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Monitoring Electromagnetic Fields and Safe Operation Levels in Electrical Power Transmission Lines

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Electrical power systems and their elements such as power transformers, transmission lines, capacitors, reactors and other elements, during normal operation generates electromagnetic fields that changes according with design, equipment distribution, current and voltage operation levels. This paper describes the monitoring electromagnetic fields and safe operation levels in electrical power transmission and distribution lines during the last five years in power lines located in warm climate with high salinity, corrosion and pollution level. A literature review was considered during the study. This paper characterizes power lines in order to guarantee safe operation to occupational exposure and general public since planning process. Results will be used in order to characterize power lines and will be used as a tool for utilities with the aim to reduce legal penalties and promote social responsibility. Results also were contrasted with International Commission on Non-Ionizing Radiation Protection (ICNIRP) recommendations with the reference levels for occupational exposure to time-varying electric and magnetic fields. Results provide recommendations for electrical grid utilities also the study compare real values with simulated values in order to guarantee an acceptable approach according with ICNIRP and international standards recommendations.
Keywords: electromagnetic field; safe operation levels; electrical power transmission and distribution lines; Non-Ionizing Radiation.

1. Introduction

The Population growth, industry development and the massive use of electric energy are part of the human modern civilization. To guarantee these needs, the security and reliability requirements of power lines seek to guarantee energy supply in urban centers, which implies generate a greater number of energy interconnection projects to supply the demand and complying security requirement. On the other hand, in order to guarantee reliability, it is required redundancy in elements, which implies a greater number of elements in operation to guarantee the required support to the requirements of the electrical energy markets and modern economic development generating additional electromagnetic fields affecting natural electromagnetic field. (Electric Power Research Institute, 2005).

The natural electric and magnetic field levels are 100 V/m and 70 μT respectively. Any additional values caused by electrical installations, communications systems and electrical energy transport systems are referred to as artificial electric and magnetic fields and are considered as electromagnetic pollution which is defined as excessive levels of electromagnetic spectrum radiation.

Electromagnetic pollution has always been a revised issue since the massification of interconnected systems and technological applications operating in the electromagnetic spectrum such as cell phones, radio, television and power transmission lines. However, all of these applications are considered non-ionizing radiation, since electric and magnetic fields are lower in magnitude and frequency, therefore they do not cause ionization. The electric and magnetic fields are ionizing when they are able to reseals electrons from the orbits of an atom, their frequency oscillates between $10^{16} Hz$ and $10^{22} Hz$. For that reason, electromagnetic fields that are under

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$10^{16} Hz$ are considered as non-ionizing radiation. However, they are capable to generate energy thought heat (Electric Power Research Institute, 2005).
In 1974, the International Radiation Protection Association (IRPA) integrate a working group on Non-Ionizing Radiation (NIR). During the Eight International Congress of the IRPA developed in 1992 a new independent scientific organization named International Commission on Non-Ionizing Radiation Protection (ICNIRP) which is charged to investigate the hazards related with NIR proposing guidelines to establish exposure limits. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) recommend an operational range of operation for electrical and electronics equipment such as power lines, communication systems and antennas (ICNIRP, 1998).
Table 1 shows the ICNIRP regulatory framework related with non-ionizing radiation established a recommended safety factors range operation in which electromagnetic field produced by electrical and electronic system may not be capable to produce health effects or occupational diseases.

Table 1. Exposure limit values to electromagnetic fields according to ICNIRP for occupational and general public exposure levels (ICNIRP, 1998).

Occupational exposure			General public level		
Frequency range	Electric Field (V/m)	Magnetic Field (uT)	Frequency range	Electric Field (V/m)	Magnetic Field (uT)
0 – 1 Hz	-	2×10^5	0 – 1 Hz	-	4×10^4
1 – 8 Hz	20 000	$(2 \times 10^5)/f^2$	1 – 8 Hz	10000	$(4 \times 10^4) / f$
8 – 25 Hz	20 000	$(2{,}5 \times 10^4)/f$	8 – 25 Hz	10000	5000 / f
0.025 – 0.82 kHz	500 / f	25 / f	0,025 – 0.8 kHz	250 / f	5 / f
0.82 – 65 kHz	610	30,7	0,8 – 3 kHz	250 / f	6.25
0.065 – 1 MHz	610	2 / f	3 – 150 kHz	87	6.25
------	-----	-----	0,15 – 1 MHz	87	0.92 / f
1 -10 MHz	610 / f	2 / f	1 – 10 MHz	$87f^{1/2}$	0,92 / f
10 – 400 MHz	61	0,2	10 -400 MHz	28	0,092
400 – 2000 MHz	$31 f^{½}$	$0{,}01f^{1/2}$	400 – 2000 MHz	$1{,}375f^{1/2}$	$0{,}0046f^{1/2}$
2 – 300 GHz	137	0,45	2 – 300 GHz	61	0,2

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ICNIRP indicates that there is not risk of exposure to electromagnetic fields caused by non-ionizing radiation, transmission power lines are still considered the major sources due to the increasing electricity energy demand required for final users. Also, the exposure to electric and magnetic field caused by non-ionizing radiation is still an open debate in science. Table 2 lists five recent works relating human diseases and occupational health problems with electromagnetic pollution. Other applications consider electric or magnetic field effect to promote applications in researches such as biomass production (Suárez, et al., 2017) or photovoltaic plants (Ramos et al., 2017).

