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Overhead lines –B2
PS 3 Environmental and safety aspects from OHL

Compliance analysis of exposure limit values of power frequency electromagnetic fields during live-line working on HV overhead lines

Iván HIGUERO-TORRES[1*], Guillem GIL-PRIETO[1], Vicente FUSTER-ROIG[2].
[1]Instituto Tecnológico de la Energía (ITE)
[2]Instituto de Tecnología Eléctrica, Universitat Politècnica de València
Spain
ivan.higuero@ite.es

SUMMARY

During some on live line maintenance works on overhead lines, workers could be exposed to power frequency electromagnetic field values higher than the *"reference levels*". These values are defined in publications of the International Commission on Non-Ionizing Radiation Protection (ICNIRP) and included in the regulatory framework in the European directive 2013/35 / EU as *"action levels"*.
The magnitudes used to verify the compliance: magnetic flux density (B) and electric field (E), are relatively easy to measure, this is why these levels are normally used. However, these values are based on several assumptions and a simplified calculation considering a uniform distribution of electric and magnetic field (approach to a plane wave) that are far from the actual situation in live-line working.
Then, the *"basic restrictions"* (ICNIRP) or *"exposure limits"* (EU directive) has to be used. These magnitudes are the ones directly related with health and sensory effects. Nevertheless, the verification of not exceeding these magnitudes inside the human body is complex and it is not possible to measure them, needing to use mathematical modelling.
This paper pretends to evaluate the exposure limits compliance in some workplace conditions on live-voltage on overhead lines, where the worker could be close to conductors and the electromagnetic field can change spatially due to the influence between conductors and the transmission tower, and the field distribution could be no homogenous. In this situation, the assumptions mentioned previously to the action levels could be not valid due to the short distance between conductors and persons. During this study some simulations by means finite elements software was carried out, considering several case studies with different geometry in transmission towers, different working conditions and different levels of voltage: (1) Overhead lines of medium voltage (20-30 kV), (2) Installation of avifauna protectors on medium voltage overhead lines (20-30 kV), (3) Live line maintenance works to replace insulators on overhead lines of double circuit of high voltage (220 kv and 400 kV) and (4) Working conditions in close proximity on tower transmission of high voltage (132 kV) of double circuit, which is a transition between overhead line- underground cable and one of circuits is not energized.
Moreover, in order to analyse the induced effect on the worker in each of the work positions, the human body has been modelled considering the standard EN 62226-3-1 (Exposure to electric or magnetic fields in the low and intermediate frequency range - Methods for calculating the current density and internal electric field induced in the human body - Part 3-1: Exposure to electric fields - Analytical and 2D numerical models).
Once these simulations have been completed and electric field, magnetic flux density and induced current density are obtained, the results have been synthesized and they are compared with limits

stablished, *Basic restrictions* and *Reference levels*. This comparison allows corroborating that there are not induced effects that can affect the health of workers in this case studies. Also, this study provides practical information about conditions, where the worker could be exposed to higher levels of induction effects related to power frequency electromagnetic fields.

KEYWORDS

Electromagnetic - Simulations -Field - Levels - Restrictions - Safety -Exposure

1. INTRODUCTION

Currently, the Directive 2013/35/UE [1] of the European Parliament and of the Council establishes the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (electromagnetic fields). In this normative, it is established that "*in order to protect workers exposed to electromagnetic fields it is necessary to carry out an effective and efficient risk assessment. However, this obligation should be proportional to the situation encountered at the workplace*". It claims reduce risks, and it forces to elaborate an action plan to avoid exceedance within certain limits.
For this evaluation, it defines Action levels (Als) and exposure limit values (ELVs) for electromagnetic fields.

