ASSESSMENT OF EMF EXPOSURE CONDITIONS NEAR TRANSMISSION LINES

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Increasing public concern about human exposure to EMFs is posing Power Utilities in Brasil several complex problems. Existing limits, expressed in International Standards, are based on maximum admissible fields or induced currents inside human bodies. Since those physical quantities cannot be readily measured, they must be estimated using techniques of computational dosimetry, based on computational modeling of human bodies. Nowadays the models available for Human body simulation (FEM, FDM, …) are quite accurate, however the determination of tissues characteristics (permittivity and conductivity) and the simulation of induced currents on real transmission line conditions require some developments. In this paper a research designed to characterize, using indirect methods, the permittivity of the human body, and the modeling of live line workers on real field conditions (simultaneous electric and magnetic non-uniform fields) is presented.

1. INTRODUCTION

The design and operation of transmission lines requires the control the environmental impacts produced. A considerable part of those impacts is related to the electromagnetic fields generated by the transmission line. The limitation of contact currents, called indirect effects, is readily done using design techniques based on conservative models, which ensure safety near the line. On the other hand the control of the so called direct effects, the interactions between electromagnetic fields and living tissues and organs, is more complex and controversial since, even if no effect has been characterized in the numerous research projects developed to date, there are ongoing research activities and some questioning remains, specially related to the exposure of sensitive groups (elderly persons, children, hospital neighborhoods, etc.).

The usual way to settle this questionings is to adopt a respected standard, the more well known being IEEE and ICNIRP. Since the standards are founded on the idea of limiting the magnitudes of induced currents inside the body, there are two
alternative ways to apply comply with them: the simpler one is to guarantee that the values of EM fields will stay below given limits; the second, more laborious one, is to verify that under the actual exposure conditions the maximum values of induced currents will stay below admissible values. This last approach, while more flexible in terms of design and operation of transmission systems, require a set of computational tools to verify the compliance to Standards, especially given that the direct measurement of quantities inside living bodies cannot be readily done, requiring use of computational dosimetry techniques.

In this paper the methodology to apply computational dosimetry to the design and operation of transmission lines is presented, and the main problem of defining the electric characteristics of living tissues (permittivity and conductivity) is addressed in a specific research, which allowed the determination of constants used in the sequence. Finally the application of the whole methodology to a real case is illustrated.

2. CHARACTERIZATION OF THE PROBLEM

2.1. FIELDS GENERATED BY TRANSMISSION LINES

A transmission line generates an electric and a magnetic field in its vicinity. In the power frequency range those fields are uncoupled (ELF EMF), the electric field being related to electric charges on conductors, the magnetic field being related to the currents in conductors. Those fields change in magnitude and direction from point to point in space, and, in polyphasic systems, the spatial components of those fields have different phase angles, the resultant filed (electric and magnetic) following an elliptical pattern, not a sinusoidal one [1].

2.2. EFFECTS ON LIVING ORGANISMS NEAR TRANSMISSIONS LINES – LIMITS AND STANDARDS

There are essentially two classes of effects resulting from the interactions between fields and living organisms:

- Indirect effects: contact currents between an insulated person and a grounded object, or between an insulated object and a grounded person.
- Direct effects: electric and magnetic fields acting directly in the tissues inside the living organism may originate induced currents which in turn may cause some effects, mainly undue stimulation of nervous system. To protect against those undesired effects there are some international standards, the more well known being IEEE and ICNIRP [2]. Those standards follow essentially the same logic: defining the maximum values of induced currents known to cause no undesired effects – basic restrictions – a modeling is undertaken – computational dosimetry –
to determine the values of external fields that would induce those currents – reference levels.

It is interesting to note that the field limits expressed as reference levels in ICNIRP’s recommendations, intended to protect against direct effects, are also sufficient to protect against indirect effects in the vast majority of situations near transmissions lines.

2.3. APPLICATION OF ICNIRP’S RECOMMENDATIONS

There are two main ways to assure compliance to ICNIRP’s recommendations:

• A simple direct way is to ensure that field intensities are below the reference levels. In this case compliance is directly guaranteed, and no special technical tools are needed, except normal project design computational programs.

• A more complete, thorough way is to recur to a computational modeling, in order to calculate the magnitudes of currents induced inside the body by external fields. This approach requires the use of computational tools to calculate the intensities, directions and phase angles of electric and magnetic fields at the exposure locations, and a computational model – finite elements, finite differences – to model human body considering internal geometries and material characteristics.

