CALCULATION METHODOLOGY AND COMPUTATIONAL ANALYSIS OF THE MAGNETIC FIELD OF TRANSMISSION LINES OPERATING AT STEADY STATE

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Abstract - **This paper aims to present a model to compute the magnetic fields generated by transmission lines operating at steady state. After analytical modeling, it will be introduced a Matlab® computational routine developed to calculate the magnetic fields in transmission lines. To validate and to prove the reliability of the computational simulation tool, some comparisons with literature will be presented.**

Keywords – **Magnetic fields, Matlab®, Modeling, Steady state, Transmission line.**

I. INTRODUCTION

The electricity generation uses the electrical power transmission lines to carrying energy to the consumers centers. In fact, the Brazilian national energy matrix, where hydroelectricity predominates, has river basins geographically distant from each other, and this makes transmission lines perform a significant role in electric power system, interlinking the generation centers to consumer units in the country [1]-[2].

Transmission lines are considered one of the primary sources of electromagnetic fields. Some transmission lines are built nearby preservation areas, commercial and industrial zones, and residential areas. This fact implies some concern in local population about biologic effects, due to exposure to electromagnetic fields and interferences in electronic systems [2]-[3].

Therefore, accredited international institutions, like International Commission on Non-Ionizing Radiation Protection (ICNIRP), makes regulations to set limits for human exposure to electric and magnetic fields. The levels established to magnetic flux density for frequencies about 1 Hz – 100 kHz to the general public is 200 µT. So that, energy utilities have to conform to these values, performing measurements and computing the magnetic field on transmission lines [4]-[5].

Therefore, this paper aims to present a modeling of the magnetic fields produced by transmission lines, estimate these fields through a computational simulation, as well as, validate it comparing the results with the contemporary literature.

II. FUNDAMENTALS CONCEPTS OF TRANSMISSION LINES

Generation, transmission, distribution, and commercialization of electricity compose the electric power system. On account of increasing demand for energy, the electric power system has been developed, and that implies, in the last years, the growing of studies beyond transmission lines [6].

The transmission line is composed of conductors, insulators, support structures and shielded wires. Aluminum wires have replaced copper conductors and nowadays, they are used more frequently in the transmission lines. Although, the cross section of aluminum conductors may be larger to compensate the losses, they are cheaper, lighter-weight and are more abundant in nature. As a result, they are widely used in the transmission line.

Insulators consist of a string of discs made of porcelain, toughened glass or polymer. The number of insulators discs in sequence increases with the line voltage of the transmission line.

Transmission lines have a variety of support structure. Their characteristics change according to operating voltage of transmission line. Phase conductors can be arranged both in a triangular configuration to minimize the height of the tower or in a vertical configuration to reduce the width of the tower.

Shielded wires are located above the phase cables and protect it against lightning. They are mostly made of aluminum with high strength with a smaller cross section than the phase cables. The number of shield wires depends on the structure of the tower; it is necessary to protect all components of the transmission line.

Transmission lines can operate in steady state, with frequencies between 50 Hz and 60 Hz, the focus of the work, or in the transitional state, where the frequencies can reach up to 10 MHz. The voltage levels of transmission lines vary due to physical parameters, environmental and economic factors. The rising voltage on a transmission line increases the electromagnetic interference levels in their passband, which can be harmful to the commercial and residential zones nearby, and living beings within the passband [7].

Therefore, computing and modeling magnetic fields are extremely importance to measure how these fields may interfere directly in the lives of people who live close to the transmission lines. This paper studies and model magnetic fields, presented on topics in following and after that, shows the results of the calculus of magnetic fields through a computation routine developed.

III. MODELING THE MAGNETIC FIELDS

The electromagnetic fields in transmission lines operating in steady state, can be analyzed separately through the electric coupling and magnetic coupling.

The variable electric current generates the magnetic fields in time in phase conductors. Before developing a model of the magnetic field, it's necessary to establish some considered premises as usual to electromagnetic problems.

In transmission lines analysis, their characteristics are considered three-phase, overhead, balanced, and uniform. They operate in state steady at 50 Hz-60 Hz. Voltages applied to phase conductors are balanced, in another words, they have same amplitude within 120° displacements between any phases and phase sequence A-B-C. Typical operating conditions base the current calculation. For this reason, they are calculated according to the nominal power in the transmission line.

