A Simplified Procedure for the Exposure to the Magnetic Field Produced by Resistance Spot Welding Guns

Please cite this paper as:
Canova A., Freschi F., Giaccone L., Manca M. "A Simplified Procedure for the Exposure to the Magnetic Field Produced by Resistance Spot Welding Guns", IEEE Transactions on Magnetics, Volume 52, n. 3, article number 5000404, March 2016, DOI: 10.1109/TMAG.2015.2479297

A Simplified Procedure for the Exposure to the Magnetic Field Produced by Resistance Spot Welding Guns

Aldo Canova, Fabio Freschi, Luca Giaccone*, and Michele Manca
Politecnico di Torino, Dipartimento Energia,
corso Duca Degli Abruzzi, 24 - 10129 Torino

Abstract

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.

keywords: Exposure, magnetic field, spot welding, low frequency.

1 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 have their own set of limits and, sometimes, the attention is focused also on 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uniform (at least in Europe) because of the introduction of the European Directive 2004/40/EC that has been recently repealed and substituted by the 2013/35/EU [2].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 a quantity that is directly related to the physiological stimulation as the induced electric field [1].

*Politecnico di Torino, Dipartimento Energia, corso Duca Degli Abruzzi, 24 - 10129 Torino, Italy (luca.giaccone@polito.it)

In this paper we analyze the exposure to the magnetic field produced by resistance spot welding guns in view of this last directive. These devices generate a pulsed magnetic flux density that likely exceeds the ALs [3]. 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.

2 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 that usually varies from 5 to 20 kA. AC guns generate a pulse made of several sinusoidal cycles at 50 Hz. The more the gun is working close to its 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. MFDC guns generate a pulse that, ideally, is 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 actual waveform was measured by a suitable probe connected to a 10 bits oscilloscope. The sample rate was fixed to 10 MSa/s. The waveform in Fig. 1 is made of 2.8 MSa and, by FFT processing, the spectrum of Fig. 2 is obtained. The spectral content of the welding current includes significant components up to approximately 10 kHz and most of the spectral lines are located below 400 Hz. Fig. 2 also includes the spectrum of the corresponding ideal waveform that can be computed analytically for a rectangular pulse [4]. The two spectra coincide at very low frequencies while at higher frequencies they are different due to the presence of finite slope up/down times and the ripple in the actual waveform.

In this paper we restrict our investigations to the MFDC technology because it generates a magnetic field that includes the highest frequency components.

3 Methods for exposure assessment

3.1 Pulsed magnetic fields

As claimed by the ICNIRP guidelines [1], the exposure quantity at low frequency is the induced *electric field*. Moreover, a pulsed magnetic field must be assessed via the *weighted peak method* (WPM) [5, 6] in time domain [2]. 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

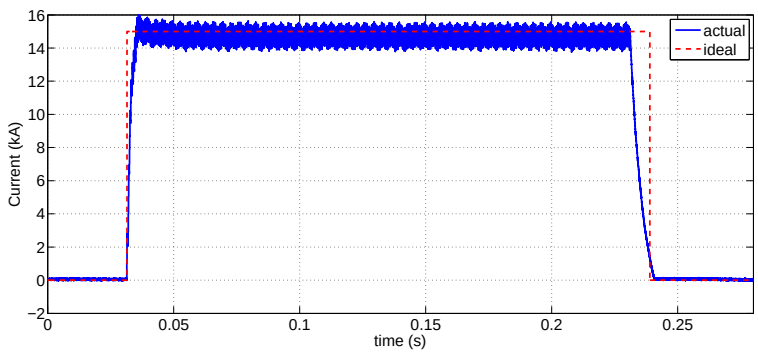


Figure 1: Example of MFDC welding current, actual vs. ideal.

