Estimation of electric and magnetic fields in a 230 kV electrical substation using spatial interpolation techniques

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Abstract
This study presents the estimation of the electric and magnetic fields level inside a 400 MVA electrical substation. Located in the northeast region of Brazil, the power plant operates with 230 and 69 kV at 60 Hz frequency. The on-site measurements were performed at previously selected locations covering the whole courtyard and followed the international and national regulatory standards. The electrical and magnetic fields 2-D contour maps over the entire courtyard are presented, which allow better visualisation and analysis of the exposure levels around all equipment. By using the GoldenSurfer V.13 tool, eight interpolation methods were applied to predict unsampled locations. The plots were made using the method that best fit the sampled dataset after the cross-validation technique is used. The measurements were taken during six days during a period of 16 h on 741 locations. For this electrical substation, the maps validate the high electric field level close to breakers and switches at 230 kV and high magnetic field close to equipment operating at 69 kV. The comparison between the exposure levels and those established in current guidelines indicate that the electromagnetic environment on this substation is safe for the occupational population as well as for the general public.

1 | INTRODUCTION

Since the 20th century, the demand for electrical energy and constant technological advances have changed the social behaviour of humanity and guided the population to growing exposure to artificial sources of electromagnetic radiation emission [1].

In Brazil, the largest country in South America, the electric power system operates predominantly at 60 Hz. To respond to this increasing electricity consumption, the country continues to expand its transmission systems, especially the 230 kV voltages lines throughout the entire territory. Thus, it is common to experience high voltage (HV) transmission lines and power substations near the large urban centres and, therefore, near areas of large circulation of people.

However, since Wertheimer and Leeper have published a pioneering study linking the intensity of electromagnetic fields (EMF) emitted by transmission lines to the development of leukaemia in children [2], the scientific community has been warned of possible adverse effects on human health from EMF exposure.

But chronic effects such as cancer have been discredited by study groups from leading institutions in many countries, such as the International Agency for Research of Cancer [3], the National Radiological Protection Board [4], and the World Health Organisation [1].

At the same time, these institutions recognise the occurrence of biological effects on living organisms during short-term exposure as well as the need to establish exposure limits to allow people to walk or work safely around electrical equipment in the most various frequency ranges [1–4].

In this context, the International Commission on Non-Ionising Radiation Protection (ICNIRP) was created, which is used as the reference guideline for the Brazilian regulatory...
agencies [5] to establish the maximum levels of exposure to electric and magnetic fields for the public in general and occupational population in various frequency ranges [6, 7].

Table 1 presents the electric and magnetic quasi-static fields short-term exposure level at 60 Hz, as indicated by ICNIRP [7], for each population type. It can be observed that the level of magnetic field exposure can also be expressed in terms of magnetic flux density, $B$.

The international and national prominent standards presented in [8, 9], respectively, are the guidelines for measurement practices, which characterise the proper instrumentation for the determination of extremely low frequency electric and magnetic field levels.

In the literature, there are numerous researches to develop computational measurements and/or modelling techniques to determine the EMFs around and inside HV electrical substations. In [10, 11], the finite element method-based modelling is proposed, aiming to determine the electric and magnetic field intensities while still in the substation design stage. For substations already deployed, measurements near sensitive areas, such as schools, were investigated in [12], while in [13], the electric and magnetic field levels were determined around HV substation equipment at different levels. In [14, 15], HV substations were investigated in terms of the magnetic field and current levels in which the 2-D contour maps results were obtained analytically based on the Biot–Savart Law. In [16, 17], the contour maps are obtained by estimation, but the methodology used is unclear. On the other hand, spatial interpolation methods have been satisfactorily applied in the elaboration of electromagnetic exposure maps for high-frequency sources [18–20]. As expected, even though adopting the same protocols and instrumentations, the measurements around power lines and electrical substations in different locations of the world result in different values for the electric and mainly magnetic fields [20]. It indicates that a set of equipment composing a power plant propagates EMF with magnitudes that vary with the voltage levels, current, and layout of each installation.

