Low-Frequency Magnetic Fields From Electrical Appliances and Power Lines

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***Abstract*—The relationship between magnetic fields and the health of people is increasingly being investigated. International organizations have proposed bylaws that put limits on the value of the generated magnetic field. In this work, we measure the magnetic field created by electrical appliances and high voltage lines and we analyze the degree of compliance with recent applicable European regulation. The simulation of the magnetic field generated by electrical lines through a simple model accurately predicts the measured values. The model is used to simulate the behavior of the lines under given conditions. In both cases, an FFT analysis of the magnetic field waveform was performed to study the frequency and amplitude of the possible induced currents.**

***Index Terms*—Electrical appliances, EMF, exposure, magnetic fields, measurement protocol, power line fields, power system harmonics, transmission line measurements.**

I. Introduction

ELECTRICAL energy can be considered indispensable for all areas of society, industrial, domestic, and social, in such a way that it is difficult to imagine a human activity that does not have some relationship with electricity. Electrical energy is transported from the power station to the substations through overhead electric lines and from there to the final users through distribution networks of medium and low voltage.

In recent years, with the purpose of improving services, "corridors" have been proposed that include common services for energy distribution, data transmission lines, gas conduits, etc. Given that the energy is transported by the electromagnetic field that is propagated throughout the line, undesired effects can be produced on the other services [1], since the high-intensity electromagnetic fields can induce important voltages and currents in conducting elements located in their proximity (fences, pipelines, telephone lines, other transmission lines, etc.).

Most objects and constructions do not present more than a weak, if any, shielding effect for magnetic fields. As a consequence, the field inside a dwelling is the result of the contribution of the internal and external field sources. In recent years, much has been said about the effects that electromagnetic fields produce in biological materials, especially humans. Epidemiological studies that seek a connection between electromagnetic fields and the health of people have been carried out [2]–[4]. As mentioned, electrical lines are one of the main sources of electromagnetic fields to which people may be exposed. This has motivated various researchers to measure and elaborate models for the determination of the magnetic fields generated by electrical lines [5]–[11], and interest has particularly increased in the study of the fields induced by transmission lines that cross residential areas [12]–[14]. Taking into account that people can be exposed to the electromagnetic fields both in the proximity of electrical lines as well as in the home (due to the use of electrical equipment), some authors have considered it convenient to characterize the electromagnetic field inside residences [15]–[20].

Though much research has been focused on electromagnetic fields, the mechanism by which electromagnetic fields might influence the health of people is still not known. What is more, so far the results found have been contradictory, and it has still not been possible to establish an "exposure dose" of low-frequency electromagnetic radiation under which it could be concluded that their effects will be harmful. It seems clear that if the electromagnetic field influences the health of people, such influence will be affected by the value of the magnetic field since the greater the field, the greater the induced currents.

Because of this, different international organizations (International Commission on Non-Ionizing Radiation Protection: ICNIRP, European Committee for Electrotechnical Standardization: CENELEC, National Radiological Protection Board: NRPB, European Commission: CE) have established levels of recommended maximum exposure [21]–[26], for workers as well as for people that find themselves exposed occasionally to electromagnetic fields. This leads to ever more in-depth study of the fields to which people can be exposed.

An additional problem of magnetic fields at industrial frequency is produced by the currents' appearance at higher frequencies (harmonic) due to the nonlinearity of given types of loads. These currents give rise to the appearance of currents induced at the same frequency but amplified, since the induced currents are proportional to the frequency. The extent of the induced currents is proportional to the intensity of the field, to its variation in time (that is to say, its frequency) and to the surface area of the circuit considered.

Taking the above into account, it seems necessary to study the problem of electromagnetic fields from several viewpoints. Thus, it is necessary to know what the levels of the field are in the proximity of equipment and electrical systems, to have knowledge of their levels over time and the type of current that they can induce.

This work is intended to study the level of magnetic fields generated by electrical appliances and by high voltage overhead lines in our immediate area (Northwest Spain) and to establish the degree of compliance with the recent European regulation [26]. At the same time, a mathematical model is developed for

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electrical lines that, once its validity has been contrasted, permits us to study the behavior of the lines under different loads and unbalanced situations. The study of the harmonics of the magnetic field is also done in this paper.

II. Theoretical Model for Lines

The sources of the electrical and magnetic fields in the environment of overhead electric lines are the electrical currents and charges that exist in their conductors, as well as those which are induced in the earth and/or in nearby objects. The starting point for the calculation of these variable fields with time are Maxwell's equations.

Generally, the electrical and magnetic fields are coupled, and it is necessary to solve Maxwell's equations to obtain them. Some authors [27]–[30] have proposed models that solve Maxwell's equations to obtain the value from the magnetic field generated by electrical lines. In practical terms, these models are not the most adequate for the calculation of the magnetic field in the vicinity of electrical lines due to their complex math, since their great precision is counteracted by inaccuracies in the knowledge of the current that circulates through the conductors as well as other necessary parameters for the models. Because of this, a simpler mathematical model, but one that offers comparable results to the real values, will be more useful, above all to designers and operators of electrical energy systems, since they will be able to study, in one easy way, the system behavior in a great variety of situations. Though the electrical and magnetic fields generated by electrical lines are coupled, in many cases and under certain conditions, some approximations can be assumed and electrical and magnetic fields calculated in an independent way. This is often the case for fields created by power lines due to the fact that the field varies so slowly in time that Maxwell's equations are converted into the electrostatic and magnetostatic equations.

Time varying currents can be represented as a superposition of sinusoidally time varying components by using the Fourier transform. In a linear medium, the total field is determined by superimposing the individual fields. In the low frequencies range (i.e., industrial frequency, 50/60 Hz), the quasistatic method can be used. This method uses the static or decoupled Maxwell's equations to derive the static electric and magnetic fields and then these fields simply oscillate in amplitude to the frequency of the sinusoidal source current.