The distances between phase cables and an observation point of the magnetic field have to be a few tens of meters away. This allows to approach phase cables with a small radius. So that, the distances between all conductors in the transmission line is considerate much larger than their respective radius. The length of conductor is of the order of hundreds of kilometers. Then, in practical terms, they can be approached to conductors that tend to infinite.

The ground of the systems in the study is considered homogeneous, linear and isotropic. For this reason, the electromagnetic properties do not vary, and the ground is considered a perfect electric conductor [6].

After all premises, it is possible to model the magnetic field through Ampere's Law. There are many ways to model and calculate the magnetic field through Ampere's Law. This paper shows two different ways of calculation, mentioned on subtopics below.

A. Analytical method

Ampere's law establishes in its integral form, showed in (1) [6], that line integral of the tangential component of magnetic field, H [A/m], around of a closed path is equal contour current, I_C [A], involved in this path.

$$\oint_C \vec{H} \bullet \overrightarrow{d\ell} = \int_S \overrightarrow{J_C} \bullet \overrightarrow{dS} = I_C \qquad (1)$$

How abovementioned, all conductors of the transmission line approach to infinite length. Thus, the solution of the (1) to an infinite length filament is demonstrated in (2) [6].

$$\vec{H} = \frac{I}{2 \cdot \pi \cdot \rho} \cdot \widehat{a_\emptyset} \left[\frac{A}{m} \right] \qquad (2)$$

Where I [A] is the current flowing through the transmission line, ρ [m] is the vertical distance between source point and the observation point of the magnetic field and $\widehat{a_\emptyset}$ is the cross product between current vector $(\widehat{a_L})$ and the position vector $(\widehat{a_\rho})$, established in (3) [6], which indicates the meaning and direction of the magnetic field at the observation point.

$$\widehat{a_\emptyset} = \widehat{a_L} \times \widehat{a_\rho} \qquad (3)$$

Equation (2) is just valid to estimate of the magnetic field in one unique environment, in this case, the air is considered the physical medium. But, the ground has influence in the magnetic field as well, and its addiction is used in the method of images.

B. Method of images

The method of images establishes that a given current configuration can be substituted for the own image below of the plan since this one be an infinite perfect conductor. As previously stated, the ground is considered a perfect electric conductor, as showed in Figure 1 for a three-phase system.
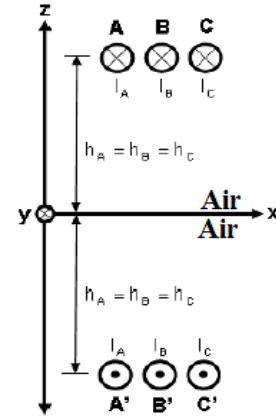

Fig. 1. The method of images to a three-phase system [6].

Therefore, the magnetic fields at an observation point are given for the overlap of the two magnetic fields, generated by a real and imaginary current. So, a term imaginary can be added in (2), indicated in (4) [6].

$$\overrightarrow{H_T} = \sum_{I=1}^{N} \frac{I}{2 \cdot \pi \cdot \rho_R} \cdot \hat{a}_{\emptyset R} + \sum_{I=1}^{N} \frac{I}{2 \cdot \pi \cdot \rho_I} \cdot \hat{a}_{\emptyset I} \left[\frac{A}{m} \right] \qquad (4)$$

In which, N is the number of phase cables of the transmission line, and the suffix "R" represents the components of the real currents and the suffix "I" represents the elements of the imaginary currents. The relationship between the magnetic field H [A/m] and the magnetic flux density B [T] is demonstrated in (5) [6].

$$\vec{B} = \mu_0 \cdot \vec{H} \ [T] \qquad (5)$$

Where μ_0 [T·m/A] is the magnetic permeability of vacuum. All aforementioned equations are fundamental to the problem in question on electromagnetic perspective.

According to the models of magnetic fields, it was designed and developed a computational routine; that performs the magnetic fields calculation to evaluate its behavior, based on

the two methods present in the literature, the analytical method and the method of images.

IV. ANALYSIS AND RESULTS

After the definitions of mathematical methods for computation magnetic fields, as previously stated; it was developed on Matlab®, software used to make advanced calculations and simulations, a computational algorithm to calculate magnetic fields produced by transmission lines.

Therefore, it is crucial to confirm the veracity and reliability of the results of the computational tool. In order to do so, the results are compared with computational results and magnetic fields measurements, disseminated in actual literature.