- Action levels (Als): "*operational levels established for the purpose of simplifying the process of demonstrating the compliance with relevant ELVs or, where appropriate, to take relevant protection of prevention measures specified in Directive 2013/35/UE*". According to exposition of electric or magnetic fields, some limits are defined:
    - Electric fields: "*low ALs' and 'high ALs' means levels which relate to the specific protection or prevention measures specified in this Directive*".
    - Magnetic fields: "'*low ALs' means levels which relate to the sensory effects ELVs and 'high ALs' to the health effects ELVs*".
- Exposure limit values (ELVs): "*values established on the basis of biophysical and biological considerations, in particular on the basis of scientifically well-established short-term and acute direct effects*".

In addition, it is established that ELVs shall not be exceeded related to electromagnetic fields exposition on workers. These ELVs will be not exceeded if exposition levels are lower than Als defined.
Verification of not exceeding limit values through Als is due to ELVs are induced magnitudes inside the body and, consequently, they cannot be measured in each workplace. Als are environmental measurable magnitudes (magnetic flux density for static fields, electric field, magnetic flux density for time variable fields and contact current), which are considered in the worst-case scenarios.
However, if Directive 2013/35/UE is analysed, the physical magnitudes, ELVs and Als established are based on the recommendations of the International Commission on Non-Ionizing Radiation Protection (ICNIRP). [2] explains that these limits (ELVs and Als) are obtained considering some approaches: a maximum field coupling, a field uniform distribution with a plane wave and the emitting source far enough away. Moreover, it is noted that levels can be exceeded when these considerations are not met. Therefore, in real working conditions next to high voltage (HV) electrical grids with a short distance to several line conductors with a current flow, there is a high probability that an exceedance of the Als does not imply a breach of the ELVs. To ensure the compliance of ELVs during live working where field distribution is not uniform and the wave is not plane, an evaluation electromagnetics methodology is needed. In this methodology should be considered: lines configuration, geometrics distribution, working position and lines operations, etc.
Thus, the methodology followed in this study consists in modelling by means of a finite elements software (Comsol Multiphysics) the power tower, conductors of HV electrical line and human body in order to evaluate the induced electromagnetic field on workers in several positions.
The human body has been modelled according to the standard EN 62226-3-1 [3], where electrical conductivity and permittivity are defined. Power tower, conductors distribution and worker positions are extracted from several maintenance working procedures on HV lines. In

each working position, electric field induced inside the body caused by electric and magnetic field is compared to Als and ELVs.

2. USES CASES DESCRIPTION BASIS ON SOME WORKING CONDITIONS

The different working conditions and different levels of voltage considered are defined below:

- **Case 1: Overhead lines of medium voltage (20-30 kV).**

  Line derivation in 20 kV power tower, considering a perpendicular configuration between conductors of line and its derivation. These working conditions can be related to replacement of insulators, avifauna protectors installation and other maintenance operations.

- **Case 2: Installation of avifauna protectors on medium voltage overhead lines (20-30 kV).**

  This case is focused on installation of avifauna protectors on 20 kV power towers. In this case, workers are usually raised by isolated lift platforms, and they perform maintenance operations with only insulator gloves.

- **Case 3: Live line maintenance works to replace insulators on overhead lines of double circuit of high voltage (220 kv and 400 kV).**

  In this case, workers replace insulators on HV lines of double circuit with voltage levels 220 kV and 400 kV. In these works, a person is very close to conductor with a conductor suit, while other persons are located over power tower arm. They have not conductor suit because they do not work at the same potential of line conductors.

- **Case 4: Working conditions in proximity on tower transmission of high voltage (132 kV) of double circuit with a transition between overhead line – underground cable and one of circuits is not energized.**

  This case is related to operations performed in a power tower on a not energized circuit, whiles in the other side of power tower there is a circuit energized with 132 kV.

Figure 1 Example of working procedures related to case 2 Installation of avifauna protectors on medium voltage overhead lines (20-30 kV).

