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Electromagnetic Pollution Assessment in Different Environments with Measurements and Modellings at Very Low Frequency

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Electromagnetic fields,
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Modeling

Abstract: A major factor of anxiety and speculation come from electromagnetic fields which represent one of the most common and fastest increasing environmental issues. The purpose of this work is to examine existing electric and magnetic fields' levels in a typical house and an office at very low frequency, and comparing the measurement results with the prior studies and also with the ICNIRP standard limits. This study also comprises the three phase conductors' electromagnetic fields analysis at a point. As a result, it is observed that the measured values are approaching to the calculated ones.

Ölçümler ve Modellemelerle birlikte Farklı Çevrelerde Çok Düşük Frekanslarda Elektromanyetik Kirlilik Değerlendirmesi

Anahtar Kelimeler
Elektromanyetik alanlar,
Maruziyet değerlendirmesi,
Standartlar,
Modelleme

Özet: Endişe ve spekülasyonların başlıca etkeni, en yaygın ve hızlı büyüyen çevresel sorunlardan birini temsil eden elektromanyetik alanlardan kaynaklanmaktadır. Bu çalışmanın amacı; çok düşük frekansta tipik bir ev ve ofiste elektik ve manyetik alanların mevcut seviyelerini, ölçüm sonuçlarını daha önce yapılan çalışmalarla ve ICNIRP standart sınır değerleriyle karşılaştırarak araştırmaktır. Bu çalışma ayrıca, tek bir noktada üç fazlı iletkenden üretilen elektromanyetik alanın analizini de içerir. Sonuç olarak, ölçülen değerlerin hesaplanan değerlere yakın olduğu gözlemlendi.

1. Introduction

In modern times, with the further development of modernization and industrialization, people begin to use universally the household appliances and office equipment such as TVs, faxes, PCs, printers, etc. which all cause an environmental pollution. This results in worrying concern regarding the safety of human beings and dependability of equipment in the electro-magnetically exposed environment.

Early studies on human body exposure to ELF and health risks were published in 1979 [1]. Milham [2] studied the mortality in workers who were exposed to electromagnetic field (EMF) associated with alternating current flowing in wires and powerlines. Later, cancer in childhood who was exposed to 60 Hz magnetic field and biological effects of EMFs were published [3 - 5]. Numerous studies have been conducted adverse biological and health effects of low-level non-ionizing radiation [6-12]. Latest study has been published in 2017 indicating that free radical damage explains the increased cancer risks associated with residential exposure to power lines, occupational exposure to extremely low frequency (ELF) and radio frequency (RF) transmitters [13]. In 1996, the World Health Organization (WHO) established the International EMF Project to address the health issues associated with exposure to EMF. The EMF Project is currently reviewing research results and conducting risk assessments of exposure to static and ELF electric and magnetic fields. In 2001, they announced that ELF magnetic fields were classified as possibly carcinogenic to humans [14].

Clinical studies on biological effects of EMF has indicated that being aware of the EMF levels are so critical. Studies of residential magnetic and electric fields have been done for instance by Kaune et al. [15] and by Silva et al. [16] in two selected offices only. EMFs associated with video display terminals (VDTs) at 150 offices and EM pollution in a typical Turkish house, hospital and plants have been measured in 1993 and in 1998, respectively [17, 18].

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Tong [19] has mentioned that indoor environmental problems are caused by both electronic products and decoration materials used in the buildings. He has initiated the idea of green dwellings to reduce the indoor pollution. Hajdarevic et al. [20] conducted measurements on personal exposures to EMF emitted from household appliances and office equipment to reveal that manufacturers have to specify reference levels of EMF and guidance for avoidance for risk of exposition of longer period of time. Similarly, in western of China, the current level of indoor electromagnetic radiation of randomly selected 118 household's living room is measured at different frequencies [21], in Alexandria [22], levels of exposure to EMF at home with the selected thirteen electrical appliances are measured, and Ibrahim et al. [23] choose Nigeria as a case study to assess the selected electric driven home/office appliances magnetic field exposure levels.

The increasing number of line-powered electronic equipment cause severe pollution in the power distribution system, mainly by producing distorted line currents and voltages. Redl et al. [24] and Lee et al. [25] have reviewed the various aspects of power-line pollution and electromagnetic interference (EMI) on computer monitors caused by current in cables, respectively. Dangerous region of the electromagnetic pollution caused by the electric fields around power line has been determined by Yougang et al. [26]. Electromagnetic pollution generated by power electronics equipment and its impact on the electromagnetic environment has been discussed in [27].