A. Comparison of computational results disclosed in the literature

1) Reference [6], by Hugo Rodrigues Vieira, 2013

In 2013, Hugo Rodrigues Vieira [6] realized a study on the magnetic fields generated by one meter from the ground on three different systems of transmission lines, operating at 60 Hz as described and presented below in Table I and Figures 2, 3, and 4.

- System 1 – Janaúba-Salinas Transmission Line (138 kV)

Table I – System 1 Configuration

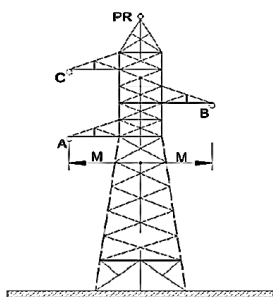| Electrical and Geometrical Configuration – System 1	
Voltage Level	138 kV
Average Height Phase A	12.15 m
Average Height Phase B	14.01 m
Average Height Phase C	15.87 m
M	3.00 m
Current Level	146.43 A

Fig. 2. System 1 Structure [6].

- System 2 – Pimenta-Barbacena Transmission Line (345 kV)

Table II – System 2 Configuration

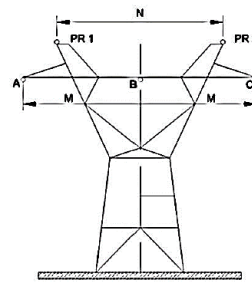| Electrical and Geometrical Configuration – System 2	
Voltage Level	345 kV
Average Height Phase A	14.00 m
Average Height Phase B	14.00 m
Average Height Phase C	14.00 m
M	9.50 m
Current Level	418.3 A

Fig. 3. System 2 Structure.

- System 3 – São Gonçalo-Ouro Preto Transmission Line (500 kV)

Table III – System 3 Configuration

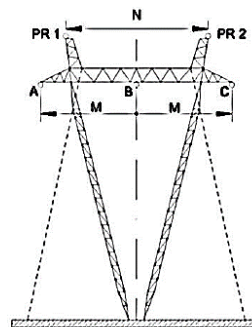| Electrical and Geometrical Configuration – System 3	
Voltage Level	500 kV
Average Height Phase A	16.53 m
Average Height Phase B	16.53 m
Average Height Phase C	16.53 m
M	10.25 m
Current Level	837.15 A

Fig. 4. System 3 Structure.

The magnetic fields were calculated from the distance to the center structure line, and the cross-section analyzed is 30 meters on each side of the center line. Using the method of images and all premises mentioned in section III, the Figure 5 and Figure 6 represent, respectively; the values calculated by [6] and the values obtained as a result of this research for all systems.
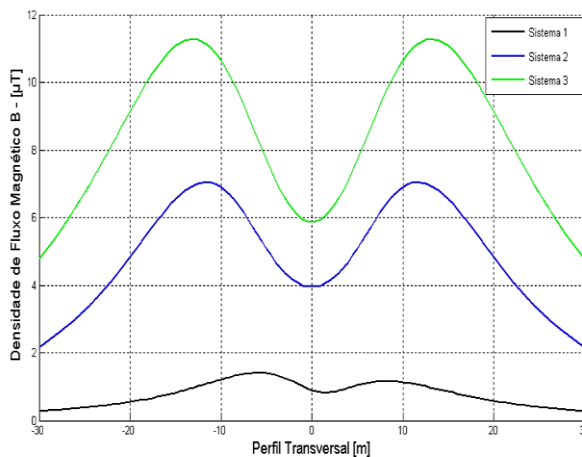

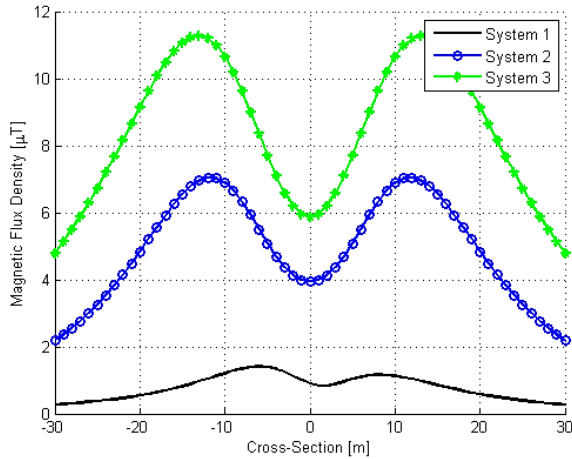Fig. 5. Curves of the magnetic fields obtained by [6].