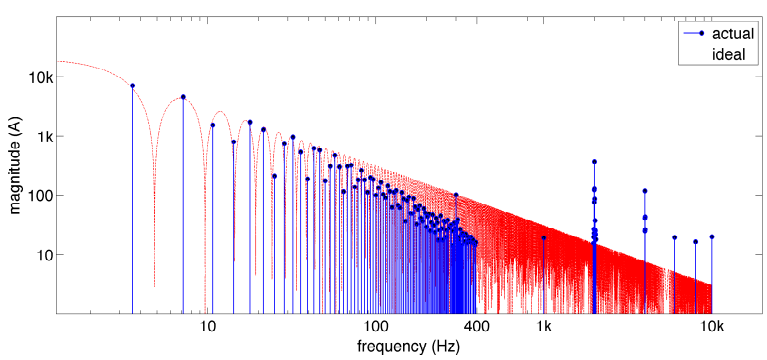


Figure 2: Spectrum of the MFDC welding current. With reference to the actual waveforms, most of the spectral lines are concentrated below 400 Hz. Significant spectral lines are found up to 10 kHz.

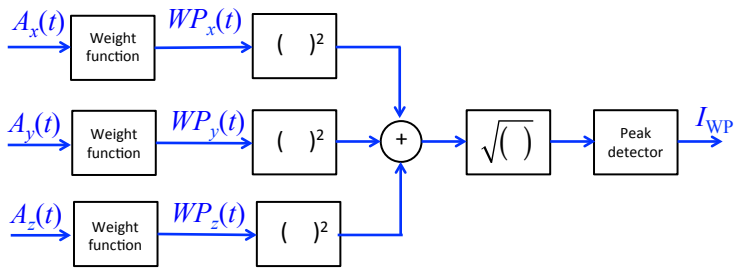


Figure 3: Block diagram of the weighted peak method (WPM).

root 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.

3.2 Full formulation

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 [7]. Under this hypothesis, the magnetic field distribution is not perturbed by eddy currents and so it can be computed independently of the conducting body. By making reference to the standard notation for discrete operators introduced in [8] the problem can be formulated in algebraic form as follows:

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

where the material parameters σ and ϵ depend on the frequency [9]. 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 for 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.

3.3 Proposed simplified formulation

Because the frequency band of the source waveform is limited below 10 kHz the influence of the displacement currents could be negligible. A qualitative confirmation is given in Fig. 4 where the ration $\omega\epsilon/\sigma$ is provided for some significant tissues. The lower the value of $\omega\epsilon/\sigma$ the lower is the influence of the displacement currents. For the sake of readability only some tissues are represented in

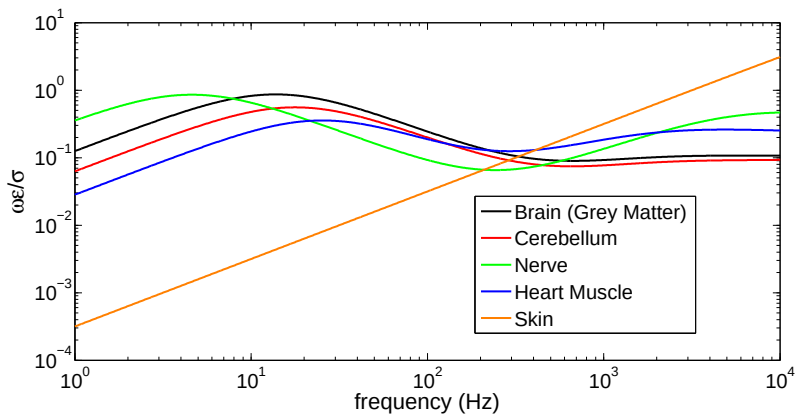


Figure 4: Analysis of the tissue properties at varying frequency. The quantity $\omega\epsilon/\sigma$ is used to understand the importance of the displacement currents in the computation.

Fig. 4, however, most of them are characterized by a ratio $\omega\epsilon/\sigma < 1$ inside the analyzed frequency range. Only few tissues have $\omega\epsilon/\sigma > 1$ for higher frequency (like the skin as shown in Fig. 4). For this reason the first assumption of the simplified method is that the effect of the displacement currents is negligible, hence $\mathbf{M}_\epsilon = 0$.