The application of computational dosimetry techniques is more flexible in the sense that it can address special situations (hospitals, schools, etc) as well as the case of existing transmissions lines, originally designed to comply with different standards. On the other hand it is more complex since it requires the availability of some specific tools and knowledge:

• The calculation of electric and magnetic field distributions in the space around the transmission line, using a 3D computational model. Usually a computer program based on charge simulation of boundary techniques is used for this step.

• The modeling of a human body in different situations (standing, circulating, working) in the vicinity of the transmission line, using a finite element / finite difference model. However the availability and use of such a computational tool is not trivial.

• The attribution of electric characteristics to the different tissues (permittivity and conductivity). This is a difficult task, and usually values available in the literature are used, but those values are mainly obtained from measurements performed with dead bodies.

• With the above the determination of maximum currents induced in the body can be calculated in various positions around the transmission line, characterizing the compliance with the safety standards.
The following item describes the studies performed to determine the value of permittivity more representative of the behavior of human bodies, to be used in subsequent calculations.

3. DETERMINATION OF TISSUES CHARACTERISTICS

3.1. HISTORIC

The study of the electric properties of tissues gives important information about possible mechanisms by which external fields produce effects in an organism. They are also needed for the calculation of the internal electric currents resulting from human exposure to electromagnetic fields. With the realistic anatomically models providing the geometrical structure, the electromagnetic properties of biological tissue are still needed in order to perform dosimetric simulations.

The dielectric properties of tissues have been extensively studied in the last fifty years, from 10 Hz to almost 10 GHz [3, 4]. In 1971, Cole [5] proposed a formula for calculating the permittivity and conductivity in a wide frequency range. In 1996, Gabriel et al [6, 7, 8, 9] published a large literature survey of dielectric properties, accompanied new measurements and by a parameter extraction for the Cole-Cole equation. At present this data set, has been used in various dosimetric computations. Some values of those parameters are presented in Table 1.

<table>
<thead>
<tr>
<th>Tissue</th>
<th>Conductivity [s m⁻¹]</th>
<th>50 Hz</th>
<th>Relative Permittivity</th>
<th>Loss Tangent</th>
<th>100 kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blood</td>
<td>0.7</td>
<td>5300</td>
<td>48000</td>
<td>0.70</td>
<td>5100</td>
</tr>
<tr>
<td>Body fluid</td>
<td>1.5</td>
<td>99</td>
<td>5.5E+06</td>
<td>1.5</td>
<td>98</td>
</tr>
<tr>
<td>Bone Cortical</td>
<td>0.020</td>
<td>8800</td>
<td>81000</td>
<td>0.020</td>
<td>23000</td>
</tr>
<tr>
<td>Brain, Grey Matter</td>
<td>0.075</td>
<td>1.2E+07</td>
<td>2.2</td>
<td>0.13</td>
<td>32000</td>
</tr>
<tr>
<td>Fat</td>
<td>0.020</td>
<td>1.5E+06</td>
<td>4.8</td>
<td>0.024</td>
<td>93</td>
</tr>
<tr>
<td>Muscle</td>
<td>0.23</td>
<td>1.8E+07</td>
<td>4.7</td>
<td>0.36</td>
<td>8100</td>
</tr>
<tr>
<td>Skin (Dry)</td>
<td>0.0002</td>
<td>1100</td>
<td>63</td>
<td>0.00045</td>
<td>1100</td>
</tr>
</tbody>
</table>

Nevertheless, recent research [10, 11] indicates variability in permittivity values, especially in lower frequencies (< 10 MHz), results from the various factors, as heterogeneous nature of biological tissues, the use of tissues from different species (as well as from different animals of the same species), the age of the samples when used, the tissue preparation procedure, whether the tissue is
anisotropic, the temperature of the sample, and systematic errors associated with the measurements technique used.

This uncertainty as regards the behavior of the human tissues at power frequency, has been motivated the present research, which was intended to estimate the permittivity of the human body, using indirect methods, through the analysis of the external electric field around the body. A brief resume these two methods are presented in a sequence.

In the first method, the methodology and the results from [12] were used, to satisfy some requirements, as not to distort the field distribution, using for this an optical field sensor.

The second method was based on the shielding effect of the body, which consists in significant reduction of the electric field in the proximity of a standing person, placed away from the line source. This method is specially suited when only common electric field meters are available.

3.2. FIRST METHOD

Most practical electric field measurements are made by measuring the voltage between two parallel plates perpendicular to the electric field [13]. However, in the case of non-uniform fields, the metallic parts causes perturbation of the field around the point to be measured, distorting the results. Furthermore electric fields are perturbed by any conducting objects, including the instrument operator. The results from reference [12], where a system was developed to visualize the spatial distribution of the ELF electric field around an object with complex shape, such as human body, was used as a reference.