There are also many studies done in different regions of Turkey to point out the importance of EMF effects on human being. Magnetic fields of transformers in an apartment building in Küçükçekmece, İstanbul have been measured [28]. EMF values are studied in a selected school in Ankara [29]. Electric field values are evaluated for electrical public service vehicles in Trabzon, Turkey [30]. The exposure effect due to radio/TV transmitters are studied in the Black Sea region of Turkey [31].

In this paper, it is aimed to evaluate field levels of the most-used devices separately and identify their contribution to overall EMF levels. In Turkey, In the first part of the study, existing levels of electric and magnetic fields of a washing machine and electric water heater in the bathroom of a residence and a cathode ray tube (CRT) of computer monitors in an office are analyzed at very low frequency (VLF). The results are compared with theoretical studies. Due to customs agreement with Europe, Turkey is obligated to use ICNIRP standards. For that reason, the simulated results are also compared with ICNIRP safety standard limits. Furthermore, to analyze the effects of the cables, this paper also covers the EMF measurements on the electrical low voltage (LV) distribution in buildings ranging from an office, a tower and an aluminum factory, respectively.

2. Measuring Equipment

The EMF measurements were carried out with a ETS Lindgren Holaday EMF Measurement HI 3604 ELF Survey Meter and HI 3603 VDT/VLF Survey Meter. HI 3604 ELF Survey Meter is designed to evaluate both electric and magnetic fields associated with 50/60 Hz power lines, line powered equipment and appliances. It provides the engineer and health and safety professional with a sophisticated tool for accurate investigation of power frequency environments. The custom Liquid Crystal Display (LCD) display indicates in milliGauss, Gauss, V/m, and kV/m. A bar-graph analog indicator aids in quickly locating maximum field orientations and "hot spots". The detailed specification of the meter is given in Table 1.

Table 1. Specifications for HI 3604.

Frequency Range	30 – 2000 Hz
Frequency Response	± 0.5 dB (50-1000Hz) ± 2.0 dB (30-2000Hz)
Dynamic Range	0.2 mG – 20 G (Magnetic Fields) 1 V/m – 200 kV/m (Electric Fields)
Detection	Single Axis
Response	True RMS
Logging	On-Board, 112 Readings (max)
Environmental	10°C – 40°C 5% - 95% Humidity, Non-Condensing

HI 3603 VDT/VLF Radiation Measurement System is designed specifically to measure EM emissions produced by VDT's, computer monitors, television receivers and other devices using CRT's for information or data display. It is one of a family of measuring devices that covers a wide range of EMF measurement needs. The HI 3603 has two switch selectable sensors for measuring both electric and magnetic fields. The instrument capabilities include data logging, waveform output, full auto-ranging, and a custom LCD with a bar graph, as standard features. The detailed specification of HI 3603 is given in Table 2.

Table 2. Specifications for HI 3603.

Sensitivity	·Electric fields - 1 - 1999 V/m ·Magnetic fields - 1 - 1999 mA/m
Frequency Response	Electric fields: ·±0.5 dB, 10 kHz to 100 kHz ·+0.5/-2 dB, 2 kHz to 300 kHz Magnetic fields: ·±0.5 dB, 12 kHz to 200 kHz ·+0.5/-2dB, 8 kHz to 300 kHz
Temperature Range	20°F - 105°F (-10°C - 40°C)
Power	Two (2) nine-volt alkaline batteries (NEDA 1604A, Duracell MN1604, or equal)

3. Measurements and Calculations in the Bathroom of the Residence

Many different measurement and analysis techniques were studied in the literature to specify the electric and magnetic fields' sources in broadcasting systems and dwellings [15-18]. In this part of the study, electric and magnetic fields are calculated and comparisons are done with the measured results.

3.1. Method

In the bathroom, spatial variations of electric and magnetic fields of a washing machine and an electric water heater were examined at ELF using the radiation meter HI-3604.

Vertical and horizontal electric and magnetic field measurements were performed in the bathroom of the residence to identify the source. To set up fields' surface plots properly, measurements were carried out in an adequate number of points.

