Measurements of Electric and Magnetic Fields Due to the Operation of Indoor Power Distribution Substations

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Abstract—In this paper, the electric and magnetic fields with a frequency of 50 Hz, caused by the operation of indoor power distribution substations of 20/0.4 kV, are examined. First, the results of previous relevant research studies as well as the reference levels for safe general public and occupational exposure given in the guidelines of the International Commission on Non-Ionizing Radiation Protection are presented. Next, basic data for standardized indoor power distribution substations used in Greece, where the measurements have been carried out as well as a brief description of the field measurement instruments used are given. The results of the electric- and magnetic-field measurements in indoor power distribution substations of all the standardized nominal power ratings in the town of Xanthi, Greece, accompanied by relevant tables and diagrams follow. After the evaluation of these results, according to international guidelines, final conclusions are set out concerning safe public and occupational exposure to the above-mentioned fields.

Index Terms—Electric- and magnetic-field measurements, extremely low frequencies, indoor power distribution substations, safe public and occupational exposure.

I. INTRODUCTION

EXPOSURE to electromagnetic fields (EMFs) is not a new phenomenon. However, during the 20th century, environmental exposure to manmade EMFs has been steadily increasing as the growing demand for electricity, and ever-advancing technologies and changes in social behavior have created more and more artificial sources. While the enormous benefits of using electricity in everyday life and health care are unquestionable, during the past 20 years, the general public has become increasingly concerned about potential health hazards of exposure to electric and magnetic fields at extremely low frequencies (ELFs).

Since about 1980, these 50/60-Hz magnetic fields (and their frequency harmonics) have been suspected of causing various types of negative health effects. For instance, many people are concerned about the assumed relationship between the exposure to ELF EMFs and the increased risk of cancer. Internationally accepted scientific groups in [1]–[6] believe that the data are not sufficient to support the conclusion that power-frequency electric or magnetic fields in the workplace or at home cause cancer or lead to reproductive and developmental abnormalities or to learning and behavior problems. The most accurate

answer to the question “do ELF EMFs present a human health hazard?” is that numerous studies around the world have failed to produce technically convincing evidence of such a hazard. Although some health effects have been statistically related to ELF EMFs exposure, these effects are poorly understood and may exist only as statistical or scientific errors. The expert working groups prepared a report [7] that evaluates possible health effects from exposure to static and ELF EMFs. The authors of [1], [8], and [9] identify gaps in knowledge that require more research to improve health risk assessments, including statistical, epidemiological, experimental, laboratory, and other studies.

Generally accepted guidelines have been established for safe public and occupational exposure to power-frequency EMFs. The reference levels for general public exposure to 50/60-Hz electric and magnetic fields are, according to the ICNIRP guidelines [2] are as follows:

- for the electric field strength, $E < 5$ kV/m;
- for the magnetic field strength, $H < 80$ A/m;
- for the magnetic flux density, $B < 100 \mu\text{T}$.

These levels for occupational exposure are:

- for the electric field strength, $E < 10$ kV/m;
- for the magnetic field strength, $H < 400$ A/m;
- for the magnetic flux density, $B < 500 \mu\text{T}$.

Various researchers have treated, at great length, the measurement and model elaboration for the determination of the electric and magnetic fields generated by transmission lines, particularly by lines that cross residential areas. Other researchers have considered it convenient to characterize the EMF inside residences. But there is little data available in the literature dealing with EMF measurements and calculations in power stations and substations of various voltage levels. Specifically in [10], measurements of magnetic-field profiles around a specific substation have verified that adding a substation under an existing transmission line does not increase the magnetic field beyond the substation boundary. In [11], magnetic fields in a 187/66-kV substation are calculated for various current conditions and described in terms of contour plots. In [12], the magnetic fields generated by a distribution substation were measured and calculated, based on a computer model that takes into account currents in the grounding systems, distribution feeder neutrals, overhead ground wires, and induced currents in equipment structures and ground grid loops. In [13], measurements of the field strength in a combined cycle gas turbine power station are described, for both the steady-state situation and the process of starting the generator. The measurement results are compared to the established safe exposure limits. In

Manuscript received March 8, 2004; revised August 24, 2004. Paper no. TPWRD-00115-2004.