The magnetic field in the vicinity of three-phase lines can be calculated by superimposing the individual contribution of the current of each one of the phase conductors and of the earth cables taking into account, furthermore, the return currents by the earth. To take into account the return currents in the expression of the magnetic field, it is necessary to resort to the equations by Carson [31]. From these equations, Parker [32] presented a simpler expression for the calculation of the mutual impedance between conductors, since, for moderate frequencies, the displacement currents can be considered negligible as compared to the conducting current (hypothesis of good conductors). As a consequence, the quasistatic approximation is obtained, since $\nabla.\mathbf{A} = 0$ [33], being $\mathbf{A}$ the magnetic vector potential.

From Parker, the mutual impedance Z_{ij} between two parallel cables located in positions (x_i, y_i) and (x_j, y_j) and parallel to the Z axis is

$$Z_{ij} = \frac{\mathrm{j}\omega\mu}{2\pi}\left[\ln\frac{r'_{ij}}{r_{ij}} - \frac{1}{12}\left(\frac{2}{\gamma r'_{ij}}\right)^4\right] \tag{1}$$

where

$$\gamma = \sqrt{\mathrm{j}\omega\mu(\sigma + \mathrm{j}\omega\varepsilon)}; \quad r_{ij} = \sqrt{(x_j - x_i)^2 + (y_j + y_i)^2}$$

and

$$r'_{ij} = \sqrt{(x_i - x_j)^2 + \left(y_i + y_j + \frac{2}{\gamma}\right)^2}$$

σ, ε, and μ are the conductivity, the permittivity, and the permeability of the earth, respectively, and ω the angular frequency.

Taking into account that the induced electric field $E = Z_{ij} I_i$ (which has only the Z direction parallel to the line, E_z), then

$$\nabla \times \mathbf{E} = \left(\frac{\partial E_z}{\partial y}\mathbf{u}_x - \frac{\partial E_z}{\partial x}\mathbf{u}_y\right) = -\frac{\partial \mathbf{B}}{\partial t} \tag{2}$$

where $\mathbf{u}_\mathrm{x}$ and $\mathbf{u}_\mathrm{y}$ are the unit vectors along the X and Y axes, perpendicular to the Z axis. Taking into account the relationship between the magnetic field and the magnetic field density, $\mathbf{B} = \mu\mathbf{H}$, and the sinusoidal nature of these magnitudes, substituting results in

$$\mathbf{H} = \frac{1}{-\mathrm{j}\omega\mu}\left(\frac{\partial E_z}{\partial y}\mathbf{u}_x - \frac{\partial E_z}{\partial x}\mathbf{u}_y\right). \tag{3}$$

After some operations, we obtain the contribution from the current I_i of the conductor i (coordinates x_i, y_i) at the point j (coordinates x_j, y_j) as

$$H_{ji} = \frac{I_i}{2\pi r_{ij}}\mathbf{u_{ij}} - \frac{I_i}{2\pi r'_{ij}}\left(1 + \frac{1}{3}\left(\frac{2}{\gamma r'_{ij}}\right)^4\right)\mathbf{u'_{ij}} \tag{4}$$

where

$$\mathbf{u_{ij}} = \frac{y_i - y_j}{r_{ij}}\mathbf{u_x} - \frac{x_i - x_j}{r_{ij}}\mathbf{u_y}$$

and

$$\mathbf{u'_{ij}} = \frac{y_i + y_j + \frac{2}{\gamma}}{r'_{ij}}\mathbf{u_x} - \frac{x_i - x_j}{r'_{ij}}\mathbf{u_y}.$$

The magnetic field intensity at point j with coordinates (x_j, y_j) is obtained by considering the contribution of all the conductor intensities I_i with coordinates (x_i, y_i) and assuming parallel lines over a flat earth

$$\mathbf{H_j} = \sum_{\mathrm{i}} \frac{I_i}{2\pi r_{ij}} \cdot \mathbf{u_{ij}}. \tag{5}$$

Taking into account the relationship between $\mathbf{B}$ and $\mathbf{H}$ and that the current that circulates through the conductors are sinusoidal functions, the magnetic field density can be represented by phasors, in such a way that

$$\mathbf{B}(t) = B_x(t)\mathbf{u_x} + B_y(t)\mathbf{u_y} + B_z(t)\mathbf{u_z} \tag{6}$$

where $\mathbf{u_x}$, $\mathbf{u_y}$, and $\mathbf{u_z}$ are the unit vectors in the spatial directions X, Y, and Z, and $B_x(\mathrm{t})$, $B_y(\mathrm{t})$, and $B_z(\mathrm{t})$ are phasors of the form

$$B_x(t) = B_{ox}\cos(\omega t + \varphi_x), \quad B_y(t) = B_{oy}\cos(\omega t + \varphi_y) \quad \text{and} \quad B_z(t) = B_{oz}\cos(\omega t + \varphi_z) \tag{7}$$

being B_{ox}, B_{oy}, and B_{oz}, the amplitudes in the spatial directions and φ_x, φ_y, and φ_z the initial phase angles.

The resultant magnetic field B_r is given by the expression

$$B_r = \sqrt{B_{ox}^2 + B_{oy}^2 + B_{oz}^2}. \tag{8}$$

III. Results for Electrical Appliances

The resultant magnetic field as a function of the distance produced by each electrical appliances was measured. The measurement direction is the usual one for normal equipment use. Similarly, measurement was made of the resultant magnetic fields created by overhead and buried cables near housing. The measurements have been made at different times with the purpose of establishing a relationship between field magnitude and electrical energy demand. To measure the rms magnetic field, we have used a Teslatronics model 70 gaussimeter (frequency response: 20 to 2000 Hz) that allows us to measure the resulting total field or the field in each one of the axes. The measurement range is from 0.1 to 1999 mG (0.01 to 199.9 μT). The gaussimeter has an analog output in megavolts proportional to the measured magnetic field. This output permits us to visualize, through a scope, the waveform of the magnetic field, and, once recorded, to determine the harmonic composition of the field through Fourier analysis. An F.W.BELL model 4060 complementary gaussimeter was also used. (ranges 0–1999 mG and 0.00–19.99 G). Given that highly nonuniform magnetic fields are produced by some electrical appliances, three probes have been used, with sensing areas of 0.5, 7, and 100 cm^2, with the purpose of reducing the measure errors due to the averaging over the cross-sectional area of the gaussimeter probe. In each case, the most adequate probe has been selected. Nevertheless, in spite of using small probes, these errors can be noticeable when the magnetic field is measured in very nearby positions to appliances whose field varies quickly with the position and the distance (case of electric shaver). The estimation of error in these measures is difficult to evaluate [36].