Table 2. Five Related works with electromagnetic fields, occupational exposure and human health problems.

Human health problem	*Document type*	*Reference*
Neurological diseases: relate electromagnetic field exposure with Alzheimer's disease, Parkinson´s disease, amyotrophic lateral sclerosis and Huntington´s disease	*Review article*	*(Terzi, et al., 2016)*
Occupational exposure levels	*Research article*	*(Tsaprouni et al., 2018)*
Outdoor exposure level: residential, transformer stations, transport systems, personal exposure.	*Review article*	*(Gajšek et al., 2016)*
Non-ionizing radiation related with cancer disease.	*Review article*	*(McColl et al., 2015)*
Biological effect from electromagnetic field exposure	*Research article*	*(Kesari, Siddiqui, Meena, Verma, & Kumar, 2013)*

In Colombia, the National Electrical Code (RETIE) consider ICNIRP reference values for industrial frequency (60Hz) described in Table 3 establishing exposure hours (Ministerio De Minas Y Energía, 2013). This paper characterizes a five years operation electromagnetic field registered in a power transmission line in

Barranquilla, Colombia. In order to guarantee safe operation to occupational exposure and general public. Results will be chosen to characterize power lines and use the results for future events and similar structures where it is unknown the contribution of electric and magnetic field of a system.

Table 3. Limit values for exposure to electromagnetic fields (Ministerio De Minas Y Energía, 2013).

Exposure level	Electric Field (kV/m)	Magnetic Field (uT)	Exposure level
Occupational exposure on an eight-hour workday	8,3	1000	Occupational exposure on an eight-hour workday
General public exposure up to eight continuous hours	4,16	200	General public exposure up to eight continuous hours

2. Methodology

This research considers the following steps to accomplish electromagnetic monitoring levels. There was analyzed the information provided by power line variables (voltage, current, temperature level), evaluating the transmission power line in the high demand scenario, it was considered the recommendations given in the standard Procedures for Measurement of Power Frequency Electric and Magnetic Fields from AC Power Lines (IEEE, 1994). The evaluation of power line considered its nominal operation and specifications.

2.1. Technical information and standards recommendations

Table 4 present technical information of transmission power line monitored. And finally results were contrasted with computational tools (Silva-Ortega, et al., 2015).

Table 4. Technical information of transmission power line monitored.

Type of power line:	Single phase air circuit	Type of cable:	AAAC
Rated Value:	110 kV.	Area:	827,2 MCM
Year built:	1993	Number of structures:	34
Temperature range:	31 – 35 °C	Type of structure:	Concrete
Total distance:	3,8 Km	peak demand hours:	8:00 – 10:00 AM

Figure 1 shows the location of the transmission power line section monitored in Barranquilla, Colombia (11° 0'43.88"N, 74°47'50.59"O)

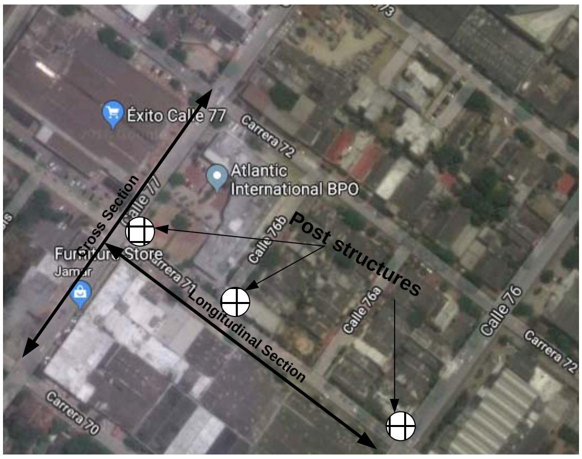

Figure 1. Profile reference in power line cross and longitudinal section.

Measurements follow the STD IEEE 644-1994. There were taken into account the following recommendations based on (IEEE, 1994) and IEEE STDC95.6-2002 (IEEE, 2002): All measurements were realized at a height of one meter from the ground; the distance between the meter and the operator must be at least 2.5 meters; there were not reported approaches or perturbations errors during the measurements; the asymmetries of the electric field meters can change the direction of the axial components with respect to the vertical coordinate of interest; the distance between the meter and objects located during measures must be separated with more than one meter; measures where realized monthly and weekly during the maximum demand day of the week; the period of observation was between 2013 to 2017.