The meter was held one meter above the floor and placed in the center of the probe. Both field strengths of appliances at various distances were measured. In the horizontal axes, the measurement interval was taken to be 20 cm. At first, in order to measure the background noise level, the machines were switched off. Later, to detect individual influences of each appliance, the machines were switched on one by one. At last, the measurements were repeated when both of the appliances were in their operating mode.

3.2. Measurements

Background noise levels for magnetic and electric fields were measured to be 85 mA/m and 8.9 V/m, respectively. Spatial variation of 50 Hz magnetic field levels of the washing machine and the electric water heater while they were both in operating mode is depicted in Figure 1. In Figure 1, the electric water heater was placed at the top left corner was, and the washing machine was at the bottom right corner.

It is clearly seen in Figure 1 that due to the current flowing on the mains cable, internal circuitry, and heater of both appliances caused to increase the magnetic field levels when they were both in operating mode.

On the other hand, when both appliances were in operating mode, it was observed that the electric field level of the washing machine was rising while level of the electric water heater was diminishing. Decreasing in the level may be due to the perfect grounding of the heater. Likewise, decreasing in the levels of electric field of washing machine occurred in the heating mode of the appliance.

3.3. Calculations

The electric water heater and the washing machine were modeled as a small current loop on which a dc current flows. They were located 35 cm above the measurement plane. So, the z coordinate of the measurement locations were taken as -35 cm during calculations. In order to find the best matching results, the average currents of both appliances were calculated to be 1.5 A. 50 Hz magnetic field was calculated by using the equation that is derived from the Biot Savart law [32]. Calculated results are given in Figure 2.

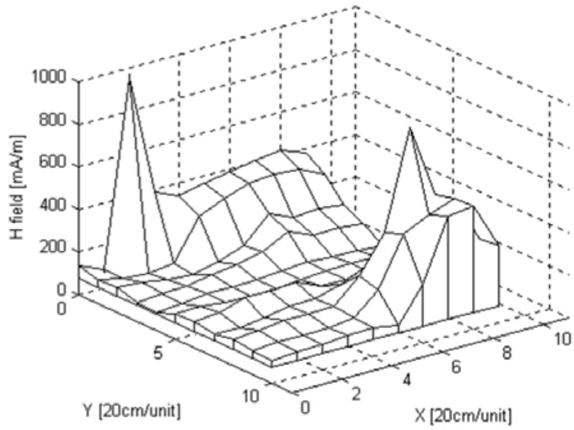

Figure 1. Surface plot of magnetic fields in the bathroom

$$H_{\phi} = \frac{I}{4\pi\rho}\left(\sin\alpha_2 - \sin\alpha_1\right) \tag{1}$$

where I is the current, ρ is the distance, $\alpha_{1,2}$ is the angles to the current for the electric water heater and the washing machine, respectively. Measured and calculated magnetic field results reasonably acceptable by keeping the assumptions in mind. At the top right corner of Figure 2, there were hot and cold water pipes which may be an alternative ground path. However, their effects cannot be seen in the calculated results.

4. Measurements and Calculations in the Office

In this part, EMF levels at VLF caused by the CRT of computer monitors were measured in an office as done in the literature [17]. Calculations of electric and magnetic fields in the office are given and also compared with the measured results.

4.1. Method

The measurements at VLF were conducted using the field meter equipment. The meter was positioned one meter above the floor with the probe center at varying distances from the screen.

In the office, electric and magnetic field measurements of one PC with 14'' Orion CRT which had 800x600 resolution, 37.879 kHz horizontal deflection frequency, 60 Hz vertical deflection frequency, 40 MHz dot rate, and 6 MHz system clock frequency was carried out. Measurement interval in the horizontal plane was 10 cm. During the measurements, capital 'E' letter was on the whole screen; the adjustments of brightness and contrast were set up to full scale.