Figs. 1 and 2 show the value of the rms resultant magnetic field (in μT) generated by different electrical equipment used in households, at the normal utilization distance (from 3 cm. for the hair-remover, to 3 m for the television). The value that is shown corresponds to the average of the measurements made on three different manufacturers' equipment. The background magnetic field at the point of measurement was at all times inferior to 0.005 μT.

As can to be seen in these figures, the user of the tested equipment is subjected to magnetic fields that vary in more than two orders of magnitude. On the other hand, some of these values are superior to those found in the vicinity of electrical lines (as we will see below). It should be noted that the inhabitants of these residential zones are subjected to these fields continuously (at least while they stay in this environment) whereas the use of domestic electrical equipment tends to be rather sporadic. It is necessary to advise that any user can be exposed to densities of the magnetic field higher than the shown values, since some appliances (depending on its construction) can produce greater fields in directions and positions different from those generally used.

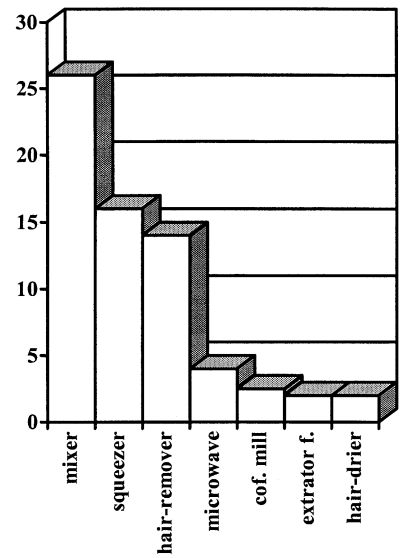

Fig. 1. Resultant magnetic field (μT) generated by different electrical equipment measured at the normal utilization distance.

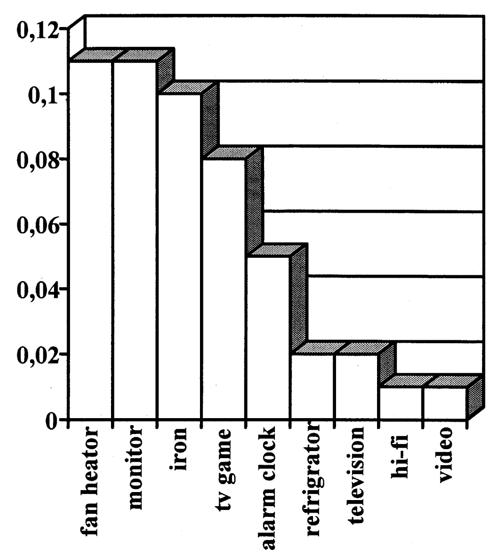

Fig. 2. Resultant magnetic field (μT) generated by different electrical equipment measured at the normal utilization distance.

With the purpose of establishing the possible influence of the equipment on its more immediate environment, we proceeded to measure the resultant magnetic field as a function of the distance and in the usual utilization direction. Figs. 3 to 6 collect the results found.

The shaver shows the highest values for the user, though the field reduces quickly with the distance, so its possible effect on other persons (at distances of over 20 cm) is below that of a vacuum cleaner or a microwave (for that distance: shaver, 7.4 μT; vacuum cleaner, 9.8 μT; and microwave,

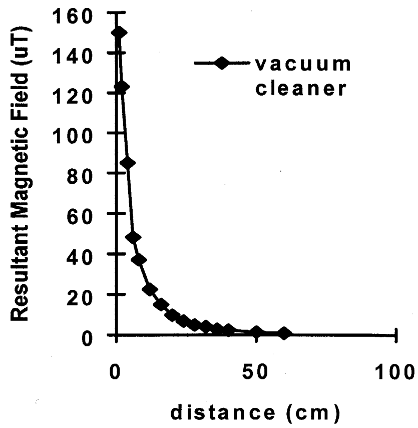

Fig. 3. Resultant magnetic field as a function of the distance created by a vacuum cleaner.

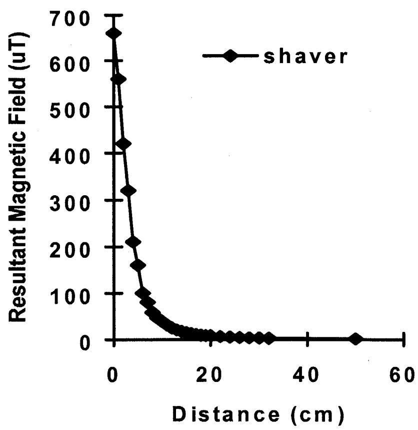

Fig. 4. Resultant magnetic field as a function of the distance created by a shaver.

8.2 μT). However, it is necessary to indicate that these values correspond to traditional shaver models. For models that operate with batteries, the values of the produced magnetic field are quite smaller, though they are connected to the electrical network. As can be deduced from the previous figures, the resultant magnetic field decreases in an exponential way with the distance from the equipment, even though the curve is different for each appliance.

Fig. 7 shows the resultant magnetic field created by a three phase mains supply of a building (44 dwellings) as a function of the distance to this supply point (located vertically flush to the building and on the sidewalk). The shown values were measured in a high load schedule (between 8 and 9 A.M.). Nevertheless, throughout the day, maximum values of over 100 μT (23 h) at a distance of 3 cm of the mains supply were registered. On the sidewalk next to the mains supply, a more usual place for people to be (between 50 and 200 cm), the field is reduced notably to values that do not surpass 0.5 μT.

Fig. 8 represents the resultant magnetic field measured in the proximity of a meter room located at the edge of a staircase access area in the same building. In this case, the maximum values to which a person can be exposed do not exceed 4.5 μT and the usual exposure values (due to the layout of stairs) are below 0.5 μT.