As a further simplification, we assume that the behavior of each tissue can be described by an equivalent conductivity throughout the frequency range. For the jth tissue we define this equivalent conductivity as:

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

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 [9].

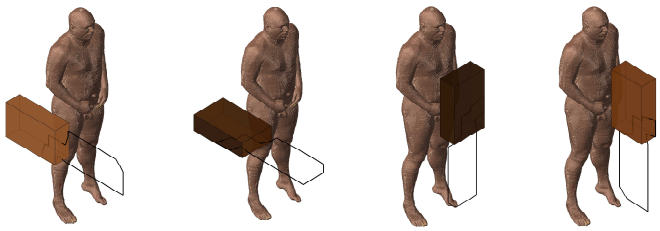
It is worth noting that, the introduction of the equivalent conductivity is the key point of the simplified method because it makes the matrix $\mathbf{K} = \mathbf{G}^{\mathrm{T}}\mathbf{M}_{\sigma_{\text{eq}}}\mathbf{G}$ independent of the frequency. Moreover, since the problem is linear, it is possible to define a normalized magnetic vector potential $\hat{\mathbf{a}}$ such that $\mathbf{a} = \hat{\mathbf{a}}\underline{I}$. In the end, considering the normalized variable $\hat{\boldsymbol{\varphi}} = \boldsymbol{\varphi}/\mathrm{j}\omega\underline{I}$ the following real system is obtained:

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

Equation (3) is neither dependent on the frequency nor on the current, therefore, it is solved only once to obtain the real vector $\hat{\boldsymbol{\varphi}}$.

4 Comparisons

The four configurations described in Fig. 5 are analyzed. The full (1) and



(a) side 1 (b) side 2 (c) front 1 (d) front 2

Figure 5: Four typical configurations in which the position of the gun varies with respect to the operator. In the first two configurations (a and b) the gun horizontal and at the side of the operator while in the last two (c and d) the gun is vertical and in front of the operator.

the simplified (3) method are employed to compute the WP index for each tissue. According to the ICNIRP guidelines, to avoid discretization uncertainties as staircasing and field singularity, the attention should not be paid to the maximum value of the electric field. It is proposed to check the exposure by choosing the 99th percentile value of the induced field inside a specific tissue. Although recent studies criticize this approach for possible underestimations [10] we make use of 99th method in order to be compliant with the ICNIRP and the current EU directive. Furthermore, the selection criteria of the maximum field value does not influence the rationale of the proposed method.

4.1 Comparison of induced quantities and performance

In this section the electric field waveforms obtained by the full and the simplified method are compared. For the sake of brevity the waveforms are provided only for configuration front 1 at the reference point of the skin (where often a high value of the electric field is induced). In Fig. 6 the three components of the induced electric field are shown during all the welding pulse. This result is obtained employing the full procedure. To better appreciate the comparison, a zoom is made in correspondence to the time ranges represented by the black dashed lines. Fig. 7 provides the comparison of the waveforms obtained with the two methods. Continuos lines refer to the full approach while the dots refer to the proposed simplified approach. It is apparent that they are in good agreement. This comparison reinforces the assumption $\mathbf{M}_\epsilon = 0$ because the agreement is very good even for tissues where the ratio $\omega\epsilon/\sigma > 1$ for higher frequency values (Fig. 4.)