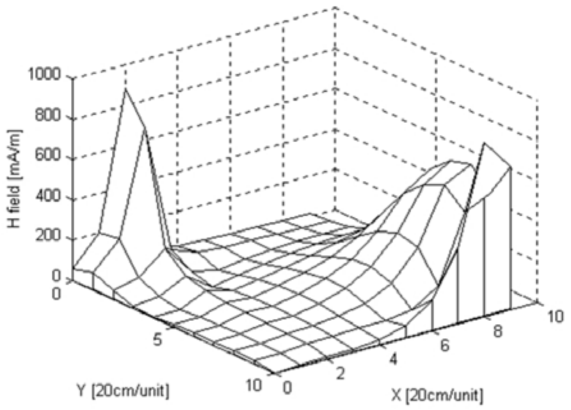

Figure 2. Calculated 50 Hz magnetic field for the bathroom of the residence

4.2. Measurements

The measured electric and magnetic fields' surface plots of 14" Orion CRT is depicted in Figure 3 and Figure 4, respectively. The maximum value for the total electric and magnetic fields in the VLF range are 4.91 V/m and 322 mA/m, respectively.

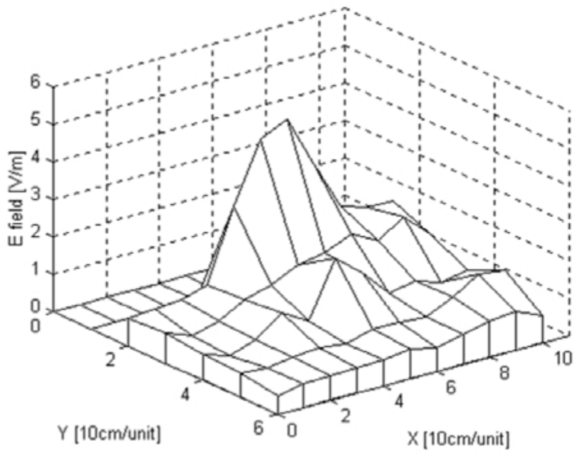

Figure 3. Measured surface plot of the electric field

At VLF, the mean value of the total magnetic field is 12 mA/m (15 nT). The measured electric and magnetic field strengths of 14" Orion CRT also complied with the limits defined in the ICNIRP regarding the human exposure to EMFs [33].

4.3. Calculations

It is acceptable to suppose that the electron beam's length in CRT, i.e., and equivalent current lines are much shorter than the wavelength of the frequencies of the system clock and the dot rate which are 6 MHz and 40 MHz, respectively [18]. Equivalent current line's length d was chosen to be 0.2 m in the calculations, and it satisfied the $d << \lambda$ condition, when λ (wavelength) was chosen to be 50 m.

In addition, the current in the electron beam was approximated to 1.5 A for the magnetic field, and 1 mA for the electric field [32]. Calculations were performed in the laboratory in front of the PC by using Hayt's data and it was observed that the results were complying with the measurements'.

The slightly difference between measured and calculated results were occurred not only because

aluminized screen and graphite film were lack of the shielding effect in the CRT, but also radiation meter, HI-3603, had ±1 dB error for the principal VDT flyback circuit emissions, and +0.5-2 dB error in 9 to 300 kHz region.

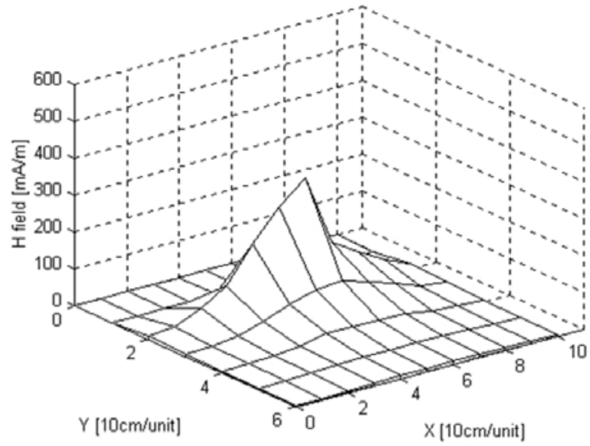

Figure 4. Measured surface plot of the magnetic field

5. Measurements and Calculations in the Factory

The measurements were performed in the aluminum factory in Gebze-Kocaeli. The factory had numbers of offices and two main production areas. The measurements were done in one of the production areas where the engine room, the main panel with the control unit, and the production line were existing.

5.1. Measurement results

It wasn't safe to measure the magnetic and electric fields in the production area, because a hot press machine was located next to the main panel. Lots of measurements had done in the engine room, next to the main panel, and around the production line in order to obtain surface plots. The 3D view of magnetic field around the production line is depicted in Figure 5.