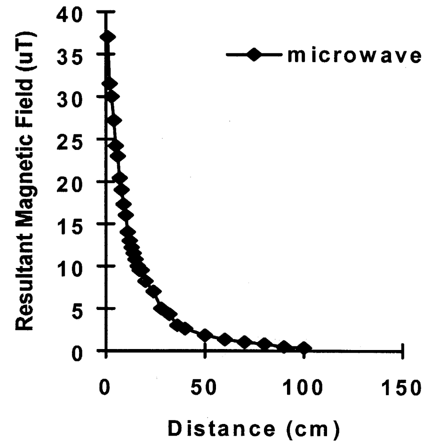

Fig. 5. Resultant magnetic field as a function of the distance created by a microwave.

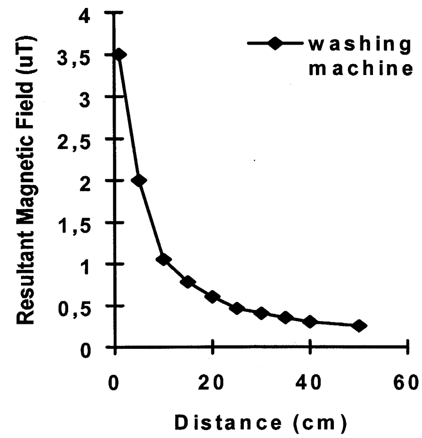

Fig. 6. Resultant magnetic field as a function of the distance created by a washing machine.

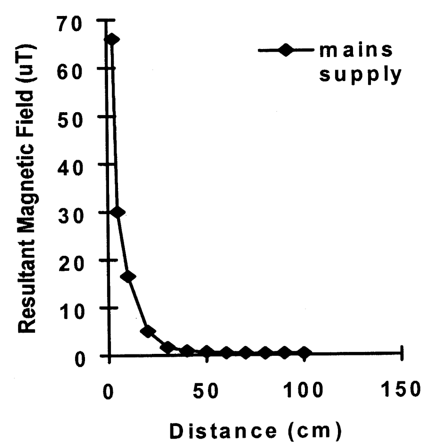

Fig. 7. Resultant magnetic field as a function of the distance created by a mains supply.

The simple value of the resultant magnetic field created by an electrical appliance, should not be the only parameter taken into account in order to consider its possible effect on the health of people. The value of the current induced by variable magnetic fields in time is directly proportional to the frequency variation of the field. There is ever greater use of domestic equipment that operates through rectifiers. Therefore, the voltage-current

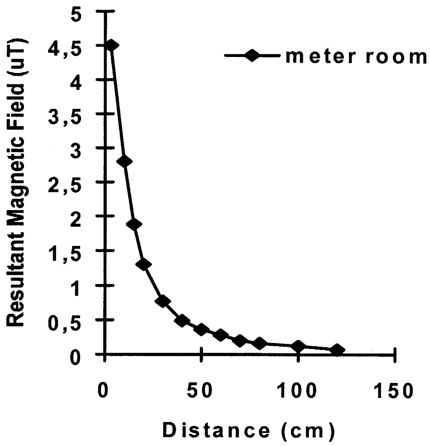

Fig. 8. Resultant magnetic field as a function of the distance created by a meter room.

characteristic is not linear. This causes the current feed of this equipment not to be purely sinusoidal. Therefore, the waveform can be decomposed into one of the fundamental frequency plus harmonics of growing order.

The greater the rms current value of the harmonic and its frequency, the greater the resultant magnetic field created by this harmonic, and therefore, the current that it can induce in the objects or persons located in its environment will grow in a linear way with the frequency. To characterize the tested electrical equipment, an analysis through FFT of the analog waveform, supplied by the meter of the magnetic field, has been carried out. Some of the obtained results are shown in the figures below.

Fig. 9 shows the waveform corresponding to the resultant magnetic field (in arbitrary units) created by a razor and recorded through a digital scope. As is observed, the field presents a form that is not sinusoidal due to the presence of harmonics of the fundamental frequency. This can be observed in the decomposition effected by the application of the FFT and that is shown in Fig. 10, in which the percentage with respect to the fundamental frequency (supposing a value of 100% for this) of the spectrum as a function of the frequency is represented. In this case, in addition to the fundamental frequency, the third harmonic (150 Hz) with a value of 21% with respect to the fundamental is obtained. Also, the seventh harmonic contributes with a value of 4%. Taking into account the proportionality of the currents induced with the frequency of the resultant magnetic field that originates them, the current produced by the third harmonic has a value of 63% with respect to that of fundamental frequency.

Fig. 11 shows the corresponding waveform for the resultant magnetic field created by a mixer (in arbitrary units), while Fig. 12 shows the corresponding frequencies spectrum for Fig. 11 when applying the FFT. In this case, the third harmonic reaches a value of 45% with respect to the value of the fundamental frequency one, while the fifth harmonic presents a value of 10%. This means that the value of the current induced at the frequency of 150 Hz is 1.35 times the value of that induced by the field at the frequency of 50 Hz, while the current induced by the fifth harmonic is 0.5 times.

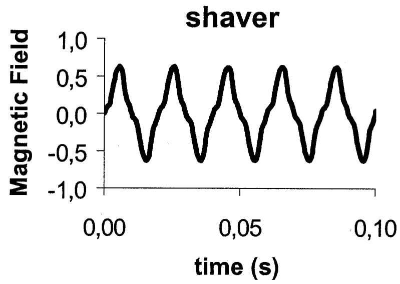

Fig. 9. Magnetic field as a function of the time created by a shaver.

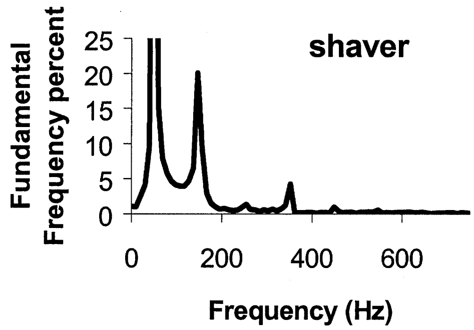

Fig. 10. Spectral decomposition of the magnetic field created by a shaver.