Regarding the formulation performance, from the analysis of (1) and (3) some conclusions can be immediately drawn. The full formulation requires to solve a linear system for each spectral line while the simplified method only

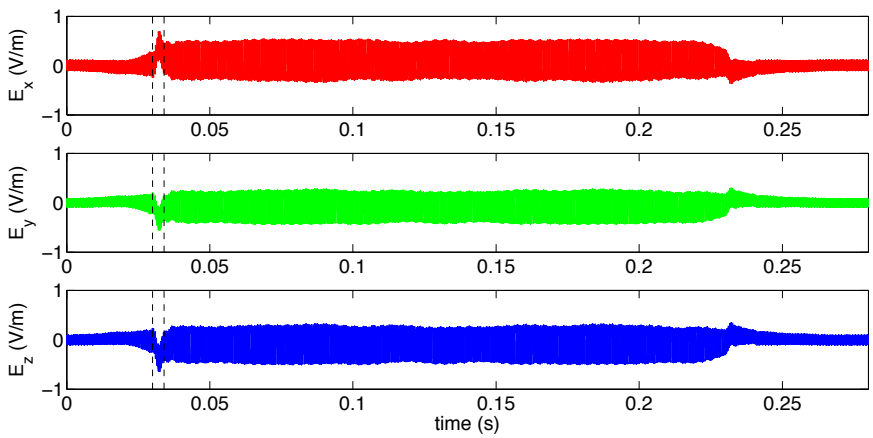


Figure 6: Electric field waveforms induced in the skin for a given configuration. This results are obtained with the full formulation. The elctric field is almost proportional to the time derivative of the magnetic flux density, In fact, in correspondence to the slope up/down a peak appears.

requires the solution of one normalized system. By comparing the elapsed times related to these tasks a speedup of approximately 350 is registered. Finally, it must be stressed that, since the proposed approach requires the solution of only one real system instead of several complex systems (of the same dimension), the memory allocation is roughly halved.

4.2 Comparison of the WP index

For the sake of completeness a third method for the computation is included along with the use of (1) and (3). It is an intermediate method that neglects the displacement currents ($\mathbf{M}_\epsilon = 0$) taking into account the dependance of σ on the frequency. The introduction of the intermediate method (called *no epsilon*) makes it possible to understand the influence of the two simplifications: $\mathbf{M}_\epsilon = 0$ and introduction of σ_{eq}.

The WP exposure index related to the most significant tissues are shown in Fig. 8, Fig. 9, Fig. 10 and Fig. 11. They are related to the configurations *side1*, *side2*, *front1* and *front2*, respectively. The full and the simplified approach are in good agreement for all the configurations at all tissues. The deviation is less than 10% at most of the tissues. Higher values are registered (up to 30%) especially at tissues where the index is very low ($I_{\text{WP}} < 0.2$). Bearing in mind that the global accuracy of these analyses is often more affected by the modeling of the welding gun (based on geometry information and/or by fitting of measurement data) we consider acceptable the accuracy of the proposed method. Finally, these deviations are mainly related to the introduction of σ_{eq} because the intermediate method provides always results in complete accordance with

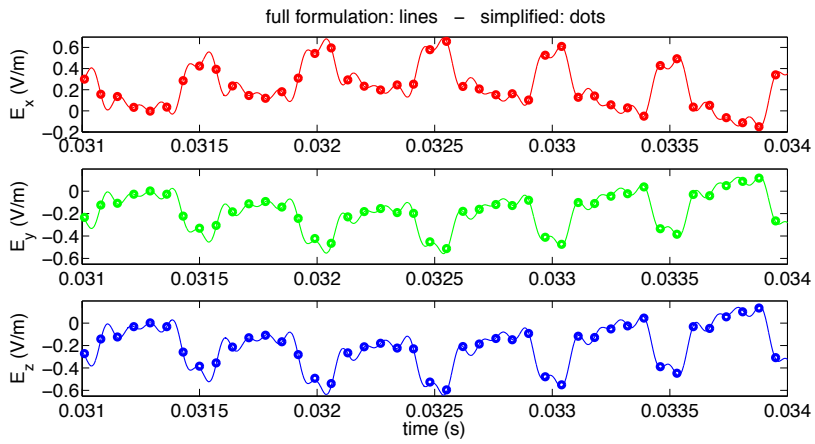


Figure 7: Comparison of the electric field waveforms obtained with the two methods. Continuos lines refer to the full approach while the dots refer to the proposed approach. The comparison is provided in the ranges highlighted in Fig. 6 by means of dashed lines.

the full approach.