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Digital Object Identifier 10.1109/TPWRD.2005.848659

[14], an integral approach method is used for magnetic-field measurements in a 69-kV SF₆ gas-insulated substation in Taiwan. Reference [15] shows the results of an initial series of measurements carried out to determine the levels of EMFs in various indoor and outdoor environments (power transmission lines, power cables, substations, domestic electrical equipment) associated with occupational and residential exposure. Finally, in [16] and [17], shielding is proposed for an in-house secondary substation in Sweden in order to mitigate the magnetic field. This shielding really reduces the field values compared to the values measured before the shielding installation. We must, however, point out that these values are already far below today's accepted safe exposure limits.

This paper examines the ELF fields caused by the operation of indoor power distribution substations 20/0.4 kV. The number of substations and their close proximity to homes and workplaces causes anxiety among people over possible health hazards from the resultant electric and magnetic fields. So, first, basic data are given for standardized indoor power distribution substations used in Greece, where the field measurements were made, and a brief description of the instruments used to make the measurements is provided. Indicative results, accompanied by relevant tables and diagrams, follow for the electric- and magnetic-field measurements in an indoor power distribution substation of nominal power 2×630 kVA in the town of Xanthi, Greece. The results of relative measurements in all of the types of standardized indoor power distribution substations are evaluated according to international guidelines. Final conclusions are set out concerning safe public and occupational exposure to electric and magnetic fields caused by the operation of such substations.

II. INDOOR POWER DISTRIBUTION SUBSTATIONS

In cities where many buildings are in close proximity to each other, the load density is high. Therefore, indoor power distribution substations, which usually have high nominal power, are located in the basement or the ground floor of buildings. It is easy to find such rooms in buildings. However, where the load density is small, such as in regional areas close to a city, pole-type power distribution transformers are used. Even when a cheap indoor room is available, it is preferable, in the second case, to divide the load between more than one pole-type substation instead of installing one big indoor power distribution substation in order to satisfy the "effective protective earthing condition." According to this condition, when a solid phase-to-neutral short-circuit occurs anywhere in the external network or in the consumer installation, the system protective devices have to interrupt the power supply within a finite time. This applies to low-voltage networks with the equipment frames connected to the neutral conductor. It protects people from dangerous touch voltages as determined in [18].

From an economic viewpoint, the real-estate purchase for the installation of an indoor power distribution substation is directly comparable to the cost of the two-pole construction needed in the case of a pole-type substation. But an indoor substation is burdened in addition with the costs of arranging the installation room (construction work, channels, doors, ventilation grids, etc.) and the costs of the requisite work (contract work cost and cost for the underground network materials). In conclusion, for technical

and aesthetic reasons as well as the impossibility of finding a place for a pole-type substation, there is often no option but to construct indoor power distribution substations within cities.

The standardized indoor power distribution substations of the Public Power Corporation (PPC) in Greece have nominal powers of 250, 400, 630, 2×400 , 2×630 , and 1000 kVA. Their number is significant. For example in the town of Xanthi, which has 50 000 inhabitants, 52 such substations are installed. Their number and their close proximity to house and workplaces justify the concern of the town inhabitants over the health hazards from the fields caused by the operation of these substations.

III. ELECTRIC- AND MAGNETIC-FIELD MEASUREMENTS

One of the instruments that can be used for the measurement of low-frequency magnetic and electric fields in the frequency range 5 Hz to 30 kHz is the EFA-3 analyzer. The analyzer, constructed by the Wandel and Goltermann Company, supports recording, storage, and evaluation functions for sequences of results and can measure electric and magnetic fields. Its characteristics are the following:

- isotropic magnetic field probe built-in;
- omnidirectional (isotropic) measurements;
- measurement ranges from 5 nT to 10 mT, 0.1 mG to 100 G, and 0.1 V/m to 100 kV/m;
- true root-mean-square (rms) or peak value measurement;
- spectral detection of field components;
- built-in frequency counter;
- preset table audible and visible alarm thresholds;
- user-definable filter frequency;
- timer-controlled recording of results;
- calibrated;
- external electric- and magnetic-field probes.

The measurements were carried out using the three-dimensional (3-D) isotropic probe that ensures omnidirectional measurements. The EFA-3 analyzer has the capability of storing 4000 result values. These values can then be output via the built-in printer interface directly to a printer or clearly displayed on a PC fitted with appropriate software. Long-term measurements lasting up to 24 h can be performed easily using the timer-controlled recording function.

