Evaluation of the exposure to magnetic field generated by welding equipment with reference to induced current density

E. Sieni[1,2], F. Dughiero, [1,2], M. Forzan [1,2]

(1) Department of Electrical Engineering University of Padova, Italy, elisabetta.sieni@unipd.it
(2) INOVA LAB srl, Leinì (TO), Italy,

Abstract : **a procedure for the simulation of the magnetic field exposure produced by welding equipments has been developed using Flux3D tools. Both homogeneous models and human body models have been used in order to compute the induced current density in biological tissues.**

I. Introduction

Acute effects due to electromagnetic (EM) fields are largely documented and studied. In order to protect people from electromagnetic emissions, ICNIRP (International Committee Non Ionizing Radiation Protection) [1] has suggested some limits for workers and general public in order to avoid acute effects that are instantaneous consequences of the field exposure.

At low frequency the most important sources are high intensity currents (*e.g.* power transformers, transmission lines, inductors, welding and melting equipments) that generate high intensity magnetic field. In some industrial environments, electromagnetic emissions can be high because electrical equipments and processes that use high intensity currents are spread. European community has recently issued a directive about the risks deriving by the exposure to electromagnetic fields [2]. This directive fixes the same limits suggested by ICNIRP for workers.

Some standards (e.g. [7]) suggest practical solutions in order to verify the assessment in terms of induced current density. Measurements and analytical computation allow the evaluation of the magnetic flux density level. Nevertheless the magnetic flux density can overcome limits, even if the corresponding induced current density respects ICNIRP basic restriction. Numerical simulation using simplified homogeneous or heterogeneous models can be used in order to estimate induced current density in a conductive medium. Some research groups have studied the effect of the magnetic field in the human body using different numerical techniques (impedance method, scalar potential finite difference and finite element methods) and suitable human body models [3]–[6], [18].

In this paper the construction of a 3D human model using Flux 3D [11] and a procedure that can be used in order to evaluate the magnetic field exposure have been discussed and applied for the evaluation of the current density induced in human tissues due to the magnetic field emission of a resistance welding equipment. The comparison between data obtained by a very simplified model (a cylinder) and the ones arising from a more complete model has been proposed. Flux 3D automation tools have been proposed and a set of geometrical models and Python scripts [17] have been prepared.

II. Evaluation of the magnetic field exposure

The effects of electric and magnetic fields on the human body vary as a function of the frequency: until 100 kHz (low frequency case) the primary effect is due to the induced current density, that is an instantaneous effect and might cause nervous stimulation [8]. ICNIRP guidelines provide basic restrictions that have been extrapolated according to the effects of induced currents on human body.

For practice, ICNIRP guidelines provide reference limits that are measurable quantities, like magnetic flux density, derived from basic restrictions. Nevertheless, in some cases the evaluation of the exposure in terms of magnetic flux density may lead to an overestimation because the corresponding effective induced current density can satisfy limits even if the magnetic field exceed them. The evaluation by means a numerical analysis of the effective induced current density can be applied to verify the satisfaction of the ICNIRP limits.

The reference limits and basic restrictions, suggested by the ICNIRP guidelines [1], are expressed as a function of the frequency of the field. The evaluation of the exposure can be performed comparing the magnetic flux density or the induced current density with the corresponding limits. In some practical cases, the magnetic field is not a single-frequency component, but, if periodic, it can be decomposed as a sum of sinusoidal components. In this case, the ICNIRP gives some rules [1] [9]. For instance, the exposition can be evaluated using:

$$a_{t,j}(A) = \sum_{i=1Hz}^{10MHz} \frac{A_i(f,j)}{A_{L,i}(f)} \tag{1}$$

where $A_{i,j}(f,j)$ is the magnetic flux density or the induced current density in a tissue j at the frequency f, $A_{L,i}$ is the corresponding limit value. In this case limits are satisfied if the (1) is lower than 1. In order to evaluate the (1) using Flux3D a magneto dynamic simulation for each frequency must be performed. Using Flux3D Scenario tools the cycling on different frequency values can be easily performed.

III. Computation method and models

Both a simplified homogeneous model and a more complex not-homogeneous human model have been implemented. The simplified model is a cylinder (Fig. 1), while the human model has been obtained from real Computer Tomography (CT) data. Each slice of the CT has been segmented and a 3D mesh has been generated using medical images segmentation software [10]. The meshed volumes have been imported in Flux 3D, Finite element simulation tool [11]. The model of the human body and the cylindrical model with the mesh of conductive volumes is sketched in Fig. 1. The human model has 239516 nodes and 1430096 mesh volume elements, whereas the cylindrical one has 57733 nodes and 346707 mesh volume elements.