5 Conclusions

In this paper a simplified but effective methodology for the assessment of the human exposure to the magnetic field generated by resistance spot welding guns is presented. The methodology is validated by comparing the results with a full formulation. It is observed that the proposed method provides reliable results accompanied by a significant speedup.

The case studies used for the validation also put in evidence another interesting result. The I_{WP} index is compliant at all the tissues even if the magnetic flux density likely exceeds the ALs. Only for one configuration (*front 1*) the exposure is not compliant at one tissue with the ICNIRP guidelines. This means that the exposure is strongly dependent on the relative position of the gun with respect to the operator. As far as the human exposure is concerned, welding guns are one of the most problematic industrial devices, therefore, it is important to have reliable and fast evaluation methods to cover all the required exposure analyses.

References

[1] ICNIRP, "Guidelines for Limiting Exposure to Time-Varying Electric and Magnetic Fields (1 Hz - 100 kHz)," *Health Phys*, vol. 99, no. 6, pp. 818–836, 2010.

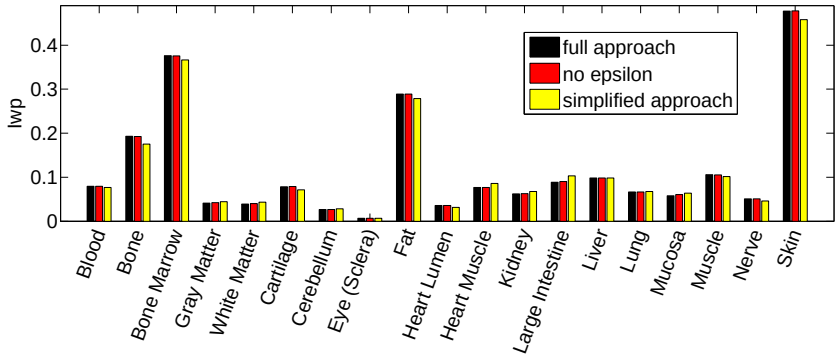


Figure 8: Comparison of the WP exposure index at different tissues. Results related to the configuration *side 1*. (Compliance condition: $I_{\mathrm{WP}} < 1$).

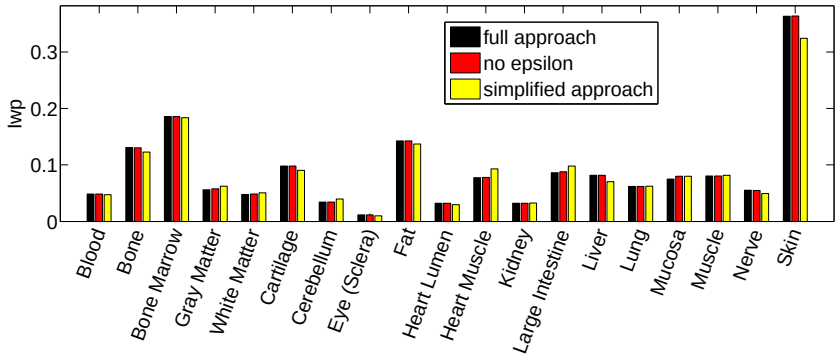


Figure 9: Comparison of the WP exposure index at different tissues. Results related to the configuration *side 2*. (Compliance condition: $I_{\mathrm{WP}} < 1$).