2.2. Finite-difference method.

There was used MATLAB to model cross and longitudinal profile scenario. This study aims to analyze the variation of EMF respect with the topology used and the physical specifications of the structures in which is installed. Finite difference Method and load simulation method are the two common techniques used to estimate electric and magnetic fields from a specific points in a profile of a power line (Electric Power Research Institute, 2005)., these methods are the most used, also in application with materials (Jiang et al., 2017) to evaluate electric field reference value. Using mathematical modeling are approached the initial conditions (Sadiku, 2014):

$$\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} = \frac{-\rho_s}{\varepsilon} \qquad (1)$$

For the initial conditions is consider the point (x_0, y_0):

$$\left.\frac{\partial^2 V}{\partial x^2}\right|_{x=x_0} = \frac{V_{i+1,j} - 2V_{i,j} + V_{i-1,j}}{(\Delta x)^2} \qquad (2)$$

$$\left.\frac{\partial^2 V}{\partial y^2}\right|_{y=y_0} = \frac{V_{i,j+1} - 2V_{i,j} + V_{i,j-1}}{(\Delta y)^2} \qquad (3)$$

Replacing (1) and (2) in (3) and considering $\rho s = 0$ it is obtained:

$$V_{i,j} = \frac{1}{4}\left(V_{i+1,j} + V_{i-1,j} + V_{i,j+1} + V_{i,j-1}\right) \qquad (4)$$

To estimate the electric and magnetic field is used Maxwell equation and the Faraday law considering time variation respectively:

$$E_{i,j} = -\nabla V_{i,j} \qquad (5)$$

$$B_{i,j} = -\oint \nabla \times E_{i,j}\, \partial t \qquad (6)$$

The finite differences method assigning values to nodes and applying (4), for all the free node to estimate the potential value, then it is repeated the process for all nodes taking as reference the previous value of the iteration. Finally, this procedure is repeated until to reach a minimal error in the iteration process. Finally, the contribution of electric and magnetic field in *(5)* and *(6)* are used following the next procedure: there must be identified zones or partial regions considered as equipotential values; select the type of element suitable for modeling each area; locate all the load points; choose points to validate the values of the surface; It was considered that the number of points must be equal to the number of load elements.

3. Results

Table 5 and Table 6 present the mean electric and magnetic field levels measured on the profile analyzed on the transmission power line located in Barranquilla during the five years of observation. The measures were made during maximum peak demand times according to the reference values for the year of reference during in all the measured points. Table 5 represent the cross section measured while Table 6 presents the measurements made on the longitudinal profile of the line. All the measured values considered STD IEEE 644-1994 recommendations. For longitudinal section were considered ten measurement points and for cross section fifteen points.

The measured values were contrasted with the modeled power transmission line represented in MATLAB, evidencing similar values between measured and modeled in clear areas on the selected section of the line. The error was not greater than 1.2%. In all the cases the power line does not exceed reference values recommended by ICNIRP and mandatory in Colombia´s National Electrical Code (RETIE). It also was detected that in areas where in places covered by trees, electric field exposure levels are considerably reduced. Also, magnetic field levels are lower and do not exceed ICNIRP recommendations.

Table 5. Mean values registered for electromagnetic field measured in transmission power line cross section.

Ref.	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Distance (m):	-31	-26	-21	-16	-11	-6	-1	0	1	6	11	16	21	26	31
Electric Field (V/m):	10	12	25	85	160	205	2555	940	2280	550	324	180	10	10	10
Occupational exposure reference value Reference limit value according with INCIRP (4166 V/m) (E: Exceeded) (NE: Not exceeded)	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE
Magnetic Field (uT)	0,25	0,23	0,35	0,62	0,56	0,70	0,57	0,56	0,66	0,54	0,44	0,40	0,36	0,25	0,20
Occupational exposure reference value Reference limit value according with INCIRP (200 uT) (E: Exceeded) (NE: Not exceeded)	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE

Table 6. Mean value registered for electric and magnetic field measured in transmission power line longitudinal section.

Ref.	Distance from reference value (m)	Electric Field (V/m)	Occupational exposure reference value Reference limit value according with INCIRP (4166 V/m)	Magnetic Field (uT)	Occupational exposure reference value Reference limit value according with INCIRP (200 uT)
1	0	60	Not exceeded	7,0	Not exceeded
2	4	309	Not exceeded	6,9	Not exceeded
3	8	340	Not exceeded	6,7	Not exceeded
4	12	735	Not exceeded	6,2	Not exceeded
5	16	1130	Not exceeded	5,7	Not exceeded
6	20	1335	Not exceeded	6,2	Not exceeded
7	24	1130	Not exceeded	7,2	Not exceeded
8	38	610	Not exceeded	6,8	Not exceeded
9	32	1090	Not exceeded	6,1	Not exceeded
10	36	905	Not exceeded	1,5	Not exceeded

4. Conclusions

This study was directed to evaluate electric and magnetic field measured focused in monitor electromagnetic fields and safe operation levels in electrical power transmission line. During measures were adopted STD IEEE 644-1994 recommendations. This monitored area can be considered safe respect to electromagnetic pollution due to real measurements of electric and magnetic field are under ICNIRP recommended values to operate an electric system at industrial frequency equal to 60 Hz. However, it is recommended to guarantee safety distance operation in power lines and do not be exposed more than eight continuous hours as RETIE recommend.

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