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Fig. 6. Curves of the magnetic fields obtained by Matlab Algorithm Calculation.

It is verified by Figure 5 and Figure 6 that there is a great similarity in the behavior of the curves presented by [6] and the curves simulated in this paper. Table IV shows a comparison of these values and confirms the veracity of the computational tool.

Table IV – Comparison between calculated values by [6] and calculated in this paper

System 1			
Position (m)	Calculation by [6] (µT)	Matlab Algorithm Calculation (µT)	Difference (%)
Limit: -30	0.26	0.26	0
Limit: +30	0.27	0.27	0
0	0.89	0.89	0
Max Value	1.40	1.40	0
System 2			
Position (m)	Calculation by [6] (µT)	Matlab Algorithm Calculation (µT)	Difference (%)
Limit: -30	2.17	2.17	0
Limit: +30	2.17	2.17	0
0	3.95	3.95	0
Max Value	7.04	7.04	0
System 3			
Position (m)	Calculation by [6] (µT)	Matlab Algorithm Calculation (µT)	Difference (%)
Limit: -30	4.78	4.78	0
Limit: +30	4.78	4.78	0
0	5.86	5.86	0
Max Value	11.27	11.27	0

As can be seen in Figure 5, the systems 1, 2 and 3 were simulated simultaneously on the same graph in the research of the author [6]. For better comparison, the systems are also simulated in the same graph in this paper. The calculations of the author, and of this study were made using the method of

images, considering the effect of ground on the resultant magnetic field. The results were satisfactory, where there was no difference between any point of the curves. This may be due computational calculation, where there is no margin for error, since the input values and the same formulations were used.

B. Comparison of measurement results disclosed in the literature

1) Reference [8] by Jaime Arturo Ramirez, 2001

In 2001, Jaime Arturo Ramirez elaborate a study about electromagnetic fields in electrical power system. The author calculated and measured magnetic fields for some structures, but this paper will analyze just one kind of them. This structure is a typical configuration with 345 kV voltage level. It is showed in Figure 7, and geometrical, and electrical configuration this structure is represented in Table V.

Table V – Configuration of the structure 345 kV used by [8]

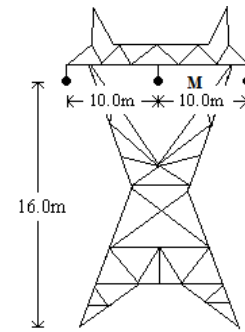| Electrical and Geometrical Configuration – 345 kV	
Voltage Level	345 kV
Average Height Phase A	16.00 m
Average Height Phase B	16.00 m
Average Height Phase C	16.00 m
M	10.00 m
Current Level	140 A

Fig. 7. Structure 345 kV used by [8].

The magnetic fields were calculated from the distance to center structure line and the cross-section analyzed is 40 meters to the right side of the center line. Using the analytical method and all premises mentioned in section III, the Figure 8 and Figure 9 represent, respectively, the values calculated and measured by [8] and the values obtained as result of this research.
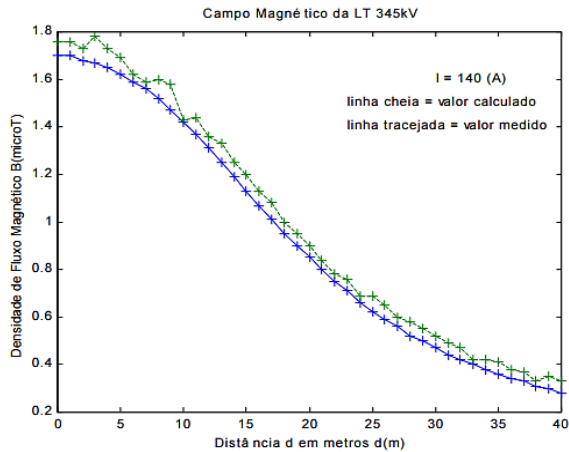
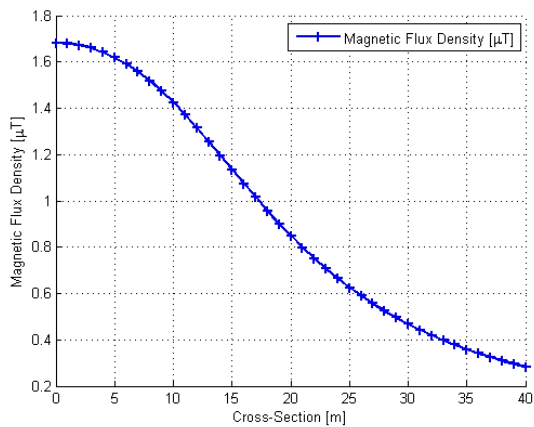Fig. 8. Curves of the magnetic fields measured and calculated by [8].