In the last case the human body tissues are described with the value of their resistivity, ρ, that vary between 1 and 50 Ωm. These values have been derived by the Gabriel model [12]. In the cylindrical model the resistivity is a weight average value that considers the real tissues inhomogeneity and has been fixed to 5 Ωm like has been suggested by standards [7].

The magnetic field source is a wire positioned as prescribed by standards [7] and amplitude and frequency of the current is derived from the Fast Fourier Transform (FFT) of the current waveform as measured on the welding machine. In general a simulation for each current-frequency couple has been performed in order to evaluate the index $\alpha_{t,j}$ on the (1).

The computation of the magnetic flux density and the induced current density in the volume that simulates the human body is obtained by means of a time-harmonic eddy current solution for each frequency of the system [13]. If the wavelength associated with field is large in comparison with the problem geometry, Maxwell equations and constitutive properties can be solved under quasi-static hypothesis.

The simulated geometry, sketched in Fig. 1, is composed by the human body, that is a conductive region (Ω_{COND}), and two vacuum region (Ω_{INT} and Ω_{EXT}) one of them contains the magnetic field source, Ω_{EXT}. In this geometry electromagnetic (EM) problem has been solved like in [14]. In the Ω_{COND} region the induced current density is computed. In this case, EM problem has been solved in terms of the phasor of the magnetic vector potential, $\dot{\bar{A}}$ and the phasor of the electric scalar potential, $\dot{V}$. In this case the Flux3D MD3AV formulation has been used and the induced current density, $\dot{\bar{J}}$ can be obtained from:

$$\dot{\bar{J}} = \sigma\dot{\bar{E}} = -\sigma(j\omega\dot{\bar{A}} + \nabla\dot{V}) \tag{2}$$

where $\dot{\bar{E}}$ is the electric field and σ the conductivity of the medium. The magnetic field, $\dot{\bar{H}}_s$, in a free space region produced by a wire that carries an electrical current is modeled using analytical Biot-Savart formula and so it has been modeled as Flux 3D non meshed coils. The use of non meshed coils sources has the advantage that they can be displaced without changing the mesh. The use of so non-meshed coils is very convenient to compute the minimum distance that provides the satisfaction of exposure limits.

