g cables, switchboards, busbars and transformers).

III. RESULTS PRESENTATION

The measurements presented below are compared to the ICNIRP reference limits [1], as outlined in §1 (Introduction).The magnetic induction measurement unit used is μT.
Table I is an analysis of all measurements taken from the H.V.C and provides a comparison to the reference limits (*see §1*).
Under the label "Substation Areas" and "Room subsections", the instruments location is indicated, whereas the distance from a magnetic field source (e.g Cables, transformers, busbars, switchboards) is given in a separate column. Whenever the magnetic field source was not obvious (i.e background magnetic fields) such as for stairwell, groundfloor and Buildings entrance, magnetic induction maximum recorded values were obtained from several positions. Hence those cases, in Table I, indicated as N/A (Not Applicable) concerning distance.
All magnetic induction measurements are presented in its magnitude (μT), and in separate columns as percentages % of ICNIRP's reference limits, viz.

$$\text{General population ICNIRP limit \%} = \frac{B}{100} \times 100\% \quad (2a)$$

$$\text{Prof. personnel ICNIRP limit \%} = \frac{B}{500} \times 100\% \quad (2b)$$

Where B is the measured magnetic induction and the denominator numbers are the respective reference limits
As previously described, every area –as shown in Fig. 2– can be divided into subsections with 4 measurements taken for area A, 5 measurements for area B, 3 measurements for area E and 2 measurements for areas C and D. In total, 16 measurements were recorded.
The maximum value recorded for each area of the specific Substation, is presented in Table II. For example, in area A this will be the maximum value from {38μT, 17μT, 6μT, 1μT}, i.e. 38μT. The same applies in the other areas. This maximum value is then used for the evaluation of the respective induced current density for the specific area

IV. CURRENT DENSITY EVALUATION

For low frequency fields, several computational models have been developed for deriving current density values. A simple approach treats the volume of the human body as if it were made up of concentric rings normal to the direction of the field, as illustrated in Fig. 3. In this picture, the field is assumed to be oriented along the long axis of the body.

Substation Areas[a]	Rooms-Subsections	Distance (m)	B (μT)	ICNIRP limit General population %	ICNIRP limit Professional personnel %
A	Cables 150kV	0.7	38	38	7.6
	Cables 150kV	1	17	17	3.4
	Cables 150kV	2	6	6	1.2
	Switchboard Cells 150kV	1	1	1	0.2
B	Transformer terminals 150kV	3	2,2	2,2	0.44
	Transformer tank	1	0,5	0,5	0,1
	In contact with the Transformer tank	0,1	0,5	0,5	0,1
	Transformer coolers	0,1	2	2	0,4
	External area of the Transformers room	7[b]	0,1	0,1	0,02
C	Cables 20kV	0,1	5	5	1
	Cables Departure-Underground tunnel	2	0,9	0,9	0,18
D	Stairwell	N/A[c]	0,1	0,1	0,02
	Groundfloor	N/A[c]	0,5	0,5	0,1
E	External ground floor room	N/A[c]	0,15	0,15	0,03
	Buildings Entrance	N/A[c]	0,5	0,5	0,1
	Area surrounding the substation	10	0.3	0.3	0.06

Table I: Analytically all the measurements taken in all Substation rooms and comparison to the reference limits.
a: as in Fig. 2, b: Distance from transformer, c: Measurements taken in several positions regarding areas without power system components (e. g cables, transformers etc)

Substation Areas[a]	B (μT)	ICNIRP limit General population %	ICNIRP limit Professional personnel %
A	38	38	7.6
B	2,2	2,2	0,44
C	5	5	1
D	0.5	0.5	0.1
E	0.5	0.5	0.1

Table II: Magnetic induction maximum values sort by substation area and compare to the reference limits. a: as in Fig. 2

The magnetic field induces an E-field within the body, having roughly circular paths, as indicated in the Fig.3. The induced E-field, in turn, produces circulating eddy currents, which follow the path of the electric field in a medium of homogeneous conductivity [1, 5, 12]. In accordance with Faraday's law the internally induced electric field E is related to the time rate of change of flux density B by

$$\oint_c E dl = -\frac{\partial}{\partial t}\iint B ds \qquad (3)$$

The first integral is taken over a closed path, and ds is the element of area normal to the direction of B. If B is uniform over the region inside a closed path of radius r, the induced electric field strength calculated from (3) is:

$$E = -\frac{r}{2}\frac{dB}{dt} \qquad (4)$$

where the direction of the induced E-field is along the circumference of the circle. In some applications the magnetic field varies as $B=B_0\cos 2\pi ft$ and (4) becomes

$$E(t) = (r\pi f B_0)\sin 2\pi ft \qquad (5a)$$

Where the term in parenthesis is the peak induced E-field during the sinusoidal cycle, and B_0 is the peak magnetic field. Frequently, calculations for sinusoidal magnetic fields express only the magnitude term in (5), leaving off the cosine term [12]:

