A simplified procedure for the exposure to the magnetic field produced by resistance spot welding guns

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This paper describes a simplified but effective methodology for the assessment of the human exposure to the magnetic field generated by resistance spot welding guns. The procedure makes it possible to compute the induced electric field in time domain as required by the standardized methodology for the assessment of pulsed magnetic fields (i.e. the weighted peak method). In this paper we show that the proposed procedure provides results in accordance with a rigorous approach allowing a huge reduction of the computational burden and, consequently, a significant speedup.

***Index Terms*—Exposure, magnetic field, spot welding, low frequency**

I. INTRODUCTION

THE concern about the exposure to electromagnetic fields is of worldwide interest, however, the exposure limits are not homogeneous. The regulatory framework in most countries is based on the ICNIRP guidelines that cover the proper limits for acute effects only [1]. Other countries has their own set of limits and, sometimes, the attention is focused also on the possible long term effects.

Regarding the professional exposure the situation is more uniform (at least in Europe) because of the introduction of the European Directive 2004/40/EC that has been recently repealed and substituted by the 2013/35/EU [2]. This directive is strongly based on the ICNIRP guidelines and formally defines the concept of *action level* (AL) and the *exposure limit value* (ELV). The former is related to a directly measurable quantity as the magnetic flux density, the latter is associated to the a quantity that is directly related to the physiological stimulation as the induced electric field [1]. In this paper we analyze the exposure to the magnetic field produced by resistance spot welding guns in view of this new directive. These devices generate a pulsed magnetic flux density that likely exceeds the ALs. Moreover, for operational reasons, it is impossible to endow the welding gun by a shielding system. Consequently, the only solution is the assessment of the ELVs. To this aim, we provide a methodology that fulfills the Directive requirements and reduces the computational burden at the same time.

II. DESCRIPTION OF THE EXPOSURE

Resistance spot welding guns are divided in two main categories: *Alternatig Current* (AC) and *Medium Frequency Direct Current* (MFDC). Both technologies use a welding pulse that lasts from 100 ms to 200 ms with a current peak in the order of 10 kA. The AC guns generate a pulse made of several sinusoidal cycles at 50 Hz. The more the gun is working close to the rated current the more the single cycle is close to a perfect sine. The spectral content of the welding current includes significant components up to approximately 1000 Hz. The MFDC guns generate a pulse that, ideally, should be a rectangular waveform. However, the static conversion that rectifies the current introduces a ripple at the main frequency of 1000 Hz, as shown in Fig. 1. The spectral content of the welding current includes significant components up to approximately 10 kHz as shown in Fig. 2. In this paper we restrict our investigations to the MFDC technology because it generates a magnetic field that includes the highest frequency components.

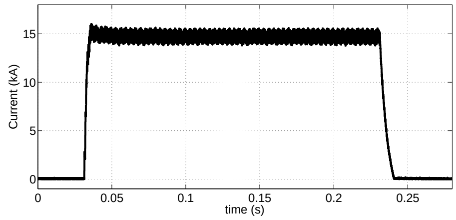


Fig. 1. Example of MFDC welding current.

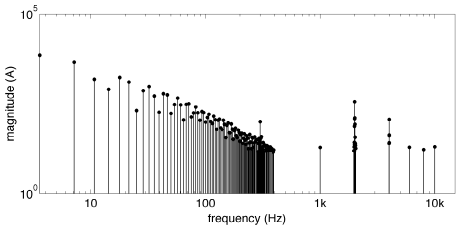


Fig. 2. Spectrum of the MFDC welding current. Most of the spectral lines are concentrated below 400 Hz. Significant spectral lines are found up to 10 kHz.

III. EXPOSURE ASSESSMENT REQUIREMENTS

As claimed by the ICNIRP guidelines [1], the exposure quantity at low frequency is the *electric field*. Moreover, a pulsed magnetic field must be assessed via the *weighted peak method* (WPM). The principle of application of the WPM is described in Fig. 3. The symbol A represents a generic time dependent vector quantity that can be either a magnetic field or an (internal) electric field. The weight function is based on the curve “limit vs. frequency” that applies to the input A. As shown in Fig. 3 each component is weighted and squared before being summed up together. Finally, the square root

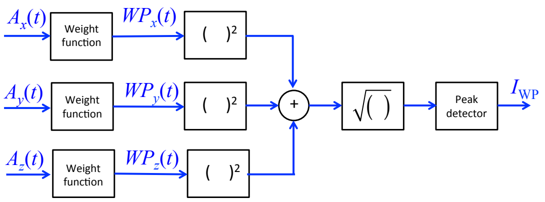


Fig. 3. Block diagram of the weighted peak method (WPM).