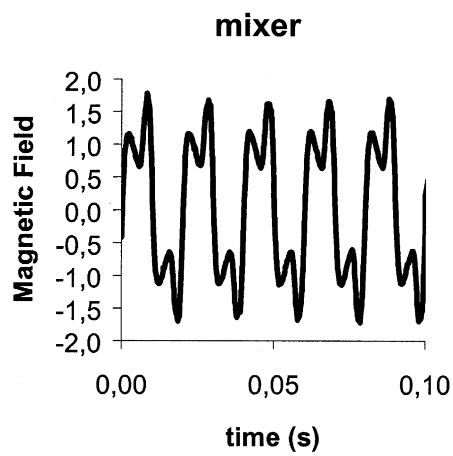

Fig. 11. Magnetic field as a function of time created by a mixer.

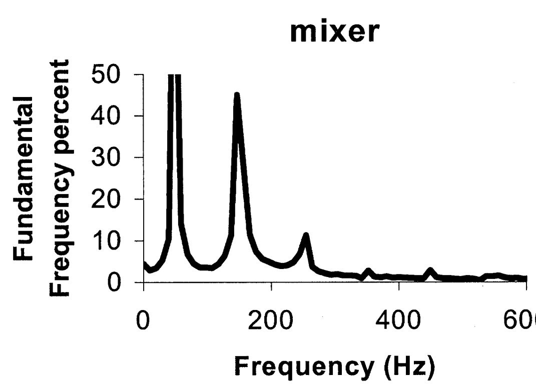

Fig. 12. Spectral decomposition of the magnetic field created by a mixer.

Figs. 13 and 14 show the data obtained for the waveform from the resultant magnetic field generated by an extractor fan. The signal is very similar to that of the mixer even though the values

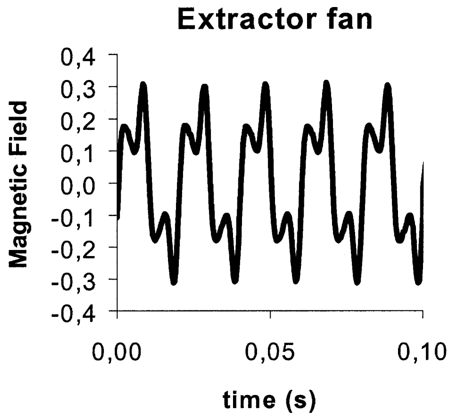

Fig. 13. Magnetic field as a function of time created by an extractor.

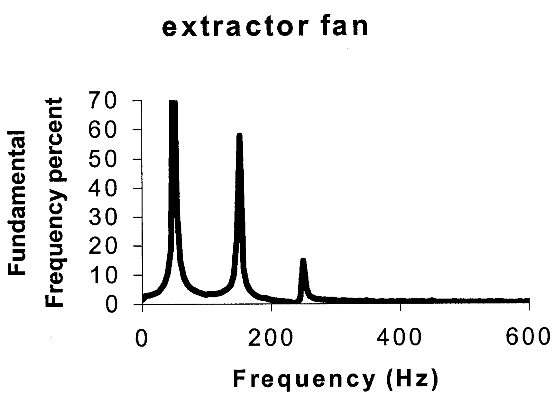

Fig. 14. Spectral decomposition of the magnetic field created by an extractor fan.

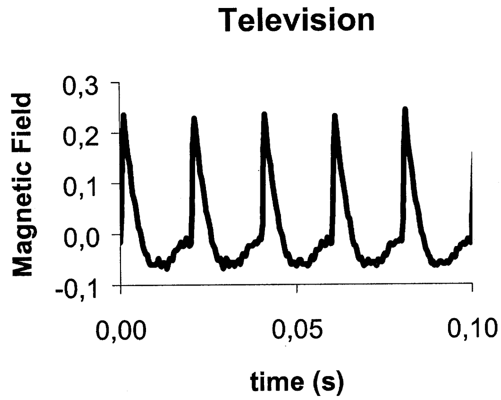

Fig. 15. Magnetic field as a function of time created by a television.

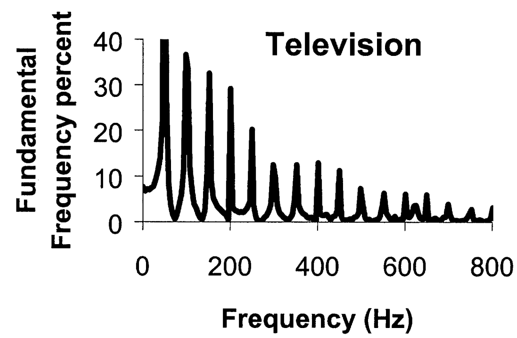

Fig. 16. Spectral decomposition of the magnetic field created by a television.

of the third and fifth harmonics present higher values (58% for third and 16% for the fifth harmonic). As a consequence, the value of the currents induced at 150 Hz is 1.74 times the value of that induced at the fundamental frequency, while at 250 Hz, it presents a value of 0.9 times the value of the fundamental.

The waveform of the field created by a television as well as its frequencies spectrum are shown in Figs. 15 and 16. In this case, all of the harmonics appear with high values until the 15th. In spite of the presence of numerous harmonics, their absolute value is reduced, according to the total field created by a television, as shown in Fig. 2.

IV. High Voltage Electric Line Results

In this part, the first objective was verified through measurements in situ of the level of the magnetic field generated by high-voltage overhead lines in our immediate environment (Northwest Spain) and to establish the degree of compliance with European regulation [26]. The study has focused on 132-kV overhead lines, due to their being the most numerous in our environment. The second objective was to contrast the validity of the above model and, depending on the values offered by it, to use it to calculate the level of the magnetic field generated by electrical lines in different situations.

To measure the magnetic field, we have used the UNESA measurement protocol [34], which is similar to the protocols of other organizations [35], [36]. The resultant magnetic field has been measured to the height of 1 m above the surface of the ground. To measure the magnetic field, we have used the same gaussimeters as in the case of electrical appliances. As the magnetic field was recorded, we proceeded to measure the electrical line current under study, by means of a clamp-on meter in the secondary of the current transformer at the origin or end substation of the line. The height of the conductors of each line was measured with a Suparule model 300E height meter.