$$E = r\pi f B \qquad (5b)$$

where both E, B are expressed in rms values

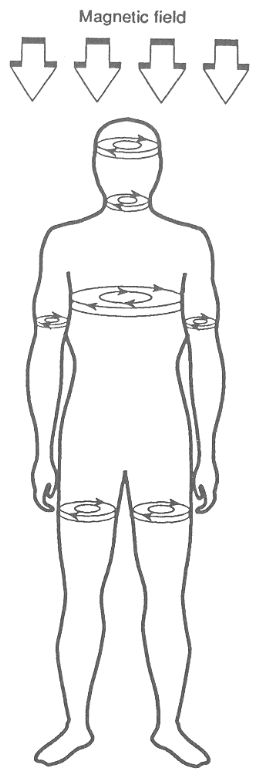

Figure 3: Distribution of internally induced electric fields from whole body exposure to time varying magnetic field.

For induction in a concentric ring model, such as that shown in Fig. 3, (4) suggests that the outermost rings would have the greatest E-field strengths. According to this simple model the maximum E-field for whole body exposure would be computed from (4) with r being the maximum circle radius that can be drawn on the body in a plane perpendicular to B. The current density, J, is related to the induced E-field by the conductivity of the medium, σ, in accordance with Ohm's law: J=σE, where combining the magnitude term from (5a) yields [1, 12]:

$J = \sigma\pi rfB$ (6)

Both J and B are expressed in rms values. For induction in living subjects, calculation of the current distribution is complicated by the widely differing conductivities of various body components (muscle, bone, blood, vessels, fat, etc). However, an average body conductivity of 0,2S/m [1, 5, 12], can be assumed for a 50Hz frequency. Moreover considering the human torso of a large person with an external radius of 0.2m [12], (6) becomes:

$J = 2\pi B$ (7a), or

$J \approx 4{,}44B_0$ (7b)

The above equations are valid for frequencies up to 10kHz, since the average conductivity remains practically the same (0,2S/m) [5]. For frequencies and torso radius different than previously stated, the relation (7a) could be modified to:

$J = 2\pi B(r/0{,}2)(f/50)$ (8)

where radius r in m, frequency f in Hz (<10kHz).

A similar equation, in case of 50Hz, r=0,2m can be derived for E:

$E= 10\pi B$ (9)

For frequencies and torso radius different than previously stated the relation (9) could be changed to:

$E= 10\pi B(r/0{,}2)(f/50)$ (10)

where radius r in m, frequency f in Hz (<10kHz).

Considering (7a) and taken into account magnetic flux densities by measurements such as previously described (III Results presentation) an evaluation of current densities can be derived. Taken into account the maximum registered measurements from Table II, and (7a), (9), the following data can be obtained:

Substation Areas[a]	B (μT)	Induced El.Field E (μV/m)	Induced Current Density J (μA/m^2)
A	38	1194	239
B	2,2	69	14
C	5	157	31
D	0.5	16	3
E	0.5	16	3

Table III: Magnetic Induction maximum values sort by substation area, the respective induced Electric Field and the induced Current Density
a: as in Fig. 2
Frequency f=50Hz, torso radius r=0,2m, average body conductivity σ= 0,2 S/m

V. DISCUSSION

By the measurements cited above and the current density's calculation, a comparison with the internationally accepted values (see §I) concerning exposure to low frequency electric and magnetic fields can be done.

For the investigated H.V.C, the highest magnetic field value appears in area A and equals 38μT (see Tables I and II). The respective current density yields 239μA/m^2= 0.239mA/m^2 (see Table III). The above can be summarized in the following Table IV:

Reference value	B (μT)	J (mA/m^2)
Maximum Measured/Calculated value in the H.V.C	38	0.239
ICNIRP general population limit	100	2
ICNIRP occupational personnel limit	500	10

Table IV: Maximum measured magnetic induction and the calculated current density into human's body, together with the ICNIRP reference limits (i.e basic restrictions) for frequency 50Hz. All the above are in rms values.

Even this maximum value for the whole substation is lower than the reference limit that applies not only for professional personnel, but also for the general population (see §I Introduction). On the other hand in areas with no electrical activity such as the stairwell, the magnetic field values remain at the same very low level, (see Tables I, II, III-D). This negligible magnetic field can not be located accurately. A possible explanation to this background values could be the dispersion from several magnetic fields e. g the next room cables, or other neighboring electrical equipments. Measurements from the area surrounding the Substation indicate that the magnetic field values are almost non-existent (see Tables I, II, III-E). Furthermore it could be mentioned that since the maximum recorded values were in this range of a few decades of μT, registering of the minimum values has not practical interest because at most cases they were close to zero, or in other words close to the instrument scale lower limit (see §III)

Generally, all the taken measurements are lower than the specified limits both for the general population and the professional [1, 2], a conclusion reached in other similar papers [5, 6, 7, 8].