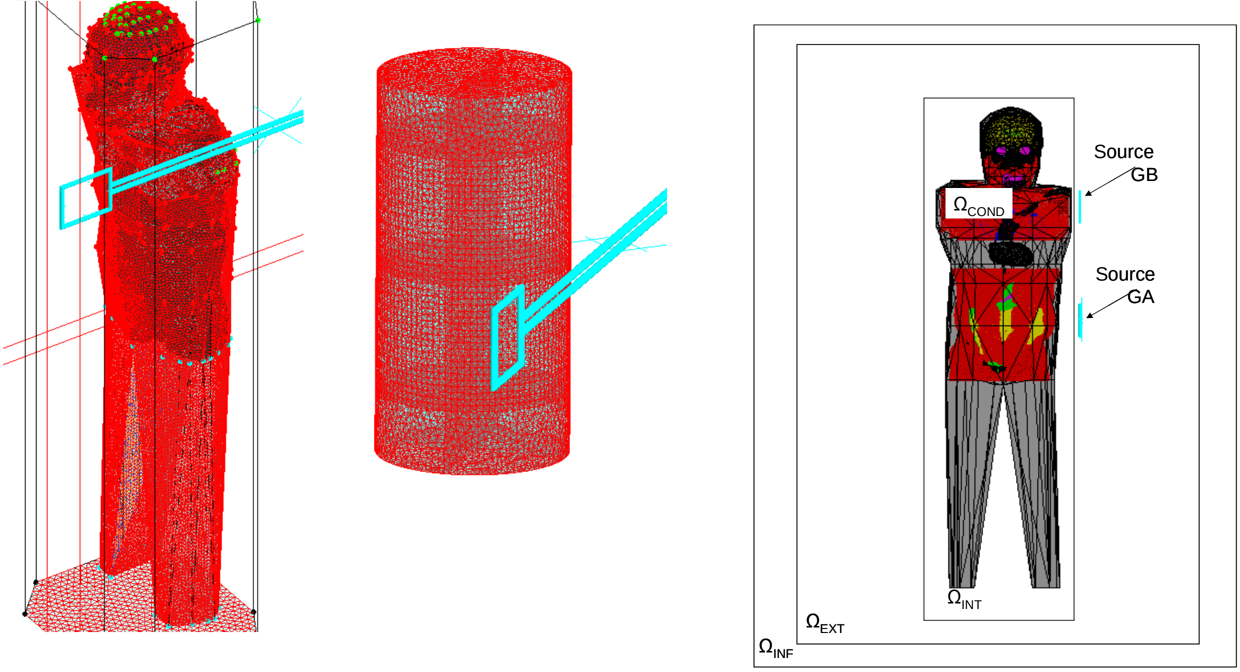

Figure 1: Human model geometry simulated in FEM SW tool. GA and GB are the sources of the magnetic field that have the same geometry of the source than in the cylindrical model.

Using this strategy, the sources can be described without using mesh elements. Because the source of magnetic field has an analytical formulation, the evaluation of the magnetic field in the vacuum volume, that contains the source (Ω_{EXT}), is solved by a reduced scalar potential formulation (MD3RED), $\dot{\phi}_{RED}$ by means:

$$\dot{\bar{H}} = \dot{\bar{H}}_j - \nabla\dot{\phi}_{RED} \tag{3}$$

where $\dot{\bar{H}}_j$ is the field contribution from Biot-Savart formula. Between Ω_{COND} and Ω_{EXT} a volume Ω_{INT} has been interposed. In this way the region Ω_{COND}, where the EM problem is solved in terms of $\dot{\bar{A}}$ and

$\dot{V}$ potentials there is a region where the EM problem is solved only in terms of vector potential $\dot{A}$ (MD3VEC formulation). At the boundary between Ω_{INT} and Ω_{EXT} proper interface conditions have been automatically posed by Flux 3D. In Ω_{INT} region the solved equation is:

$$\nabla \times \frac{1}{\mu} \times \nabla \dot{A} = \dot{J} \quad \nabla \cdot \dot{A} = 0 \tag{4}$$

At the boundary of the simulation domain, Ω_{INF}, infinite boundary conditions have been posed in order to let the magnetic field vanish at infinite distance by means of the Infinite Box.

VI. Results

In order to evaluate the current density induced by a magnetic field produced by a resistance welding equipment in the human body model, simulations using two magnetic field sources, GA and GB as shown in Fig. 1, have been performed, whereas for the simulations with the cylindrical model only the GA source position has been considered. In both simplified and human body models a current of 6938 Arms at 50 Hz flows in the source.

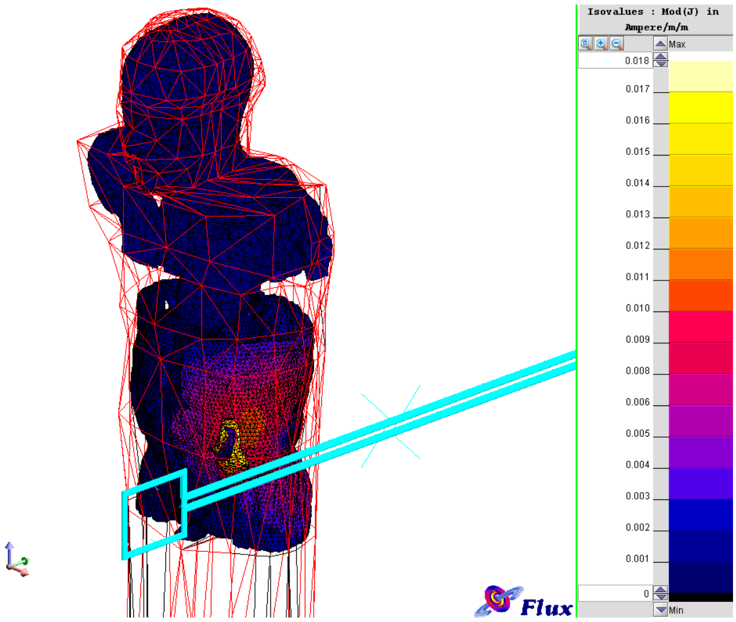

Figure 2: Induced current density in human body model.}

For each tissue the maximum values of the magnetic flux density and the induced current density have been derived from simulation results, using a Python script that cycles on all volumes of the geometry. The program extracts the map of the magnetic flux density and the one of the induced current density from each volume of the geometry. These maximum values have been compared with corresponding limits (in the examined case at 50 Hz are 500 μ T and 10 mA/m^2 respectively).