This study aims to determine the electric and magnetic fields level into a zone delimited for electrical equipment operating outdoor of a substation at 230 kV/60 Hz that integrates the Brazilian power line transmission system. For this, on-site measurements were performed at previously established points with the aid of an isotropic meter that simultaneously measures electric field, $E$, and magnetic flux density, $B$, as advised in [8, 9]. A contour map is presented based on spatial interpolators that correlate the EMF magnitudes with their distribution in the space. The estimated EMF values beyond the measured points, similar to those discussed in [18–20], are also provided, which allows the identification of the areas with a higher incidence of electric and magnetic fields. The levels obtained are compared with those established in [7], to verify if the values found for $E$ and $B$ are within the acceptable exposure limits, with emphasis on occupational exposure.

2 | METHODOLOGY

2.1 | Electrical substation description

The object of this study is a 400 MVA step-down electrical substation, 60 Hz, installed outdoor, on an area of 107.550 m², located in the northeast region of Brazil and part of the Sistema Interligado Nacional, that is, the Brazilian electric power National Interconnected System.

Figure 1 shows an aerial view of the electrical substation, in which it is observed that it is installed in a populated area, whose neighbourhood is marked by highways and residential and commercial areas.

Within the borders limiting the electrical substation (trapezoid shape), a 34.650 m² courtyard is reserved for the equipment. Mostly, one can find electrical switchgear, protection equipment such as air-insulated disconnect switches, $N$ circuit breakers, current and voltage transformers, and transformers operating at different voltages, and loads whose arrangement in space can be seen in Figure 2.

The substation is powered by three three-phase initial circuits with three conductors at 230 kV (L1, L2, L3) and connected to a flexible double bus-single breaker with five disconnect switches. Then, it is interconnected to $4 \times 100$ MVA transformers (T1, T2, T3, T4), which reduce the 230 kV voltage to 69 kV, with T2 and T3 capable to provide a new 13.8 kV transforming voltage that feeds the auxiliary circuits of command and control.

### Table 1: International Commission on Non-Ionising Radiation Protection Reference Levels [7]

| Population Types         | Electric Field (kV/m) | Magnetic Field (A/m) | Magnetic Flux Density (µT) |
|--------------------------|-----------------------|----------------------|---------------------------|
| General Public Exposure  | 4.17                  | 160                  | 200                       |
| Occupational Exposure    | 8.33                  | 800                  | 1000                      |

**FIGURE 1** Aerial view of substation terrain boundaries (perimeter and courtyard) and its vicinity (highway and residential and commercial constructions)
The 230 kV output circuits (L4 to L8) feed other transmission substations in the region, including a wind power plant, which requires an additional 22.14 MVar reactor on 230 kV busbar.

In the 69 kV zone, there are nine output circuits (L9 to L17) supplying other substations and customers at this voltage level, as well as a flexible double bus-single breaker with three disconnect switches, a grounding transformer (T8) and a particular
transformer of 20 MVA (T7) that serves a specific customer at 69/3.3 kV voltages.

Among the equipment, at 13.8 kV stand out four capacitor banks of 3.6 MVar, three reactors (R2 to R4) at 5 MVar, and two power transformers.

It is understood that there are equipment in three different voltage levels located in the courtyard of this substation, and those in 230 kV occupy a larger area. Due to their higher voltage, the equipment requires greater distance from each other than those of smaller voltages as well as greater heights.

In this context, it is important to note that the top of the 230 kV equipment has an average height of 3.8 m above the ground level, while the 69 and 13.8 kV are 1.9 m in height.

### 2.2 | EMF measurement

In order to characterise the exposure to the EMF in the zone delimited by the equipment composing the substation, 741 spacing of 5 x 5 m, except the 230 kV busbar has a fairly long longitudinal dimension of 231 m in length, and 69 kV busbar, has a small latitudinal dimension of 14 m. Thus, the 230 kV busbar had the spacing of its grid increased in the longitudinal dimension, forming a 5 x 16 m grid sampling points were distributed over the whole courtyard. The regions close to the equipment are gridded in a regular way, while the 69 kV busbar had its grid reduced to 2 m x 5 m.