In summary, the measurements for electric and magnetic fields can be summarized as follows:

- Engine room: Electric Field → 1.48 V/m and 30.6 V/m, Magnetic Field →330 mA/m and 2.26 A/m
- Near main panel: Electric Field → 1.40 V/m and 180 V/m, Magnetic Field → 1.016 A/m and 322 A/m

- Around the production line: Electric Field → 1.38 V/m and 12.30 V/m, Magnetic Field → 20.8 mA/m and 850 mA/m.

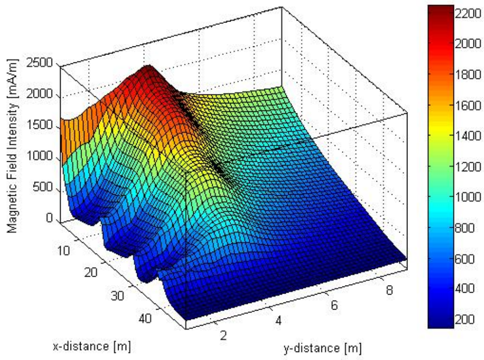

Figure 5. The 3D view of magnetic field around the production line (H [mA/m])

The maximum values for measured electric and magnetic field strengths in the factory are given in Table 3.

Table 3. Maximum field strengths and ICNIRP limitations.

	H (A/m)	E (V/m)
Main panel	322	180
Engine room	2.26	30.6
Production L	0.85	12.30
Occupational exposure L	400	10000
General exposure L	80	5000

5.2. Calculated values

In this section, the electric and magnetic fields were calculated theoretically according to the EMF formula given in [25]. Theoretical surface plot of magnetic field intensity around the production line is given in Figure 6.

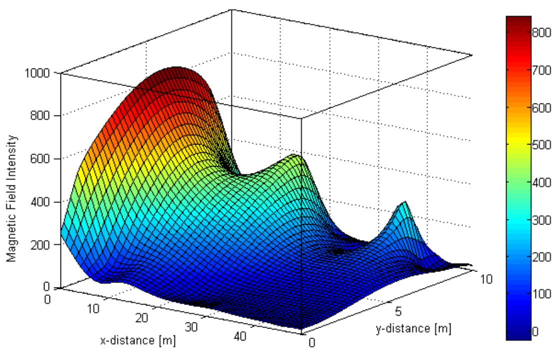

Figure 6. Theoretical surface plot of magnetic field intensity around the production line

When the measurement and theoretical results of magnetic fields in Figure 5 and Figure 6 are compared, it can be noted that there are some reasons that these two values does not match one-to-one. Firstly, there were plenty of cables in which currents were flowing to the reference sources. Secondly, the electricity distribution plan of the factory was not available; therefore the only information source about the electrical appliances was the electrical engineer of the factory. Thirdly, the production place had a very high interior ceiling, so examining the effect of fluorescent lights and other cables close to the ceiling was not possible. However, the measured and calculated values for maximum electric field strengths are close to each other (14.1 V/m calculated and 12.30 V/m measured), but the calculated value for maximum magnetic field strength is 2040 mA/m whereas the measured value is 850 mA/m.

6. Analysis of the EMFs Generated by Three Phase Conductors

In the tower blocks, LV lines containing bus bars and conductors in which the high currents are flowing are used. It has to be noted that, not only the level of the electric field generated by high currents, but also the level of the magnetic field generated by the complex equipment are also needed to be measured.

This part of the study examines the analysis of the EMFs generated by three phase conductors which are positioned at different distances. For this aim, by changing cable positions, to analyze the magnetic field values, a realistic laboratory model developed and the measurements were carried out in air, inside the model wall and compared with the calculated values.

6.1. Calculations

A theoretical study that explains the variation in the electromagnetic fields at a specified distance from the cables will be explained in this section. The sinusoidal currents flowing from the cables are in Figure 7. The cables are equally spaced and carrying balanced three-phase sinusoidal currents given as follows.

$$\begin{aligned} I_R &= I_R\cos(\omega t) \\ I_S &= I_S\cos(\omega t + 120^0) \\ I_T &= I_T\cos(\omega t + 120^0) \end{aligned} \tag{2}$$

The magnetic field generated at each conductor current at point P will be;

$$H=I_M/(2\pi r) \tag{3}$$

where I_M is the maximum current of the cable and r is the distance between the conductor and P. Also α is determined as follows:

$$\alpha=\tan^{-1}(h/L) \tag{4}$$

The magnetic fields for the each phase will be:

$$H_R= I_{RM} / (2\pi L_r);\ H_s = I_{SM} / 2\pi L;\ H_{TM} = I_T / 2\pi L_r \tag{5}$$

where L_r is the distance between the conductor R and P, and also L is the distance between S conductor and P.