3. SIMULATIONS

Once the geometric distribution of conductors and all elements of power tower are defined, the models have been created in finite element simulation software (Multyphisics Comsol), employing AC/DC Module. The creation of these models is linked to some geometry simplifications, avoiding details without loss of accuracy. In these simulations, a ground plane was defined with 0V whiles conductors have an RMS value voltage depending on overhead line voltage level and human body is modelled according to 3D geometric shape defined in [3]. Simulations have been divided in two parts:

1. Als evaluation:
   Simulations without body human model, to analyse electric and magnetic field separately and evaluate Als compliance. In this part, the results obtained are: electric field in (kV/m) caused by electric field and magnetic flux density in (T) caused by magnetic field. Simulation conditions are like the measurement procedures carried out on field to check if Als do not exceed allowed values. In this case, persons do not disturb electric and magnetic field distribution.

2. ELVs evaluation
   These simulations include the body human model according to EN 62226-3-1, where electrical conductivity and electric permittivity are considered. The results obtained from simulations is the internal induced current J (A/m^2) on the human body caused by electric and magnetic field separately. To compare these values with ELVs, it is needed to apply the following equation, which provides a direct relation between current density and electric field induced inside the body (E_0). Where, σ (S/m) is electrical conductivity of human body.

$$J = \sigma \cdot E_0$$

Subsequently, power tower models in 3D created and working positions considered are shown for each analysed case.

- **Case 1: Overhead lines of medium voltage (20-30 kV).**

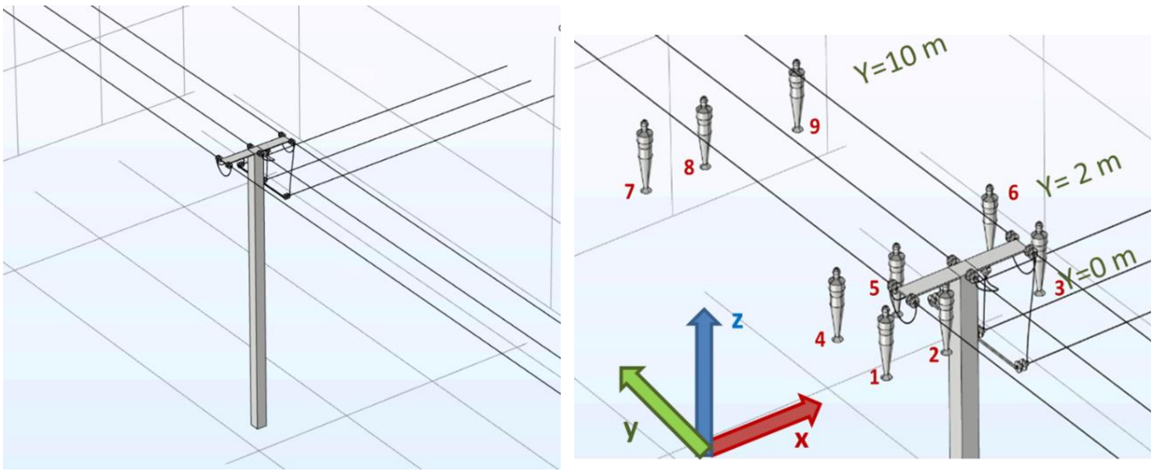


Figure 2 Model created in 3D for case 1 Overhead lines of medium voltage (20-30 kV).

- **Case 2: Installation of avifauna protectors on medium voltage overhead lines (20-30 kV).**