The Flux 3D procedure used in order to evaluate the welding equipment magnetic field exposure can be resumed with following main steps:

1. Evaluation of the welding current and determination of the amplitude and frequency of sinusoidal components
2. Construction of a simplified geometry (cylinder) or the human body geometry

3. Physical definition (in the human body model the tissues resistivity must be varied with the frequency)
4. Generation of a set of scenarios, one for each couple current amplitude and frequency
5. Simulation of the models
6. Use of Python scripts for the results extraction
7. Evaluation of results.

In Table 1 the ratio α as described in (1) have been reported for some human organs for both geometries GA and GB. The ratio α has been computed for magnetic flux density, α (B), and for the induced current density, α (J), values. In this case, the evaluation of the exposure on the basis of the magnetic flux density can be worst with respect to the one evaluated from the induced current density. Fig. 3 reports the colored map of induced current density in the human body tissues for the geometry GA. Obtained results with human body model and geometry GA have been compared with the ones of the cylindrical model (last bottom row in Table 1). It is pointed out that the cylindrical model is proposed by Standards [7] for the evaluation of the exposure to the magnetic field generated by welding equipments. From data in Table 1 it can be pointed out that the more accurate model might show a worst exposure in term of induced current density than the one of the cylindrical model. This fact is reasonable because the resistivity of some tissues is lower than the one used in the cylinder [15]. For instance in [16] a comparison between homogeneous and heterogeneous models has been performed. The homogeneous models might give lower induced current densities than heterogeneous ones.

Table 1: tissue resistivity value, ratio of equation (1) for the magnetic flux density and induced current density in human body tissues and in the homogeneous cylindrical model.

		GA		**GB**				**GA**		**GB**	
Tissue	**ρ[Ω m]**	**α(B)**	**α(J)**	**α(B)**	**α(J)**	**Tissue**	**ρ[Ω m]**	**α(B)**	**α(J)**	**α(B)**	**α(J)**
Liver	27.26	0.78	0.03	0.26	0.02	**Spleen**	11.67	3.37	0.2	0.33	0.04
Heart	12.09	0.64	0.06	0.66	0.03	**Intestine**	1.92	5.3	1.22	0.2	0.09
Colon	18.34	3.37	0.13	0.26	0.02	**CerebellarFluid**	0.5	0.06	0.07	0.63	0.56
Bone	49.85	2.68	0.05	33.38	0.18	**BrainStem**	13.29	0.09	0.01	1.02	0.1
Pancreas	1.92	1.37	0.34	0.25	0.07	**Cerebellum**	10.5	0.08	0.02	1.19	0.19
Kidney	11.21	2.2	0.1	0.24	0.03	**Brain**	18.77	0.07	0.01	1.17	0.08
Bladder	4.87	0.58	0.09	0.08	0.02	**Stomach**	1.92	1.32	0.45	0.3	0.09
Lung	14.62	0.48	0.04	2.09	0.09	**Fat**	51.15	9.37	0.87	95.85	2.51
Muscle	4.29	7.29	0.73	27.75	1.8	**Cylinder**	**5**	**49,3**	**1,97**	**47,4**	**1,5**

Considering data in Table 1 the two numerical simulation strategies with the human body model (GA and GB) lead to different results in terms of satisfaction of exposure limits because the source is placed in different positions and consequently organs and tissues near the source are different.

With the source in the position GA, induced current density in each tissue computed with the human model is lower than the ones computed using the homogeneous cylindrical model, whereas using the cable configuration GB, the human model provides in some tissues (muscle) an higher induced current density than the homogeneous cylindrical model.

The more complex model gives more accurate information than the simplified homogeneous one. A lower induced current density in some tissues with respect to the one computed in the simplified model is due to their relative position from the source, their real dimension and their own resistivity.

VIII. Conclusions

In this work a procedure for the evaluation of the exposure to magnetic field generated by welding equipments has been implemented. Python script for a partial automation of the computation has been also implemented in order to reduce Flux 3D model generation. New feature, like "scenario" has been used in order to reduce the number of models used. In fact in each scenario the frequency can be changed without generate another physical model. This investigation shows that Flux 3D is a powerful tool really suitable for the evaluation of the human exposure to magnetic field.

VIII. Acknowledges

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