One indoor power distribution substation of each standardized nominal power found in the town of Xanthi (i.e., 250, 400, 630, 2×400 , and 2×630 kVA), was selected in order to measure the electric and magnetic field in the context of this paper. This selection is sufficient because the dimensions of the room, where such a substation is installed and the equipment arrangements, are about the same (standardized by the PPC) for the indoor power distribution substations of all the standardized nominal power ratings. Bigger rooms are provided for the substations with two instead of one transformer. All of the substation rooms are naturally ventilated and far from any other equipment using high amounts of power, such as air conditioning units, elevator motors, etc. As a consequence, the measured field values are affected only by the substation load and not by the substation room configuration. Fig. 1 shows the ground plan sketch of a 2×630 kVA power distribution substation room. The dimensions of the floor surface are about 5.5×13.5 m. The origin of the axes x,

TABLE I
MAGNETIC FLUX DENSITY VALUES IN A 2×630 kVA POWER DISTRIBUTION SUBSTATION ROOM

Measurement position	Distance from the axis origin, (m)		rms magnetic flux density values B_z (μ T)			Measurement position	Distance from the axis origin, (m)		rms magnetic flux density values B_z (μ T)		
	x	y	Head	Waist	Floor		x	y	Head	Waist	Floor
M1	3.10	10.30	14	19	24	M38	0.00	8.50	3	3	7
M2	3.10	9.45	6	8	16	M39	0.00	7.60	2	2	5
M3	3.10	8.60	4	5	15	M40	0.00	6.75	3	5	7
M4	3.10	7.80	4	5	12	M41	0.00	5.90	5	6	7
M5	3.10	7.05	10	18	15	M42	0.00	5.00	3	3	4
M6	2.40	7.05	22	35	33	K1	0.70	0.00	18	24	23
M7	2.40	7.80	5	9	35	K2	0.70	0.80	59	81	105
M8	2.40	8.60	6	9	42	K3	0.70	1.60	144	24	54
M9	2.40	9.45	11	16	53	K4	0.70	2.40	20	32	23
M10	2.40	10.30	51	74	113	K5	0.70	3.20	38	108	46
M11	2.70	12.45	38	26	24	K6	0.70	3.95	9	17	30
M12	1.75	12.95	7	9	9	K7	0.70	4.75	4	5	6
M13	1.75	12.10	18	25	32	K8	1.50	4.75	3	4	29
M14	1.75	11.30	101	148	334	K9	1.50	3.95	5	8	31
M15	1.75	10.50	157	244	197	K10	1.50	3.20	13	23	26
M16	1.75	9.70	17	24	48	K11	1.50	2.40	9	14	21
M17	1.75	8.90	5	9	43	K12	1.50	1.60	19	24	31
M18	1.75	8.10	4	7	36	K13	1.50	0.80	19	24	28
M19	1.75	7.30	9	14	34	K14	1.50	0.00	10	13	12
M20	1.75	6.50	49	67	67	K15	2.30	0.00	4	4	4
M21	1.75	5.70	307	429	164	K16	2.30	0.80	5	5	5
M22	1.75	5.00	18	21	49	K17	2.30	1.60	5	6	7
M23	0.80	5.00	6	8	10	K18	2.30	2.40	4	5	7
M24	0.80	5.90	13	16	14	K19	2.30	3.20	4	5	20
M25	0.80	6.75	8	10	14	K20	2.30	3.95	2	3	36
M26	0.80	7.60	3	3	6	K21	2.30	4.75	4	6	21
M27	0.80	8.50	3	4	11	K22	3.00	4.75	15	17	15
M28	0.80	9.35	5	6	12	K23	3.00	3.95	6	6	8
M29	0.80	10.25	16	23	25	K24	3.00	3.20	2	3	6
M30	0.80	11.15	22	32	45	K25	3.30	2.40	2	2	3
M31	0.80	12.05	10	13	19	K26	3.30	1.60	2	2	3
M32	0.80	12.95	7	7	8	K27	3.30	0.80	2	2	2
M33	0.00	12.95	5	6	7	K28	3.30	0.00	2	2	2
M34	0.00	12.05	7	9	12	K29	4.50	0.00	1	1	1
M35	0.00	11.15	10	13	16	K30	4.50	0.80	2	2	2
M36	0.00	10.25	7	8	11	K31	4.50	1.60	5	4	4
M37	0.00	9.35	4	5	7	K32	4.50	2.40	3	3	4

y and the successive positions, where the measuring instrument was placed, are marked in Fig. 1. The selected substation is installed in the basement of a multistory building in the town center and supplies about 1500 of the town's 31 800 consumers.