It is also worth mentioning that samples were suppressed when, due to spacing, the location of the points overlapped with the location of the equipment or the bases of the metal structures that anchor the conductors.

In Figure 3, it is possible to see the location of some of the 741 sampled points chosen on the substation courtyard disposed from top to the bottom and from left to right.

For data collection, a Tenmars isotropic meter, TM-190, capable of performing omnidirectional measurements and returning the root mean square (RMS) value of each field, was used. The TM-190 functionality allows simultaneous measurements of the electric field, \( E \), in V/m and magnetic flux density, \( B \), in \( \mu T \) by using free-space measuring mechanisms for the electric field and induction coils for the magnetic field.

Other instruments such as a Garmin GPSMAP 78s device, to georeference the sampling points and enable the elaboration of contour maps, as well as measuring tapes to assist the operator between the adopted spacers and a tripod in polyvinyl chloride, to isolate the meter from the inductive effects of soil were used during the measured campaign. Figure 4 shows the tripod coupled to TM-190 meter and near to the reactor R1 during measurements.

To minimise the operator influence on the electric field measurements, a minimum distance of 2.5 m between operator and meter was adopted [8].

Other protocols have also been adopted, as recommended in [8, 9], such as prevention of people moving around the measurement locations, turning off any electronic equipment that is not part of the required instrumentation, taking measurements during peak load times, recording the temperature and humidity conditions, and placing the meter 1.5 m above the ground [9].

Besides, the measurements were taken in a 6-day period from 8:00 to 12:00 AM, where the electrical substation had stabilised to its normal operating values, which means the transformers were operating at 42% of its capacity.

In this time interval, the greatest amount of peak current occurs, according to the frequency histogram of Figure 5. It
TABLE 2 Voltage and current levels during measurements

| Circuits | Voltage (kV) | Current (A) | Circuits | Voltage (kV) | Average Current (A) |
|----------|-------------|-------------|----------|-------------|---------------------|
| L1       | 230         | 90          | L17      | 69          | 160.26              |
| L2       | 230         | 91.73       | T1       | 230         | 107.93              |
| L3       | 230         | 417.2       | T2       | 230         | 110.36              |
| L4       | 230         | 29.66       | T3       | 230         | 110.63              |
| L5       | 230         | 68.3        | T4       | 230         | 112.83              |
| L6       | 230         | 13.15       | T1       | 69          | 344.13              |
| L7       | 0           | 0           | T2       | 69          | 351.1               |
| L8       | 230         | 22.2        | T3       | 69          | 344.66              |
| L9       | 69          | 120.43      | T4       | 69          | 356.66              |
| L10      | 69          | 149.53      | T5       | 13.8        | 210.83              |
| L11      | 69          | 20.8        | T6       | 13.8        | 0                   |
| L12      | 69          | 71.0        | T7       | 69          | 52.16               |
| L13      | 69          | 127.86      | R1       | 0           | 0                   |
| L14      | 69          | 250.53      | R2       | 13.8        | 207.06              |
| L15      | 69          | 177.9       | R3       | 0           | 0                   |
| L16      | 69          | 343.8       | R4       | 0           | 0                   |

correlates the number of times the maximum peak current takes place in the equipment with the time of occurrence per day.

During the measurements, the temperature conditions varied from 28 to 33°C, while the humidity ranged from 64% to 70%.

As previously reported, the various equipment in this substation is at different voltage and current levels. Table 2 presents the voltage levels of the respective circuits and average current values observed during the measurements for each circuit. The conductors of the same circuit are balanced, which constitute the normal operation levels of the substation in times of maximum demand.