Another conclusion stemming from the measurements is the further decrease seen in the magnetic field as distance increases. In particular, as shown in Table I when examining the measurements, taken in area A (150kV) near the cables, it is noted that the values decrease as the distance increase.

Further decrease can be caused by other factors as well as distance such as that of "magnetic immunity". For instance, among the recorded measurements, it can be seen that fairly low values occur when in contact with the transformer (TF) tank (area B, Table I), as well as near the switchboard cubicles (area A, Table I). Although these measurements were taken when in contact, i.e. zero distance, the magnetic field values were exceptionally low. This is due to the phenomenon of magnetic immunity, which is equivalent to "Faraday's cage".

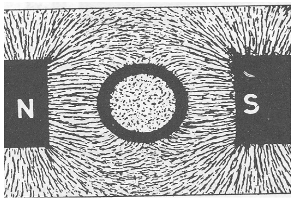

Fig. 4: Magnetic shield's (immunity) general principle Magnetic lines, showing that inside the iron ring, the magnetic whirles does not enter and the magnetic field does not exist

The general principle of magnetic immunity is shown in the Fig. 4: The metal tank of a TF as well as the metal casing of a switchboard can be characterized as simple cases of immunity, where –as proven by the measurements (Table I) the magnetic field does not disperse outwards and instrument measurements are close to zero.

If the tank or casing were not made of a metallic material capable of magnetization, immunity would not exist, the magnetic lines would disperse unimpeded, and therefore an increase in magnetic field values measured in this paper would be expected. This could happen, for instance, in the case of a dry type TF without a tank or in the case of switchboards in outdoor constructions.

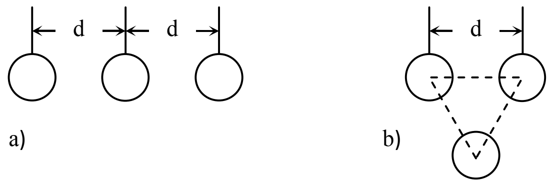

Fig. 5: Three conductors separated by distance d in a) side by side arrangement, b) triangular arrangement

Apart from the aforementioned factors, measurements could also be affected by the conductor arrangement. A triangular conductor arrangement is more advantageous in terms of magnetism than three conductors side-by-side, separated by distance d (Fig. 5), as substantiated not only by theory [13, 14], but also by measurements of three-phase arrangements [15]. Hence in Substations where the triangular conductor arrangement or the 3-core cables is employed, low magnetic induction values should be expected. On the other hand, the same contemplation entails that the single-core cables (see Fig.5 a)) appearing to disperse higher magnetic induction values. Those remarks concerning Cable arrangements could give a possible explanation for the maximum registered value in area (A) (see Tables I, II III) which is equipped with single core cables (paper-oil in low pressure) [13]. In the same area, regarding to the switchboards, measurements are lower since the 150kV cubicles contain SF6 gas into iron pipes encasing the busbars in triangular arrangement (see Fig 5 b)). Both the arrangement and the metallic enclosure, render a sufficient magnetic field restriction. The same applies –as far as the arrangement is concerned- to area (C), -20kV side- in which the 3-core cables (YHSY type) is employed [13], and the magnetic induction values remain to the same low level.

Those futures render to this substation an effective magnetic immunity, contributing to the fact that the taken measurements are below limits. Additional techniques, like the configuration of conductors in twisted pair wire of minimum self-induction (Bifilar coil) [16], could limit the magnetic field still further. However, this is not considered necessary for the Substation examined.

VI. CONCLUSION

In general, it can be stated that the measured values are significantly lower than the internationally accepted reference limits. Moreover the estimated induced current density does not exceed the adopted basic restrictions. Given that tests were conducted in a typical H.V.C located in the city center of Athens, the conclusion that could be drawn is in the case of Substations of the electric power network, the magnetic induction measurements are anticipated to be lower than internationally accepted limits, and thus extra measures for magnetic field containment are not required. Certain conclusions have stemmed from analysis of the measurements, which can also be theoretically substantiated. In particular, further magnetic field decrease was noticed with the increase of distance, the use of metallic (magnetic) materials and the use of triangular arrangement for conductors.

These conclusions could prove useful in cases where the magnetic fields exceed the limits. It is considered useful to conduct this type of assessment in other areas as well, since every Substation is unique in terms of features including, among others, power, voltage, architecture, equipment and apparatus. Besides the prescribed measurement procedure is general and provides an *objective* indication concerning the so called "electromagnetic pollution" or "electrosmog". For the moment it is a way (possible the unique) to explore our artificial electromagnetic environment and to lead in notable conclusions. In any case, the particular behavior of each individual against an artificial electromagnetic field should be taken into consideration. The restrictions adopted by the WHO (ICNIRP limits) are precautionary measures not only to prevent well established health risks but also to give a protection against uncertain health risks. Thus it can be conducted that those measures minimize the possibilities of appearance of biological effects in humans. In this way the duty of an engineer-scientist is to investigate with measurements an environment and to see if they comply with the international accepted limits.

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