Fig. 17 shows the profile of the resultant magnetic field $\mathrm{B_r}$ as a function of the distance to the center of the line. The figure shows the values measured as well as those calculated through the model. The values shown correspond to a double-circuit electrical line (one to each side of the towers) with phases in parentheses. The lowest conductors are at a height of 9.12 m, the separation from the center line is 3, 3.3, and 2.8 m for each phase, respectively and the vertical separation between phases is 4 m. The arrangement of the phases (R, S, T) is the same in both circuits. The current in the conductors presented a light unbalance ($<1\%$) with mean values of 91 A in one circuit and 104 A in the other. The conductors of both circuits are of Condor type. As can be observed in the figure, the maximum value of the magnetic field is obtained in the center of the line and it is below 18 mG (1.8 μT), a value very inferior to the maximum limit (100 μT) fixed by European regulation. The values calculated through the model present slightly lower values to the measured ones, the greater difference being obtained at the central point of the line.

Fig. 18 shows the profile of the resultant magnetic field for a line of a single-circuit with the three conductors (Condor type) placed at the same height (horizontal line). The height of the

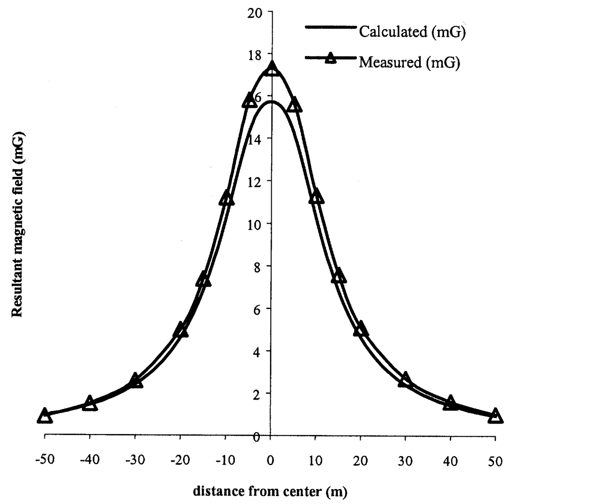

Fig. 17. Calculated and measured profiles of the resultant magnetic field under an overhead double-circuit high voltage line with 91 and 104 A in each circuit.

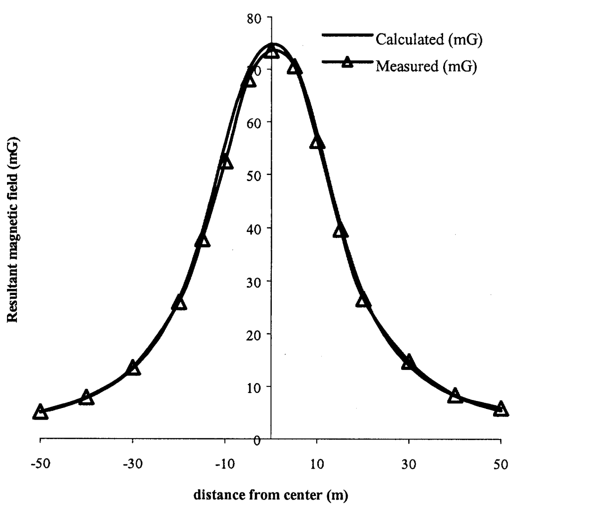

Fig. 18. Calculated and measured profiles of the resultant magnetic field under an overhead horizontal high voltage line with 485, 472, and 488 A in each phase.

conductors with respect to the soil at the measurement point is 12.12 m and the separation between phases is 7.8 m (The greater separation is due to it being an old line of 220 kV that is now used at 132 kV). The mean current in the conductors at the moment of measurement is 482 A (approximately 60% of its full load value) with a light unbalance between phases (485, 472, and 488 A for the phases R, S, and T, respectively). As is observed in the figure, the maximum value of the field is reached in the center of the line and is below 75 mG (7.5 μT, far below the limit of 100 μT). The values obtained through the theoretical calculation show a perfect conformity with the measured values. In this case, the calculated values are slightly superior to the measured values.

Fig. 19 shows the transverse profile of a triangular line of 132 kV formed by three Condor-type conductors located at three different heights. The conductors are located at the measurement point at a height of 20.8, 24, and 27.4 m, their lateral distance with respect to the center of the line being 3.3, 3.2, and 3.2 m, respectively. The mean current in the conductors at the moment of measuring of the magnetic field was 320 A with a

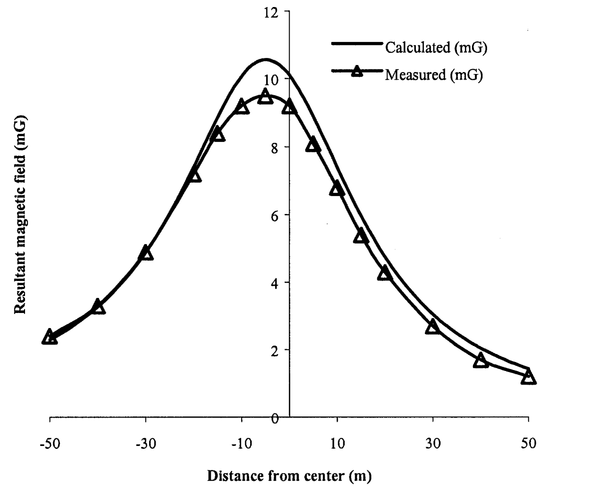

Fig. 19. Calculated and measured profiles of the resultant magnetic field under an overhead vertical high voltage line with 320 A in each phase.

light unbalance between phases (3%). Due to the asymmetry of the arrangement, the magnetic field presents its maximum value at 3 m from the center of the line. As can be observed, the values calculated with the theoretical model coincide with the measured values, though some differences appear about the center of the line. The theoretical values are greater than the experimental ones. In this case, the difference could be due to the uncertainty in the height of the conductors, since, with the available equipment, it has only been possible to measure the height of the lowest conductor, locating the other two at the distance given in the installation project. Though the currents that circulate along the line are large (40% of full load), the measured magnetic field is below 10 mG (1 μT), far below the established limits. The height at which the conductors of this line is placed explains the low value of the field, if compared with that of Fig. 18.