Table 2 also shows that the supply circuit L3 followed by the 69 kV output circuit of T4 are the most loaded circuits; the circuit L7 was disconnected, and from the reactors, only R2 was in operation during the measurements.

In addition, only the 230 kV main busbar of the double bus was in operation, while for the 69 kV busbar, both buses were being used.

2.3 Spatial interpolation

For the development of 2-D contour maps, one uses interpolation methods that estimate unsampled values near measured points through a continuous function that reflects the behaviour of these points in space [18].

There are several interpolation methods, which are classified into spatial statistics, such as the kriging method; spatial geometry, such as nearest neighbour and inverse distance weighting techniques; and algorithm functions, including linear, cubic forms, and so forth [19].

Here, seven interpolation methods were applied using the GoldenSurfer V.13 computational tool. They are distance weighted inverse method, minimum curvature, modified Shepard’s method, natural neighbour (NaN), nearest neighbour, triangulation with linear interpolation, and ordinary kriging (KO).

The kriging method was used with different types of semivariograms, such as linear, Gaussian, cubic and exponential (KO-E).

The method that best fits the sampled dataset, and thus presents greater accuracy when estimating EMF values, is selected using statistical parameters. The RMS error (RMSE), presented in Equation (1) and the mean absolute error (MAE), given in Equation (2), are obtained using the cross-validation technique:

\[
RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} [Z'(x_i) - Z(x_i)]^2} \quad (1)
\]

\[
MAE = \frac{1}{n} \sum_{i=1}^{n} |Z'(x_i) - Z(x_i)| \quad (2)
\]

where \(n\) is the number of samples, \(Z(x_i)\) is the measured point, and \(Z'(x_i)\) is the point estimated by the interpolator.

The cross-validation technique consists of suppressing a sample from the dataset and then estimating it by interpolation, which is then compared to the actual value of the sample so that a prediction error can be deduced for the entire sample frame when the process is repeated numerous times for all samples in the same dataset [20].
TABLE 3 Cross-validation results for interpolation methods

| Method  | Electric field | Magnetic flux density |
|---------|----------------|-----------------------|
|         | Root mean square error (RMSE) (V/m) | Mean absolute error (MAE) (V/m) | RMSE (µT) | MAE (µT) |
| IDW     | 406.6809       | -1.2138               | 2.1834     | 0.1054    |
| MC      | 381.7896       | 0.4291                | 1.7218     | 0.00028   |
| MSM     | 404.1507       | 14.9529               | 2.2583     | 0.1941    |
| NaN     | 360.7801       | -11.9486              | 1.5851     | -0.01651  |
| NeN     | 485.265        | 3.7083                | 2.1551     | -0.0107   |
| TLI     | 376.6288       | -6.764                | 1.675      | -0.0255   |
| KO-L    | 357.3292       | -0.6681               | 1.6687     | 0.0072    |
| KO-G    | 366.2395       | 2.5901                | 2.0764     | 0.0133    |
| KO-C    | 362.8564       | 2.7718                | 1.6049     | 4.4086    |
| KO-E    | 355.2718       | 0.4437                | 1.715      | 0.0255    |

Note: IDW is distance weighted inverse; MC is minimum curvature; MSM is modified Shepard’s method; NaN is natural neighbour; NeN is nearest neighbour; TLI is triangulation with linear interpolation. The kriging method (KO) used with different types of semi-variograms: Linear (KO-L), Gaussian (KO-G), cubic (KO-C) and exponential (KO-E).

TABLE 4 Maximum, minimum and average points of $E$ and $B$

|                          | Maximum | Minimum | Average |
|--------------------------|----------|---------|---------|
| Electric field (V/m)     | 1.996    | 2       | 797     |
| Magnetic flux density (µT)| 30       | 0.02    | 3.56    |

The RMSE parameter expresses the accuracy of the method, while the MAE indicates if there is bias in the samples. Then, the smaller the RMSE is, the more accurate the interpolator, and the closer to zero the MAE value is, the better the estimation [18].