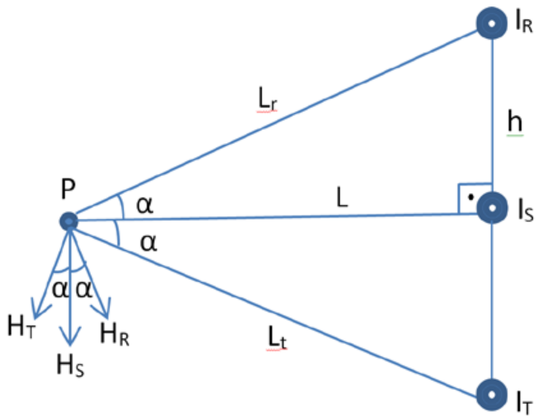

Figure 7. Vertical magnetic field at P point

The vertical components of the magnetic field in Figure 7 will be :

$$\begin{aligned} A &= H_S \cos 120^0 + H_T \cos 120° \cos\alpha + H_R \cos\alpha \\ B &= H_S \sin 120^0 - H_T \sin 120^0 \cos\alpha \end{aligned} \quad (6)$$

The total vertical magnetic field for P point is in the following:

$$H_v = (A^2+B^2)^{1/2} \quad (7)$$

Similarly, the horizontal components of the magnetic field in Figure 8 will be :

$$\begin{aligned} C &= H_R \sin\alpha - H_T \cos 120^0 \sin\alpha \\ D &= H_T \sin 120^0 \sin\alpha \end{aligned} \quad (8)$$

The total horizontal magnetic field for P point is in the following:

$$H_h = (C^2+D^2)^{1/2} \quad (9)$$

In conclusion, the total magnetic field in the P point is in the following:

$$H_P = \sqrt{H_V^2 + H_h^2} \quad (10)$$

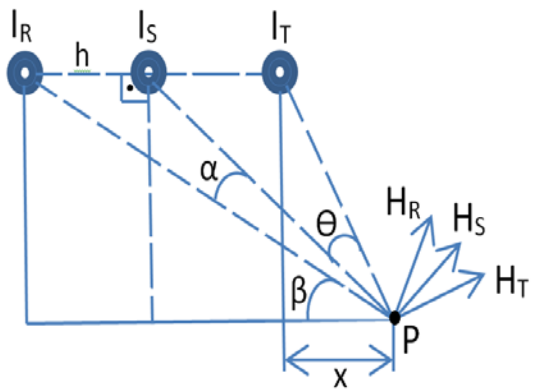

Figure 8. Horizontal magnetic field at P point

6.2 Laboratory model

To examine the EMF generated in the buildings, a movable plate made with rectangular iron rod having a height of 2.3 m was designed (Figure 9). One of the three cored 120 mm² PVC isolated cables were used in the laboratory model. The distance between the cables could be arranged by shifting the cables. The three phase currents up to 50 A were driven by the three-phase adjustable autotransformers. The magnetic field values were noted in air and inside the model wall with different distances in a range of 0.1 m to 3 m as the energy consumption was ascended to obtain higher current values.

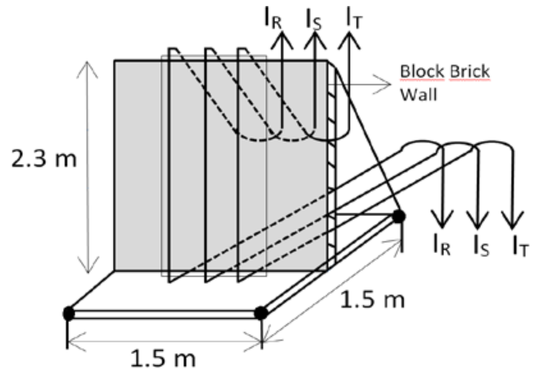

Figure 9. Perspective appearance of laboratory model

6.3. Results

Furthermore, PC monitors were positioned in front of the laboratory model. The influence between PC monitor and the cables were analyzed and the results were examined with varying distances of cables [8, 25].