Fig. 20 shows the transverse profile of the corresponding magnetic field for two lines next to each other, both with the conductors in horizontal arrangement with Hawk-type conductor and two conductors per phase (bundled). The conductors of the left line are located at a height of 15.6 m with a separation between phases of 5 m. At the moment of measuring the magnetic field, a mean current of 246 A circulated through their conductors. The conductors of the right line are located at a height of 13.2 m with a separation between conductors of 5 m. At the moment of measuring the magnetic field, a mean current of 226 A circulated along the line conductors. As is observed in the figure, the values obtained with the model coincide perfectly with the experimental measurements. The measured maximum value of the magnetic field is below 22 mG (2.2 μT). As can be seen, the maximum field of the left line is lower than that of the right line, in spite of the fact that a smaller current circulates through the latter. Evidently, this is due to the fact that the height at which the conductors of the right line are placed is inferior to that of the conductors of the left line. The maximums are obtained in the center of each line (the centers of the lines are located at 5 m for the line on the right and -29 m for the line on the left). The arrangement of the phases is R-S-T, R-S-T, which causes a greater cancellation

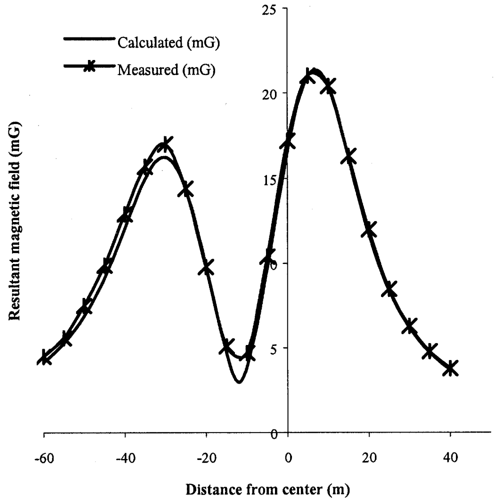

Fig. 20. Calculated and measured profiles of the resultant magnetic field under two close overhead horizontal high voltage lines with currents of 246 and 226 A in each line.

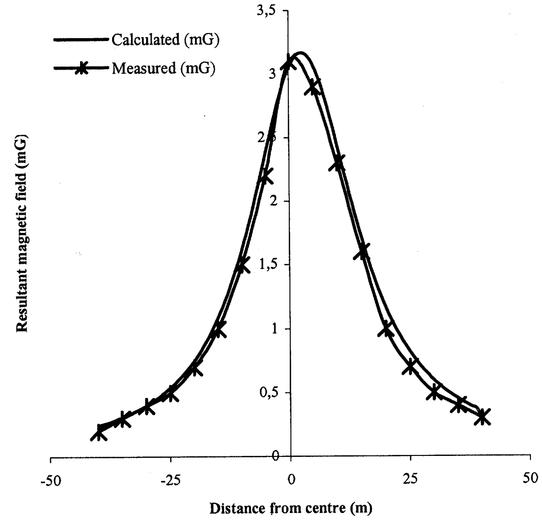

Fig. 21. Calculated profiles of the resultant magnetic field under an overhead triangular high voltage line with 35.5 A in each phase.

of the magnetic field in the intermediate zone between both lines than if another arrangement is used.

Fig. 21 shows the transverse profile of the magnetic field of a triangular line at three heights with L-180 type conductor located at heights of 11.6, 13.2 and 15.9 m and a horizontal separation of the conductors to the center of the line of 3.1 m. The mean current through the conductors at the moment of measuring was 35.5 A. As can be seen from the results, the theoretical values are very close to the measured values for the magnetic field.

The results shown in the previous figures., as well as from other tested lines, have permitted us to confirm the validity of the developed model. We have proven that the greater errors are produced in those lines that present a low level of generated magnetic field (or because the load is small and/or because the conductors are quite high), that is to say, the smaller the measured field, the greater the difference found between the theoretical results and the experimental ones. This difference does not have to be attributed to the model, but to the measuring process itself since, although several measurements of the current were taken during the measuring of the magnetic field, the fluctuations in the load of the line and the errors in the measuring appliances for small values can cause the differences found.

As the lines cannot be acted on to study their behavior under different load conditions and/or unbalance between phases, the model has been used to study these possible situations. For the lines corresponding to Figs. 17–21, taking into account the type of conductor used and the admissible limits for the current, at full load and balance, resultant magnetic fields of 8, 12.4, 2.7, 10.9, and 3.8 μT were obtained, respectively. These values hardly surpass 12% of the recommended maximum limit.

Also, with the model, we can study what configuration of the line is the most adequate to reduce the generated magnetic field, for the same load conditions. Figs. 22 and 23 show the results obtained with the model for the four basic configurations of the studied lines: configuration in parentheses, triangular, vertical, and horizontal. In order to compare results, the center of gravity as a function of the distance and height of the conductors to the center of the line has been calculated for each configuration. For all of the configurations, the center of gravity is located at 12 m over the ground, the conductors are Condor type and a current of 400 A circulates through them. In the configuration in parentheses (with two independent circuits), the load by phase is 200 A and the arrangement of the phases (from the top down) is R-S-T, T-S-R. Also, the influence of the situation of each one of the phases in the circuit has been studied for each configuration.

As can be seen in Fig. 22, the configuration in parentheses is the one which presents the smallest magnetic field. The remaining configurations generate growing magnetic fields according to the order: vertical, triangular, and horizontal. The field generated by the horizontal configuration is practically double that generated by the configuration in parentheses. Fig. 23 shows the magnetic field generated by the configuration in parentheses in the same conditions as in the previous figure, but changing the position of the phases. The position of the phases (from the top down in each circuit) is parentheses 1: R-S-T, T-S-R and parentheses 2: R-S-T, R-S-T. The configuration parentheses 3 corresponds to the situation in which the current (400 A by conductor) circulates along only one of the circuits. As is observed in the figure, the configuration parentheses 1 presents a lower value to that of the other two.