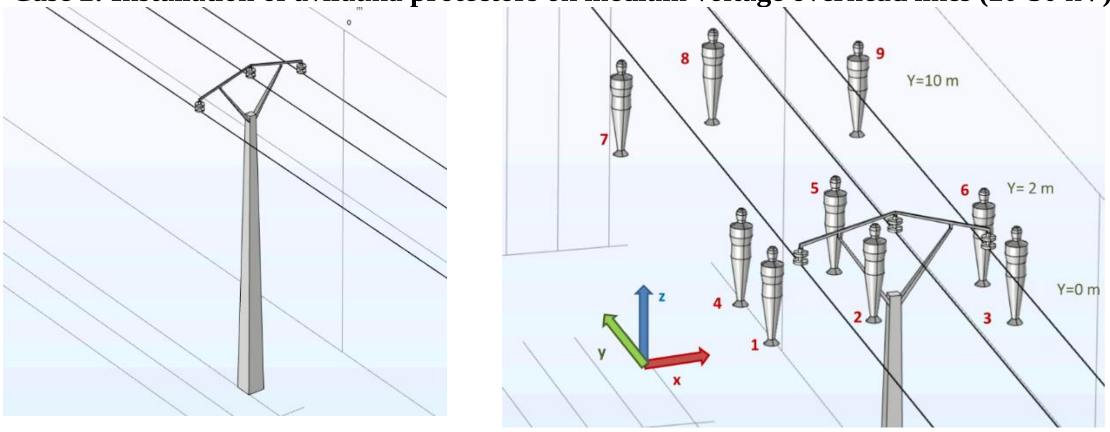


Figure 3 Model created in 3D for case 2 Installation of avifauna protectors on medium voltage overhead lines (20-30 kV).

- **Case 3: Live line maintenance works to replace insulators on overhead lines of double circuit of high voltage (220 kv and 400 kV).**

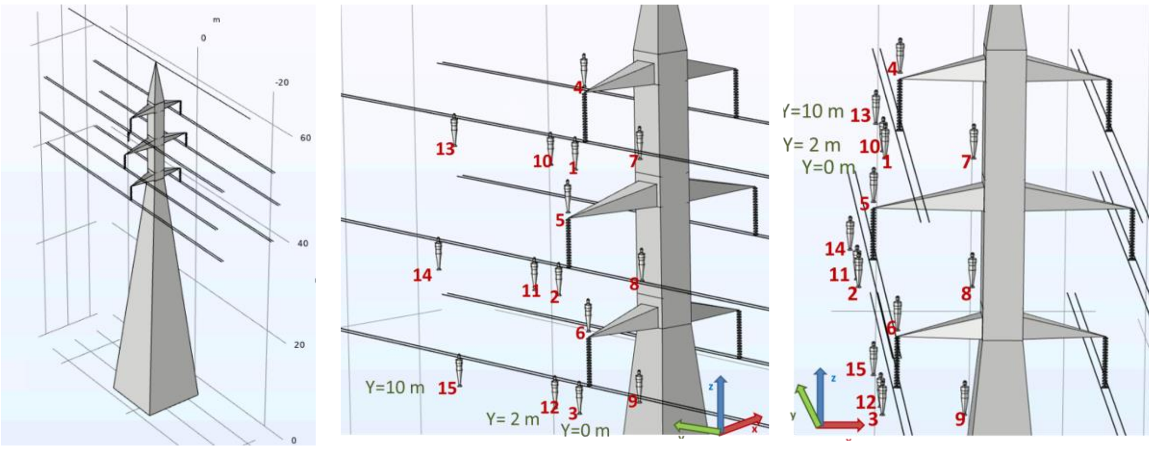


Figure 4 Model created in 3D for case 3 Live line maintenance works to replace insulators on overhead lines of double circuit of high voltage 220 kV