In Table I, the positions of the measurement instrument are registered, as well as the distance of these positions from the axis origin and the measured magnetic flux density values (rms values in μ microTesla). The measurement positions Mx, where x is the location number as shown in Fig. 1, are in the transformer room. The measurement positions Kx are inside the room for the switchboards and the distribution fuse boxes. Three measurements correspond to each position. The first one refers to a head height (1.80 m), the second to a waist height (1 m), and the third to the floor surface. The stability of the measurement

height was obtained by using a special wooden support stand, where the measuring instrument can be placed at successive positions that are 30 cm apart, from the floor surface to a height of 2 m. All of the measurements were carried out at 50 Hz.

Diagrams are given in Fig. 2 showing contour and surface maps for the magnetic flux density at a waist height based on the values in Table I. The diagrams for head and floor heights are relative. Positions, where measurements were impossible, have been excluded from the above diagrams. The diagrams have been plotted taking into account the reference levels for safe occupational exposure, because only the PPC technicians can enter the substation room. Access to the public is forbidden.

Apart from the magnetic flux density, the electric-field strength was measured inside the power distribution substation

Fig. 1. Ground plan sketch of an indoor 2×630 kVA power distribution substation room. M_i , K_i : measurement positions.

room with the doors of the distribution fuse boxes open. The electric-field sensor was placed at the measurement positions and connected to the main instrument with a 10-m fiber-optic

cable. This connection and the distance between the sensor and the main instrument were necessary in order to ensure that the electric-field strength would not be perturbed by the presence of people. In the transformer room, the measured electric-field strength at the frequency of 50 Hz did not exceed 3 V/m. The maximum electric-field strength in the switchboards and the distribution fuse boxes room, at the same frequency, was 2 V/m.

During the field measurements, the three-phase currents at the low-voltage side of each transformer were also recorded. At the low-voltage side of transformer 1, the three-phase currents were $I_{1a} = 670$ A, $I_{1b} = 760$ A, $I_{1c} = 640$ A. The relative currents of transformer 2 were $I_{2a} = 635$ A, $I_{2b} = 590$ A, $I_{2c} = 600$ A. Consequently, the maximum phase currents for each transformer were, respectively, $I_{1\max} = 760$ A and $I_{2\max} = 635$ A.

The nominal current of a 630-kVA transformer is

$$I_n = \frac{S}{\sqrt{3} \times U} = \frac{630 \text{ kVA}}{\sqrt{3} \times 0.4 \text{ kV}} = 909.33 \text{ A}$$

where S is the nominal power of the transformer and U is the line-to-line nominal voltage.

The ratio of the maximum measured to the nominal current of transformer 1 is, according to the following:

$$\frac{I_{1\max}}{I_n} = \frac{760 \text{ A}}{909.33 \text{ A}} = 0.836 \text{ i.e. } I_n = 1.196 I_{1\max}.$$

The same ratio for transformer 2 is

$$\frac{I_{2\max}}{I_n} = \frac{635 \text{ A}}{909.33 \text{ A}} = 0.698 \text{ i.e. } I_n = 1.433 I_{2\max}.$$

IV. EVALUATION OF THE MEASUREMENT RESULTS

In the 2×630 kVA indoor substation during the measurements, transformer 1 operated under 83.6% of the nominal load while transformer 2 operated under 69.8% of the nominal load.

In the transformer room, the magnetic-field reference level for the public ($100 \mu\text{T}$) was exceeded in four positions (M10, M14, M15, and M21, with bold letters in Table I). Three of these positions were at the low-voltage side of transformer 1 while the fourth was at the low-voltage side of transformer 2. In the switchboards—distribution fuse boxes room, the magnetic-field reference level for the public was exceeded in three positions in front of the distribution fuse boxes (K2, K3, and K5, with bold letters in Table I).

Measurements inside other standardized power distribution substation rooms have given similar results. The maximum measured currents and magnetic flux density values inside the substation rooms as well as the magnetic flux density value for every standardized transformer, extrapolated to the nominal transformer power, are given in Table II. This extrapolation was made giving due consideration to the fact that the magnetic flux density variation is proportional to the relative current variation.

It should be clarified that the maximum measured current $I_{\max}$ in the case of substations with two transformers (2×630 kVA or 2×400 kVA substations) according to Table II corresponds to the load of one of these transformers only. Specifically, this is the current of the transformer closest to which the

Fig. 2. Magnetic flux density distribution at a waist height in a 2 × 630 kVA power distribution substation room. (a) Contour map. (b) Surface map.