High voltage distribution lines tend to present small unbalances in the value of the current that circulates along each phase (it tends be smaller than 3%). Some of the measurements have been able to prove these unbalances. Angle unbalances are less frequent. With the purpose of studying the influence of the unbalances on the value of the generated magnetic field, several unbalance situations were simulated for the different configurations employed. Fig. 24 shows the profiles of the magnetic field generated by a line with configuration in parentheses (phases arrangement R-S-T, T-S-R), for current in the R phases greater by 3, 5, 10, 15, and 20% than the 200 A that circulate along the phases S and T. As can be seen in the figure, unbalances of 3 and 5% hardly affect the value of the generated magnetic field. For greater unbalances, the effect is amplified at the same time as the maximum field point is displaced toward the right of the center of the line. Nevertheless, in spite of the large unbalances

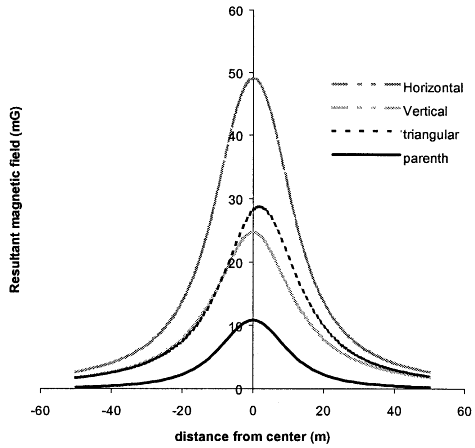

Fig. 22. Calculated profiles of the resultant magnetic field under overhead high voltage lines with configuration in parentheses, triangular, vertical, and horizontal.

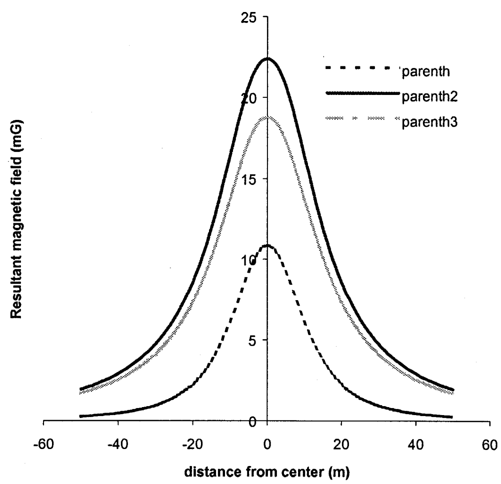

Fig. 23. Calculated profiles of the resultant magnetic field under overhead high voltage lines with configuration in parentheses and three different position of the phases.

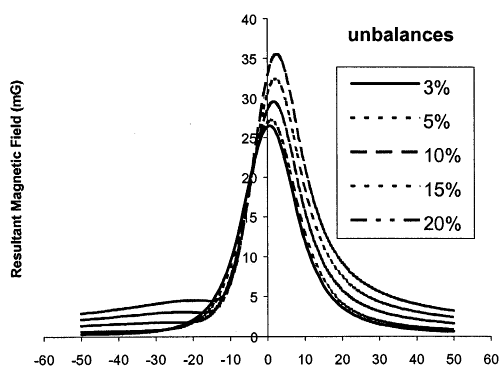

Fig. 24. Calculated profiles of the resultant magnetic field under overhead parentheses line with unbalances.

used, the value of the magnetic field does not exceed 4% of the recommended limit for maximum field.

Often some lines, it should be noted, supply power to industrial zones that can present very varied electrical loads. As a consequence, the current in the line is not perfectly

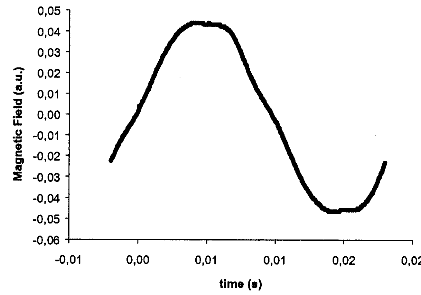

Fig. 25. Magnetic field as a function of the time created by an electrical line feeding an industrial zone.

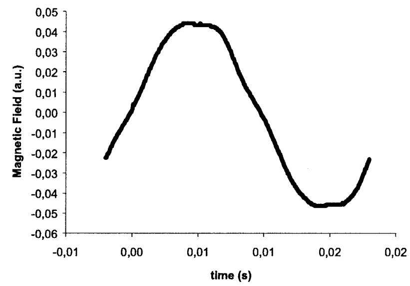

Fig. 26. Spectral decomposition of the magnetic field created by an electrical line feeding an industrial zone.

senoidal, and therefore, neither is the created magnetic field. Fig. 25 shows the waveform of the magnetic field of a line that feeds an industrial zone. Making a Fourier analysis of this form, the harmonic decomposition shown in Fig. 26 has been obtained. It is worth noting the presence of a fifth harmonic with a percentage of 4.5% with respect to the fundamental and a seventh harmonic with a percentage of 1.5%. In all of the lines observed, the prevailing harmonic is the fifth with percentages that go from 0.5 to 4.5%.

V. CONCLUSIONS

This work involved the study of the magnetic field generated by electrical appliances and electrical lines of 132 kV in northwest Spain. This study attempts to verify the degree of compliance with European procedures on magnetic field limitation, and at the same time, to contrast a model that could be useful to approach theoretical lines study in situations and configurations that are not possible to study in real situations but that can arise under different service conditions. From the obtained results, it should be noted that some equipment presents values for the field much higher than those which can usually be found near electrical lines. On one hand, the studied lines present a level of small magnetic field, since in no case does it surpass 8% of the maximum limit. The results obtained with the model coincide adequately with the experimental values; therefore, the model is valid to study the magnetic field in different situations. The simulation at full load with the lines studied does not exceed 13% of the limit of the maximum field in any case. The model has also served to study better line configuration, as well as to see the behavior under different unbalance conditions. On the other hand, the harmonic generated by some electrical appliances can give rise to induced current of a higher value than that generated by the fundamental frequency field. In the case of electrical lines, the FFT analysis of the generated fields has found, fundamentally, a fifth harmonic.

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