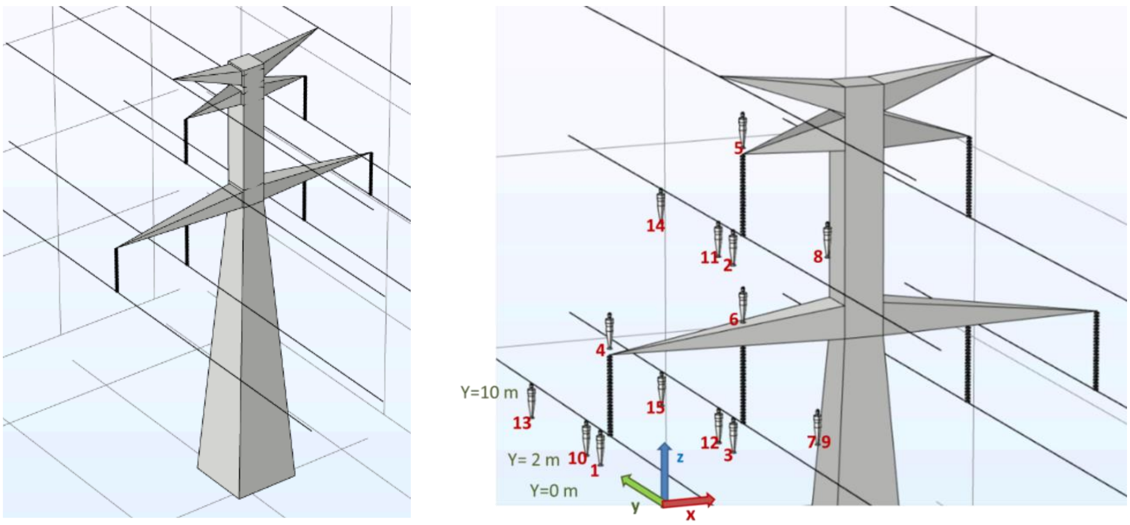


Figure 5 Model created in 3D for case 3 Live line maintenance works to replace insulators on overhead lines of double circuit of high voltage 400 kV

- **Case 4: Working conditions in proximity on tower transmission of high voltage (132 kV) of double circuit with a transition between overhead line – underground cable and one of circuits is not energized.**

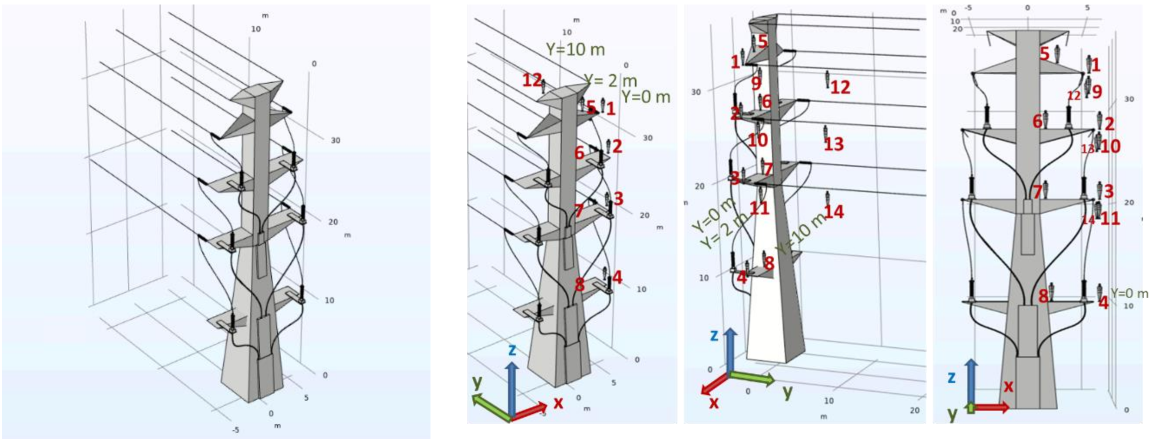


Figure 6 Model created in 3D for case 4 Working conditions in proximity on tower transmission of high voltage (132 kV) of double circuit with a transition between overhead line – underground cable and one of circuits is not energized