TABLE II
CURRENT AND MAGNETIC FLUX DENSITY VALUES INSIDE STANDARDIZED
INDOOR POWER DISTRIBUTION SUBSTATION ROOMS

Nominal substation power S_{ns} (kVA)	Maximum measured current I_{max} (A)	Maximum measured magnetic flux density values B_{max} (μT)	Ratio of the nominal current to the maximum measured current, $I_{\text{n}}/I_{\text{max}}$	Magnetic flux density value extrapolated to the nominal power, (μT)
250	82	24	4.4	106
400	250	81	2.3	186
630	370	466	2.45	1142
2x400	280	255	2.1	536
2x630	760	429	1.2	515

maximum magnetic flux density value was measured. The current of the second transformer of the substation is approximately the same, but smaller.

No serious differentiation was noted in the measured magnetic flux density values in relation to the body height. Therefore, no clear conclusion can be drawn about the body height (head, waist, floor) where the field is stronger.

No excessive magnetic-field reference level for safe occupational exposure ($500 \mu\text{T}$) was noted during the measurements, either in the transformers room or in the switchboards—distribution fuse boxes room. Marginal excess has resulted in the extrapolation of the measured magnetic flux density values for the actual transformer loads to their nominal power, as Table II shows. But power distribution transformers rarely operate at

their nominal power. If this happens, such operation is fleeting and, therefore, the above excess is not alarming.

Additional measurements taken at public-access places have shown magnetic flux density values to be much lower than the reference level for safe public exposure (building entrance $0.8 \mu\text{T}$, ventilation grid on the pavement $0.8 \mu\text{T}$, feed pole $0.9 \mu\text{T}$, at the water and electricity meters $1.5 \mu\text{T}$). Public access to the substation rooms is prohibited. Only the PPC technicians have access to these rooms, where they are not required to spend much time. During repairs or scheduled maintenance, which demand lengthy procedures, the substation is not under voltage and so no field exists. Guidelines suggest that the measured magnetic flux density values are not dangerous and, therefore, are no cause for concern.

The electric-field strengths measured inside all of the substations were far below the relative reference level for safe public exposure (5 kV/m).

The relatively high magnetic flux density values in positions that are in very close proximity to the transformers or to the distribution fuse boxes (for instance, the value $466 \mu\text{T}$ within the 630-kVA substation, although it has a load smaller than half of its nominal load) can be justified by several factors. These include: 1) the asymmetry in the values of the three phase currents; 2) the space asymmetry of the phase conductors (conductors placed in a flat plane and not at the vertices of an equilateral triangle); 3) the asymmetrical position of the measuring instrument with reference to the three-phase conductors; and 4) the small distances between this instrument and the phase conductors, etc.

Fig. 3. Diurnal variation of the $B/I_{\max}$ ratio in a random position of a 2×630 kVA power distribution substation room.

In order to ascertain whether the extrapolation of the measured magnetic flux density values to the nominal transformer power, which preceded and is recorded in Table II, was reliable, an additional measurement has been carried out for the purpose of determining the exact relation between the magnetic flux density and the current. Specifically, in the 2×630 kVA indoor power distribution substation, which has measured magnetic flux density values higher than those of the other substations because of the higher currents, the magnetic-field analyzer was placed at position M13 in front of transformer 1 and at waist height. It was programmed to measure the magnetic flux density every 15 min for 24 h. At similar intervals, the values of the currents flowing through the three phases on the low-voltage side of the transformer were recorded. From these records, the three phases were unequally loaded but without great imbalances. Fig. 3 shows that for currents between 210 and 620 A, a typical diurnal variation, the magnetic field was proportional to the current with the constant of proportionality $B/I_{\max}$ being $0.04 \pm 0.01 \mu\text{T/A}$.

V. CONCLUSION

In recent years, as the demand for electricity has steadily increased, the general public and working personnel have become increasingly concerned about the health hazards of exposure to ELF EMFs. National and international guidelines have enacted reference levels for safe exposure, while researchers from different areas of expertise deal with the above-mentioned health effects.

This paper reports the results of electric- and magnetic-field measurements within indoor power distribution substations. The measurements were made to determine whether internationally accepted reference levels for safe exposure were violated. Both these measurements and the elaboration of the relevant results show that the magnitudes of the measured field values are within recognized guidelines, suggesting that the fields are not dangerous and, therefore, are no cause for concern among the public or working personnel.

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