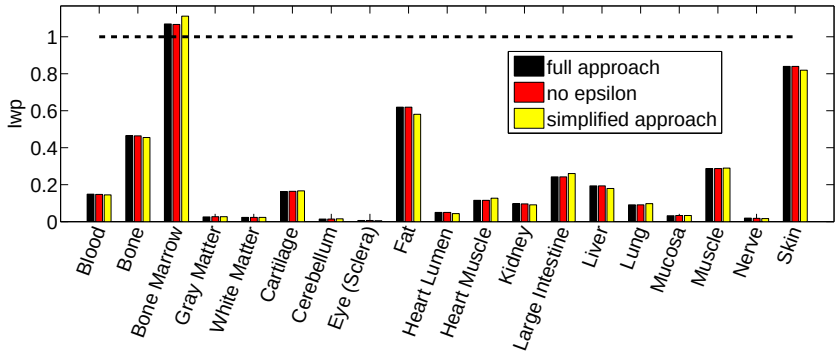


Figure 10: Comparison of the WP exposure index at different tissues. Results related to the configuration *front 1*. (Compliance condition: $I_{\mathrm{WP}} < 1$).

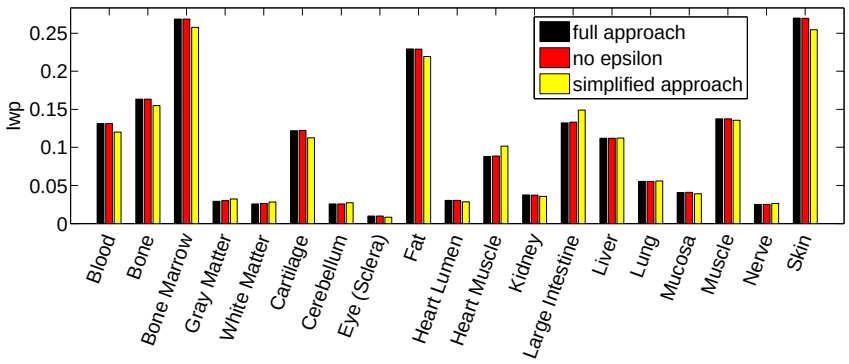


Figure 11: Comparison of the WP exposure index at different tissues. Results related to the configuration *front 2*. (Compliance condition: $I_{\mathrm{WP}} < 1$).

[2] "Directive 2013/35/EU of the European Parliament and of the Council of 26 June 2013 on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (electromagnetic fields) (20th individual Directive within the meaning of article 16(1) of directive 89/391/EEC) and repealing directive 2004/40/EC."

[3] A. Canova, F. Freschi, L. Giaccone, and M. Repetto, "Exposure of working population to pulsed magnetic fields," *IEEE Transaction on Magnetics*, vol. 46, pp. 2819–2822, Aug. 2010.

[4] C. R. Paul, *Introduction to Electromagnetic Compatibility*. Wiley, 2006.

[5] K. Jokela, "Restricting exposure to pulsed and broadband magnetic fields," *Health Phys*, vol. 79, no. 4, pp. 373–388, 2000.

[6] ICNIRP, "Guidance on determining compliance of exposure to pulsed and complex non-sinusoidal waveform below 100 kHz with icnirp guidelines," *Health Phys*, vol. 84, no. 3, pp. 383–387, 2003.

[7] T. Dawson, K. Caputa, and M. Stuchly, "Electric fields induced in humans and rodents by 60 Hz magnetic fields," *Physics in Medicine and Biology*, vol. 47, pp. 2561–2568, 2002.

[8] A. Canova, F. Freschi, and M. Repetto, "Evaluation of workers exposure to magnetic fields," *The European Physical Journal - Applied Physics*, vol. 52, no. 23311, pp. p1–p6, 2010.

[9] P. Hasgall, E. Neufeld, M. Gosselin, A. Klingenböck, and N. Kuster, "IT'IS Database for thermal and electromagnetic parameters of biological tissues." www.itis.ethz.ch/database, September 26 2011.

[10] X. L. Chen, S. Benkler, N. Chavannes, V. De Santis, J. Bakker, G. van Rhoon, J. Mosig, and N. Kuster, "Analysis of human brain exposure to

low-frequency magnetic fields: a numerical assessment of spatially averaged electric fields and exposure limits," *Bioelectromagnetics*, vol. 34, no. 5, pp. 375–384, 2013.