Fig. 9. Curve of the magnetic field obtained by Matlab Algorithm Calculation.

The Figure 8 has two curves, upper line (green) and bass line (blue). The upper line curve represents the measurement of the magnetic field, and the bass line curve represents the calculation of the magnetic field. The Figure 9 is similarity to both curves, what prove the veracity of the computational tool, because the errors were minimal. Table VI confirm this results.

Table VI – Comparison between measured values by [8] and calculated values in this paper.

Position (m)	Measured by [8] (µT)	Matlab Algorithm Calculation (µT)	Difference (%)
0	1.75	1.56	-8.62

The analysis and calculating method used for the system 4 simulation are based in analytical method. As can be seen in Figure 8 and Figure 9, the behavior of the three curves, simulated and measured by the author [8] and the simulated curve in this paper, is equivalent. Simulated values also did not get errors because the values used were the same. However, between the author [8] measurement and Matlab simulation, there was a difference of -8.62% in the zero position. This variation can occur for several reasons. One of them, that the operating current at the time of measurement may vary due to the line's stability. Physical configuration can

also vary as the average line height, due to wind or temperature at the location.

2) Reference [9] by Gernan Edson Guimarães, 2005

In 2005, Gernan Edson Guimarães realized a study about a transmission line operating 500 kV voltage level. The Table VII shows the configuration of the line and Figure 10 illustrates the structure analyzed.

Table VII – Configuration of the structure 500 kV used by [9]

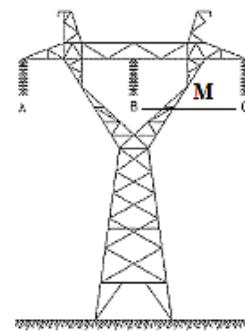| Electrical and Geometrical Configuration – 500 kV	
Voltage Level	500 kV
Average Height Phase A	18.06 m
Average Height Phase B	18.06 m
Average Height Phase C	18.06 m
M	12.00 m
Current Level	650 A

Fig. 10. Structure 500 kV used by [9].

The magnetic fields were calculated from the distance to the center structure line and the cross-section analyzed is 35 meters on each side of the center line. The transmission line operates at 60 Hz. Using the analytical method and all premises mentioned in section III, the Figure 11 and Figure 12 represent, respectively; the values calculated and measured and simulated by [9] and the values obtained as a result of this paper.
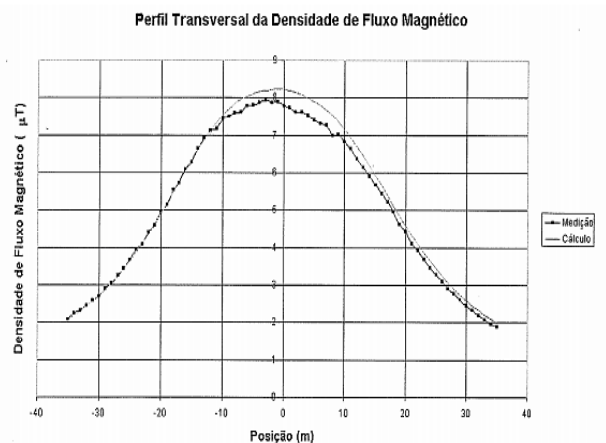

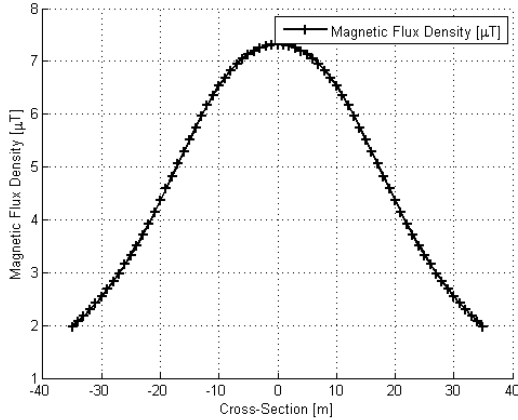Fig. 11. Curves of the magnetic fields measured and calculated by [9].