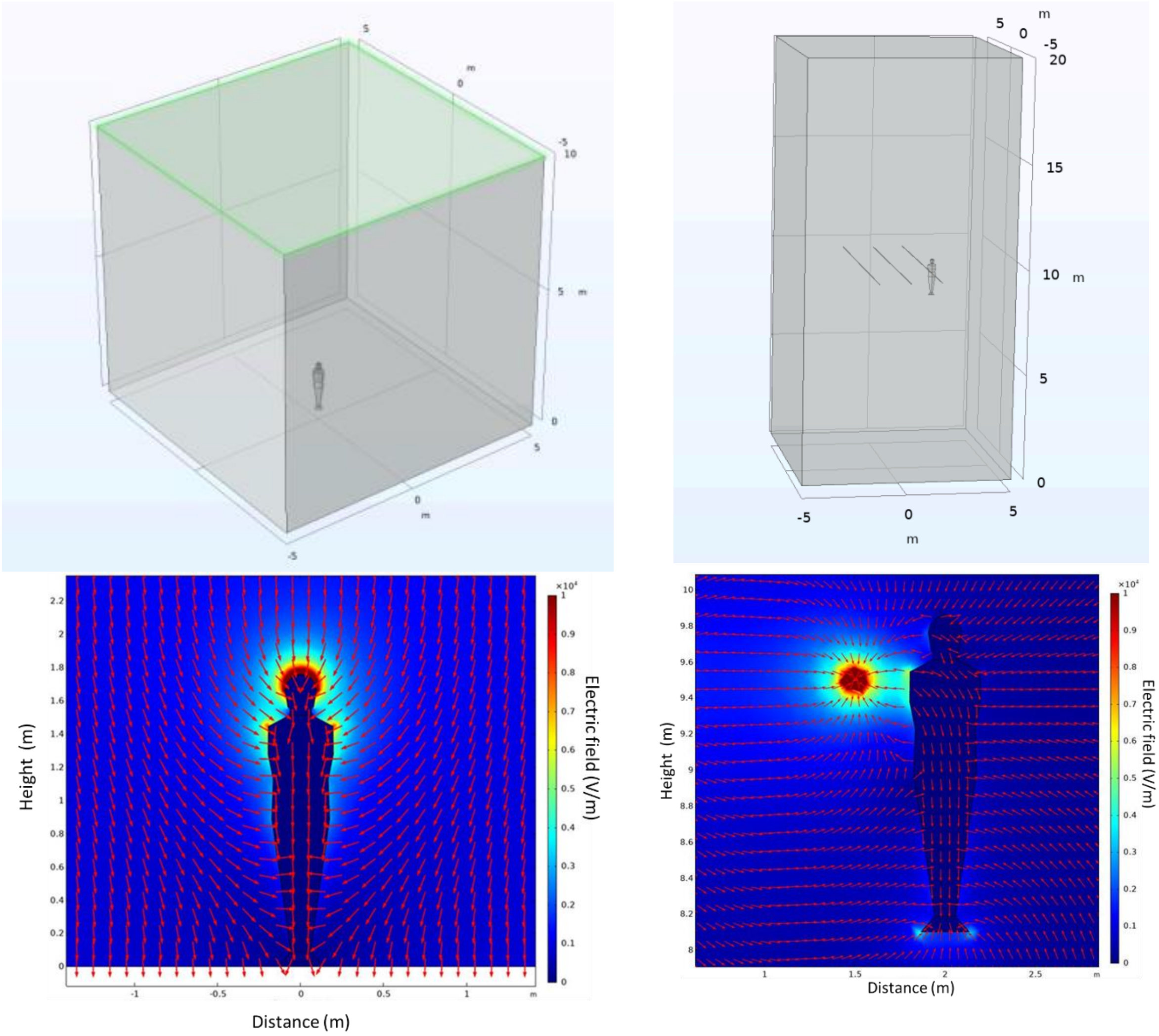
Results of simulations were obtained by means of an iteration process employing a parametric study tool and obtaining maximum values for each working position considering model geometry in each case.

4. CONSIDERATIONS ABOUT RESULTS INTERPRETATION

To reveal differences between the conditions assumed by standards (EN 62226-3-1) and possible working conditions, two cases are simulated. The main differences between these cases are:

- Standard conditions:
  It is based on a homogeneous electric field distribution with a plane wave considering the emitting source far enough away. So, in this case, top plane is in 10 kV and the human body is located on the ground. It provides a homogeneous electric field equal to 10 kV/m.
- Working conditions:
  It represents conditions like working conditions, where the proximity to conductor parts leads a non-homogenous electric field distribution. So, cylindrical conductors are in 26 kV like a three-phase overhead line. It a non-homogeneous electric field equal to 10 kV/m about 0,5 meters away from conductors.