Measured magnetic field in air and inside the model wall with the calculated values are shown in Figure 10 and in Figure 11 at distance 0.1 m and 0.4 m with 0.4 m of cable separation.

To diminish the measurement faults, it had to be certain that radiation meter's probe was used properly and there were not any live organisms between the device and the source. The calculated and the measurement values examined coincide with each other.

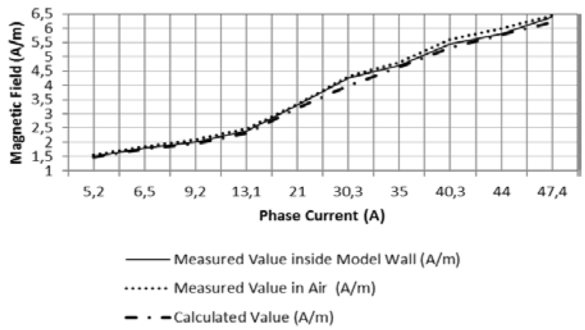

Figure 10. Magnetic fields values at 0.1 m with 0.4 m cable separation

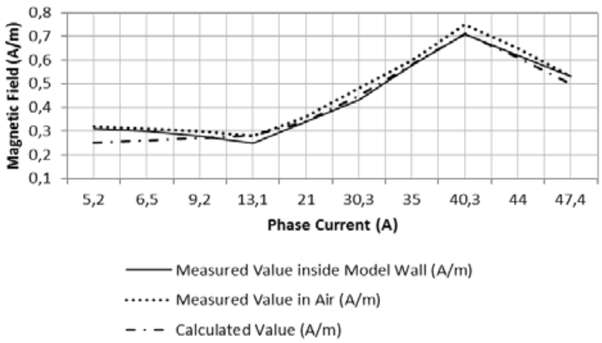

Figure 11. Magnetic fields values at 0.4 m with 0.4 m cable separation

7. Discussion and Conclusion

In this study, not only theoretical and experimental analysis, but also measurements at around hundred points on the laboratory model have been performed.

All the measurements done in the bathroom of the residence, office, buildings and the factory are compared with ICNIRP safety limit values. Electric field limits (r.m.s.) defined in ICNIRP regarding the human exposure to electromagnetic fields is 30 kV/m for workers, and 10 kV/m for general public for low frequency (0 Hz to 10 kHz) [33]. Magnetic field limit (r.m.s.) defined in the standard is 1.6 mT (1280 A/m) for workers, and 0.64 mT (512 A/m) for general public.

To begin with, in the bathroom of the residence, EMF generated by a washing machine and an electric water heater appliances were examined. The measured maximum electric and magnetic field strengths of both appliances while they were in their operating mode were 28 V/m and 950 mA/m, respectively. It is clearly seen that the results are under the ICNIRP limit values. There was a slight difference in between the measured and the calculated results which might be caused by negligence of the thickness of the small current loop's wire used in calculations.

Next, EMF levels of 14" Orion CRT computer monitors were measured in an office at VLF. Although the measured electric and magnetic field strengths of CRT were under the limits defined in the ICNIRP, the calculated field levels differ from the measured results by a factor of 1.2 for the electric field, and by a which was considerably acceptable occurred because the radiation meter was highly sensitive to the proximity of the people. There were also other effects that made this difference such as 40 MHz dot rate in the CRT, screen flicker effects on PC and the reflection from the walls of the room. Contribution of these sources may cause different field levels than those presented in this section.

Finally, EMF levels were examined in the aluminum factory. It was observed that the measured values were not exceeding ICNIRP occupational exposure limits. Main panel measurements were performed when the main panel was not operating with full capacity; such that it was flowing 500A of 800A maximum level. If it was operating with maximum capacity, the magnetic field intensity could be higher than exposure limits.

In conclusion, careful planning in placing the electrical equipment in the buildings and offices is vital. This means that the technical specification of the equipment used in the buildings, the location of electrical and high power transmission lines have to be taken into account to enable safety EMF levels. It is our belief that our study will aid the society to strengthen the protection consciousness and lead the young academicians in their future studies about the ELF measurements.

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