Fig. 12. Curves of the magnetic fields obtained by Matlab Algorithm Calculation.

The Figure 11 has two curves, the dotted line and a full line. The Dotted line curve represents the measurement of the magnetic field, and the full line curve represents the calculation of the magnetic field. The Figure 12 is similar to both curves, so it proves the veracity of the computational tool. Table VIII confirm this results.

Table VIII - Comparison between measured values by [9] and calculated values in this paper

Position (m)	Calculation by [9] (μT)	Matlab Algorithm Calculation (μT)	Difference (%)
0	7.80	7.32	-6.15
-35	2.00	1.97	-1.50
+35	1.90	1.97	3.68

The system 5 analysis is similar to system 4. Figure 11 and Figure 12 shows how the behavior of the curve measured and simulated by [9] and simulated curve in this paper is equal. However, values measured by [9] and simulated values in this study were different. In the zero horizontal position, for example, the difference was -6.15%. The reason for this variation can be the same as cited for the system 4.

C. General analysis of the results.

Base in all curves of the magnetic fields, can observe some results:

- The magnetic fields level does not exceed the reference level established by ICNIRP, previously stated in section I.
- The addition of the ground in the calculation changes the behavior of the curves even considered a perfect electric conductor.
- The magnetic fields are intensified with current increasing.
- The magnetic field is also sensitive to the geometry of the structure and changes its behavior.
- Measurements can vary from simulations due to physical and electrical effects on the measurement time.

In fact, the accuracy and reliability of the Matlab computational algorithm developed, makes values and shape of the magnetic fields in a transmission line, readily available.

V. CONCLUSIONS

Initially, it was presented the physical and construction characteristics of a transmission line to show the origin of the magnetic field on transmission lines.

After carry out this analysis, it was possible to model the magnetic field for a transmission line with some assumptions embedded in the calculating methodology. Thus, a computational algorithm was built, in Matlab®, to calculate the magnetic field in a transmission line.

The validation of the magnetic field results was made by comparing some measurement and computational results presented on literatures in the area. Through graphs and numerical tables proved the reliability of the computational tool.

As previously mentioned, some analysis can be made from the results. For example, the magnetic field simulated for all configuration values do not exceed reference levels established by ICNIRP.

Finally, it was shown that the Matlab® computational algorithm introduced in this research is versatile and reliable since it can analyze any geometry and electrical characteristics of a transmission line with minimal errors on the final results.

REFERENCES

[1] O. L. Campos, "Estudo de caso sobre impactos ambientais de linhas de transmissão na Região Amazônica, " BNDES Setorial, vol. 32, pp. 231-266, September 2010.

[2] L.B. dos Reis, and E.C. Santos, Energia elétrica e sustentabilidade: aspectos tecnológicos, socioambientais e legais. São Paulo: Manole, 2015.

[3] L.A. Costa and V.B. Monteiro, "Minimização do campo magnético em linhas de transmissão, " December 2005.

[4] W.D. Becker, "Estudo de técnicas para redução de campos magnéticos gerados por linhas de transmissão de potência," 95p. MA Thesis. Universidade Federal de Santa Catarina, Florianópolis, 2008.

[5] International Commission on Non-Ionizing Radiation Protection. "Guidelines for limiting exposure to time-varying electric and magnetic fields (1 Hz to 100 kHz)," pp. 818-836, Health Physics, 2010.

[6] H.R. Vieira, "Acoplamento magnético entre linhas de transmissão operando em regime permanente e dutos metálicos aéreos," 158p. MA Thesis. Universidade Federal de São João del-Rei, 2013.

[7] Glover, J. Duncan, M. Sarma, and T. Overbye. Power System Analysis & Design, SI Version. Cengage Learning, 2011.

[8] J.A. Ramírez, "Campos Eletromagnéticos devido a Sistemas de Energia Elétrica." In press: Efeitos Biológicos Devidos à Ação de Campos Eletromagnéticos. São Paulo, 2001.

[9] G.E. Guimarães, "Medições e cálculos de campos elétricos e magnéticos de uma linha de transmissão de 500 kV," MA Thesis. Universidade Federal de Belo Horizonte, 2005.