3 RESULTS AND DISCUSSION

Table 3 presents the cross-validation results for each of the spatial interpolation methods applied, in terms of RMSE and MAE, for the electric field, $E$, and magnetic flux density, $B$.

Thus, for the electric field, the exponential semi-variogram for kriging method (KO-E) stood out in terms of RMSE with 355.2718 V/m while presenting an MAE close to zero, with a value of 0.4437 V/m. For the magnetic field, NaN interpolation presented the lowest RMSE with a value of 1.5851 µT and an MAE of -0.01651 µT selected as the most satisfactory method.

Figure 6 shows the contour map of the electric field, $E$, in V/m around the substation courtyard equipment obtained by KO-E interpolation. Figure 7 shows the contour map of exposure to the magnetic field in terms of magnetic flux density, $B$, in µT based on NaN interpolation. Table 4 presents the maximum, minimum, and average levels of $E$ and $B$ obtained over the exposure zone.

It is observed in Figure 6 that larger values of the electric field, indicated by curves with a darker colour ranging between 1.600 V/m and 2.000 V/m, are obtained in the regions closest to equipment submitted to the highest voltage level (230 kV), such as circuit breakers and disconnect switches, while equipment at 69 kV is subjected to levels of $E$ below 1000 V/m and at 13.8 kV to values below 600 V/m.

It is also verified that lower electric field levels, less than 200 V/m (white colour), are obtained near the reactors, the 230 kV
transfer busbar and the L7 circuit. This occurs because this equipment does not present voltage at their poles since they were not in operation during the measurement.

For the magnetic field, Figure 7, it is observed that small magnetic flux density values below 6 µT, illustrated in the lighter colour, are obtained in most of the courtyard, while the highest values are concentrated near the equipment at 69 kV. This is because, in general, the conductors and equipment of this area have higher loading, they are also closer to the ground and, therefore, closer to the measuring point than the 230 kV equipment. As the EMF decays with the source distance in all directions, either in the vertical or horizontal plane, points closer to the source are subjected to higher EMF intensities.

Furthermore, a higher intensity around 14 µT is felt near the L3 circuit equipment because of its high loading around 417.2 A.

From Table 4, it is understood that there is a wide variation of electric field and magnetic flux density around the courtyard equipment. The 1.996 V/m electric field peak occurs near the L5 circuit breaker, while the maximum magnetic flux density peak of 30 µT occurs near the disconnect switches and circuit breakers of the T4 transformer output, which has the largest charging in the 69 kV area, 356.66 A.

However, most of the courtyard is exposed to levels of 797 V/m and 3.56 µT, which is 9.56% and 0.36% of the limits set by ICNIRP for occupational exposure to the electric field and magnetic flux density, respectively.

Even considering the maximum values in Table 4, only 23.96% and 3% of the limits established for occupational exposure to the electric field and magnetic flux density, respectively, are reached.

Even for the general population, that is, the general public who, for some reason, circulates in the vicinity of the most heavily loaded equipment would be subject to less than 50% of the electric field exposure limit and 15% of the established limit for exposure to the magnetic field in terms of flux density.

4 | CONCLUSION

Systematic measurements were made around the equipment in the courtyard of a 23069 kV substation in Brazil. In addition, contour maps were obtained through interpolation methods validated by statistical parameters and then overlapped on the substation layout. The contour maps allowed an analysis of the location of maximum EMF exposure points, which demonstrated that the 1.996 V/m maximum electric field and the 30 µT of maximum magnetic flux density are obtained close to a specific circuit breaker in 230 kV for electric field and 69 kV for magnetic flux density. These maximum values do not exceed the limit set by ICNIRP, either for occupational exposure or for the general public itself, either for electric field or magnetic field, expressed in terms of B in this article.

Thus, it is concluded that point measurements combined with interpolation estimation fulfilled the objective of this work, allowing the diagnosis that the whole exposure zone, that is, the whole substation courtyard constitutes a safe environment in terms of occupational exposure and non-occupational exposure to EMF.

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