Despite the higher-level voltage in working conditions, the induced current on human body is higher when a uniform electric field is considered in standard conditions. It should be noted that in working conditions, human body is floating, while in standard conditions human body are on ground with 0V. Potential gradient is very different in these situations, and it is linked with internal induced current density (J).



Jmax= 1.100 µA/m² **Jmax= 75 µA/m²**

Figure 7 Comparison between considered conditions of EN 62226-3-1 and ICNIRP with working conditions close to conductors

5. RESULTS ANALYSIS AND COMPARISON WITH STABLISHED LIMITS

The maximum values obtained from simulations have been compared with stablished limits in the Directive 2013/35/UE, which are shown in Table I, which represent the worst cases of working positions analysed in this study.

Table I Stablished limits from Directive 2013/35/UE about electromagnetic fields exposition [1]

Action Levels (ALs)		
Action Levels for electric field strength E	Low AL (E) 10.000 V/m (RMS)	High AL (E) 20.000 V/m (RMS)
Action Levels for magnetic flux density B	Low AL (B) 1.000 µT (RMS)	High AL (B) 6.000 µT (RMS)
Exposure Limit Values (ELVs)		
Health effects ELVs for internal electric field strength	1,1 V/m (peak)	
Sensory effects ELVs for internal electric field	0,14 V/m (peak)	

This comparison is shown in Table II, where in some cases, Low and High Als are exceeded. It should be noted that these positions are close to conductors under the influence of its electric potential. However, if internal electric field is compared with limits, it is observed that results are very low values. The maximum value achieved is approach 32% of Sensory effects ELVs, but in no case, the values ELVs are exceeded.

Table II Comparison of electric field, magnetic flux density and internal electric field with limits defined in the Directive 2013/35/UE

% E of Low ALs (E)	**% E of High ALs (E)**	**% B of Low ALs (B)**	**% B of High ALs (B)**	**Internal electric field caused by electric field**		**Internal electric field caused by magnetic field**	
				% E_0 of Health effects ELVs	**% E_0 of Sensory effects ELVs**	**% E_0 of Health effects ELVs**	**% E_0 of Sensory effects ELVs**
Case 1							
209%	105%	1.3%	0.2%	1.20%	9.40%	0.01%	0.10%
Case 2							
189%	95%	1.3%	0.2%	0.52%	4.11%	0.01%	0.06%
Case 3 for 220 kV							
256%	128%	0.1%	<0.1%	0.43%	3.38%	0.03%	0.24%
Case 3 for 400 kV							
363%	182%	40.8%	6.8%	4.08%	32.03%	0.25%	1.98%
Case 4							
17%	9%	1.1%	0.2%	0.99%	7.75%	0.03%	0.27%

In some cases, electric field obtained in some positions is higher, but internal electric field caused is lower. It mainly depends on boundary conditions, proximity to conductor, voltage level and potential difference caused by working conditions position. When, the person is exposed to the same electric field, its potential difference is higher on ground floor than floating conditions. It affects directly to internal electric field caused.
Other studies have carried out previously [4] [5] [6], however this study collects specific conditions for some overhead lines of several voltage levels.

6. CONCLUSIONS

Considering the stablished limits (ELVs), bibliography and standards recommend taking measurements and compare with Als. These values are defined under consideration of homogeneous electric field and person located on ground plane. However, in some working conditions it cannot apply due to the proximity of conductors and the non-homogeneous distribution of electric field. Moreover, in many positions workers are not in contact with the ground plane. In these positions, despite achieving higher values of electric and magnetic fields, induced internal field obtained is lower than standard conditions. It is important to note that Exposure Limit Values (ELVs) in these working conditions evaluated in this study are not achieved in any case and Internal electric field induced are significantly below these limits. It excuses that Als are exceeded in working positions but induced internal field are always lower than ELVs. In these positions, an evaluation of ELVs is needed due to non-uniformity distribution of electromagnetic field.

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