The approximate dielectric constant of the human body, was estimated through the ratio between perturbed and unperturbed external electric field ($E/E_0$), adjusting the results of the simulation using a FEM Program [14] with the measured values [12]. This adjust was realized for a range of the permittivity values.

- In first stage, called test case, an object with simple shape, a cylinder, was modeled and then, the accuracy of the numerical calculation, using finite element method modeling and axial symmetry, was confirmed by comparison of the results from [12].
- In second stage, after checking the validity this method, it was applied to the human model, using element finite modeling and axial symmetry.

3.3. RESULTS

- Test Case – Cylinder

For this case, were realized simulations using range of relative permittivity values between 10 and 100.
Fig. 1 shows the mesh was used in the calculations, and Fig. 2 shows the electric field distribution around the cylinder, specifically for the relative permittivity value equal to 30.

- **Human Model Case**
  For this case, simulations were performed using a range of relative permittivity values between 10 and 50.
Fig. 3 shows the mesh used in the calculations, and Fig. 4 shows the electric field distribution around the human model, specifically for a relative permittivity value equal to 30.

Subsequently measurements were made in the laboratory, around a human volunteer, in order to draw a field pattern to be compared to computer simulations using different permittivities. However, the analysis of the measured values led to the conclusion that the instrument used was interfering with the field, distorting the
values obtained. This was due to the fact that the instrument was both too big for this purpose and containing several metallic parts.

3.4. DISCUSSION

Using this method a rough estimate of permittivity was obtained, comparing simulations to measurements in laboratory. Yet it clearly stood that measurements were not sufficiently accurate, since the field meter available was not adequate to use in non-uniform field patterns. Still the most adherent value of relative permittivity obtained was in the range of 30-50, which was considerably different from literature to justify a second phase of the research.

3.5. SECOND METHOD

Exact knowledge of the electric field around human body is considered essential to correct characterization of the permittivity value however, in practical situations, the first method, as concluded in the previous section, is not entirely adequate.

So a second method was proposed, designed to use with conventional electric field meters, although also using measurements of the electrical field around the human body.

The second method is based on shielding effect, which consists in significant reduction of the electric field in the proximity of a standing person, placed far away of the line source. In this way a good agreement was obtained when comparing field measurements with computational simulations. In the sequence some details of this experiment are described.

The measurement was done at High Voltage laboratory from CEPEL, using a real line arrangement. It is a 500kV transmission line, and the conductors are at 10 m above ground.

The person was placed at a distance of 8 m from line center, and three transversal profiles, at heights of 0.5, 1.0 and 1.4 meters were measured. These results are shown in Fig. 5. These experimental data were compared with the simulation data obtained with TRICAMP (3D charge simulation) Program. In the simulation, the human was approximated by a cylinder. Some variations of the cylinder radius were calculated in order to define the best representation. These results are shown in Fig. 6.

Finally, the contour conditions obtained from this simulation on the TRICAMP Program were used as input boundary condition to the MEF (finite element) Program. The person was then represented by a cylinder, according to Fig. 7, with a radius of 0.4 m, and then simulations were executed using a range of relative permittivity values between 30 and 100. These results are shown in Fig. 8.
Fig. 5 – Adjust measurements/simulation.

Fig. 6 – Variations of the human representation – cylinder radius.
3.6. ANALYSIS OF THE RESULTS

This investigation indicated that a permittivity value of 30 was the most adherent to the measured values, using a real person on a transmission line field. Thus this value was subsequently used in the sequence of the simulations.
4. APPLICATION TO A REAL TRANSMISSION LINE

The whole methodology was then applied to a real case, consisting in calculating the field distribution (electric and magnetic) near the transmission line, modeling (using finite elements) a human body in different locations around the line, and then calculating maximum the induced currents generated by the components of both the electric and magnetic fields, and finally combining those contributions with respective magnitudes and phase angles, to obtain the total maximum induced current at each point. Then those results were combined in a visualization (Fig. 9) representing currents induced in a person in different situations near a transmission line.

Fig. 9 – Map of induced currents around a 500 kV transmission line.

5. CONCLUSIONS

The proposed methodology, consisting of several computational models, used in sequence, is a valuable tool to the design and operation of transmission lines, allowing the establishment of safety regions near the line, in order to assure compliance to safety standards, considering different situations (circulations, agricultural activities, live line work, sensitive areas, etc.).

The ongoing research, designed to determine electric characteristics of human bodies, will provide more accurate data in order to guarantee the sound application of the modeling.

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