operator is applied and, in the end, the peak I_{WP} is detected. The exposure is compliant if $I_{WP} < 1$. Bearing all this in mind, it is clear that in order to apply the WPM it is required to compute the induced electric field in time domain. At first, the problem is approached in frequency domain analyzing all the spectral lines of the source current separately. We make use of the assumption that the magnetic field created by the induced currents is small with respect to the one created by the source currents [3]. Under this hypothesis, the magnetic field distribution is not perturbed by eddy currents and so it can be computed independently on the conducting body. By making reference to the standard notation for discrete operators introduced in [4] the problem can be formulated in algebraic form as follows:

$$\mathbf{G}^{\mathrm{T}}\left(\mathbf{M}_{\sigma}+\mathrm{j}\omega\mathbf{M}_{\epsilon}\right)\mathbf{G}\underline{\varphi}=-\mathrm{j}\omega\mathbf{G}^{\mathrm{T}}\left(\mathbf{M}_{\sigma}+\mathrm{j}\omega\mathbf{M}_{\epsilon}\right)\underline{\mathbf{a}}_{\mathrm{s}} \tag{1}$$

It is apparent that, by exploiting the hypothesis that the magnetic field is not modified by the eddy currents, the magnetic vector potential created by the sources is a known term that can be used at the right hand side. Equation (1) is solved at each spectral line updating the matrices $\mathbf{M}_{\sigma}$, $\mathbf{M}_{\epsilon}$ and $\underline{\mathbf{a}}_{\mathrm{s}}$. Finally, at a given point of the human body, the use of the Inverse Fourier Transform provides the waveforms of the three orthogonal components of the electric field required as input of the WPM. Because the frequency band of the source waveform is limited below $10\ \mathrm{kHz}$, the displacement currents has a negligible effect on the exposure ($\mathbf{M}_{\epsilon}=0$). In addition, it is possible to define an equivalent conductivity for each tissue suitable for all the spectral analysis. For the jth tissue we define this equivalent conductivity as:

$$\sigma_{\mathrm{eq}}^{j}=\frac{\sum_{f=0}^{f_{\max}} I(f)\sigma^{j}(f)}{\sum_{f=0}^{f_{\max}} I(f)} \tag{2}$$

where $I(f)$ is the magnitude of the current at the frequency f and $\sigma^{j}(f)$ is the conductivity of the jth tissue at the frequency f [5]. It is worth noting that, thanks to the introduction of the equivalent conductivity, the matrix $\mathbf{K}=\mathbf{G}^{\mathrm{T}}\mathbf{M}_{\sigma_{\mathrm{eq}}}\mathbf{G}$ is independent of the frequency. Moreover, since the problem is linear, it is possible to define a normalized magnetic vector potential $\mathbf{a}^*$ such that $\mathbf{a}=\mathbf{a}^*\underline{I}$. Finally, the normalized variable $\boldsymbol{\varphi}^*=\boldsymbol{\varphi}/\mathrm{j}\omega\underline{I}$ is considered:

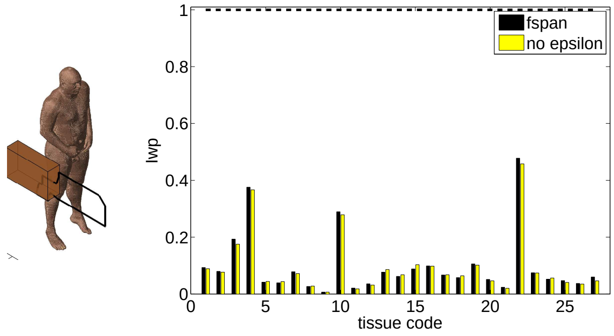
$$\mathbf{K}\boldsymbol{\varphi}^{*}=-\mathbf{G}^{\mathrm{T}}\mathbf{M}_{\sigma_{\mathrm{eq}}}\mathbf{a}^{*} \tag{3}$$

Equation (3) is neither dependent on the frequency nor on the current, therefore, it is solved only once to obtain the real vector $\boldsymbol{\varphi}^*$. The solution at a given spectral line related to the angular frequency ω and the current $\underline{I}$ is then obtained as:

$$\mathbf{u}=-\mathrm{j}\omega\left(\mathbf{G}\boldsymbol{\varphi}^{*}+\mathbf{a}^{*}\right)\underline{I} \tag{4}$$

IV. Comparison and Conclusions

In this section the welding configuration described in Fig. 4(a) is analyzed. This is the most common working configuration in which the welding gun is handled horizontally at the side of the operator. The full and the simplified method (eq. (1) and (3), respectively) are employed to compute the WP index in the human body. For each tissue a reference point is identified by the 99th percentile approach [1]. As shown in Fig. 4(b) the two methods provide comparable results. The difference is always below 10% which is clearly acceptable for these kinds of analyzes. This test is performed on a human model with resolution $6\times6\times6\ \mathrm{mm}$. The full procedure lasts slightly less than one hour and the simplified method provides a speedup of 11.5.



(a) (b)

Fig. 4. Subfigure (a) describes the analyzed configurations. Subfigure (b) shows the comparison of the I_{WP} values obtained with the full and the simplified method.

Another interesting result is that the I_{WP} index is compliant in all the tissues even if the magnetic flux density exceeds the ALs. In the full paper we will show that this is not a general result because the exposure strongly depends on the welding gun position and geometry.

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