Human Exposure Assessment in Dynamic Inductive Power Transfer for Automotive Applications

Human Exposure Assessment In Dynamic Inductive Power Transfer For Automotive Applications

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This paper proposes a methodology for the assessment of the human exposure to magnetic fields generated by dynamic inductive power transfer systems for automotive applications. Since the magnetic field is pulsed, current safety standards and guidelines require the use of time-domain approaches to evaluate the peak exposure which has to be limited under the prescribed limits. This paper shows that, for these kind of systems, the peak exposure can be efficiently evaluated by means of a time-harmonic formulation. Furthermore, a methodology to identify the worst case scenario is proposed.

Index Terms—**Inductive power transfer (IPT), dosimetry, pulsed fields, magnetic fields.**

I. Introduction

The use of inductive power transfer (IPT) seems an effective technology for the growth of the electric mobility. Moreover, its application for the charge during the motion of the vehicle (dynamic IPT) is promising to overcome the barriers represented by the heavy on-board battery storage and the long recharging time. IPT is essentially based on the resonance of two magnetically coupled inductors: the transmitter, placed on the ground, and the receiver, placed under the vehicle floor. The frequency typically ranges from $20\ \mathrm{kHz}$ to $100\ \mathrm{kHz}$. The coupling between the two inductors takes place through a large air-gap, usually about $10-30\ \mathrm{cm}$. This large gap implies a high level of stray field in the vicinity of the coils that can represent a problem in terms of exposure to magnetic fields for passengers or people that could approach the vehicle during the charge operations. In the dynamic IPT, the different transmitters are sequentially energized for few milliseconds [1] in correspondence to the passage of the vehicle, giving rise to pulsed magnetic fields.

This paper presents the methodology and the results for the assessment of the human exposure to the magnetic field applied to an actual IPT installation. The case study is a $20\ \mathrm{kW}$ IPT system for a light commercial vehicle operating at the frequency of $85\ \mathrm{kHz}$. The dynamic charge is performed by means of several independent transmitters activated only when the vehicle is above them. Each transmitter is $1.5\ \mathrm{m}$ long and $0.5\ \mathrm{m}$ wide. The methodology has been developed according to the requirements of the latest ICNIRP guidelines [2]. The results show that the methodology proposed for the analysis can be efficiently applied in the frequency domain avoiding the use of time-domain approaches.

II. Methodology for the exposure assessment

A. Pulsed magnetic fields

The ICNIRP guidelines propose a two-step approach for the assessment of the human exposure to magnetic fields. Firstly, the compliance with the limits has to be verified considering the magnetic flux density B by means of measurements or calculations. The exposure is compliant if the magnetic flux density does not exceed the so called *reference levels*. If the reference levels are exceeded, a dosimetric analysis has to be carried out to compute the dosimetric quantities. The exposure is compliant if these induced quantities are below the so called *basic restrictions*. In the low frequency range, the dosimetric quantity is the induced electric field [2].

When dealing with pulsed magnetic fields, the ICNIRP guidelines propose the adoption of the weighted peak method (WPM). The WPM was developed by prof. Jokela in [3] and was included by the ICNIRP in the statement of 2003 [4] and formally adopted in the latest guidelines related to low frequency fields [2]. The WPM is summarized by the following expression:

$$\left|W_j A_j \cos\left(2\pi f_j t + \theta_j + \varphi_j\right)\right| < 1 \tag{1}$$

where: A_j and θ_j are the amplitude and the phase of the jth spectral line of the field under analysis. W_j and φ_j are the amplitude and the phase of the weight function at the same frequency. The amplitude of the weight function at a given frequency is defined as the inverse of the peak limit at that frequency. The weight function for the magnetic flux density is shown in Fig. 1.

The assessment of the magnetic flux density using the WPM is, in general, analogous to apply a suitable high pass

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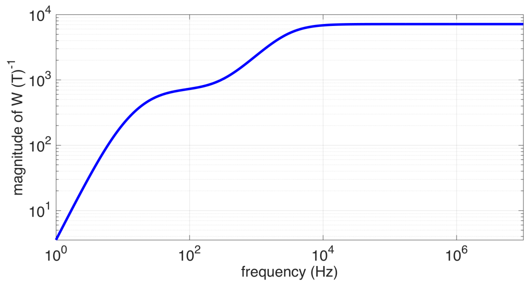


Fig. 1: Magnitude of the W used to weight the magnetic flux density.

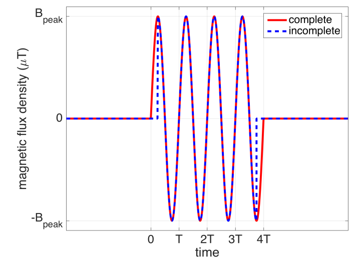
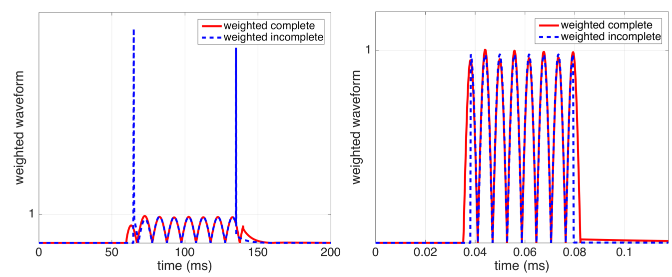


Fig. 2: Complete and incomplete sinusoidal bursts.



(a) (b)

Fig. 3: Weighted waveforms of the complete and incomplete sinusoidal bursts at 50 Hz (a) and 85 kHz (b). The incomplete burst at 50 Hz is characterized by two peaks in correspondence with the sharp variations. The second waveform at 85 kHz is not characterized by any peak.

filter to the field waveform in time domain [4]. However, for a waveform whose spectrum is limited above 10 kHz, the WPM corresponds to the application of a scale factor because the weight is constant above this threshold as shown in Fig. 1. The current in the transmitter of a dynamic IPT system for automotive applications is a sinusoidal burst at frequencies above 20 kHz. For this reason, the waveform of the magnetic field due to the activation of the transmitter can be considered as a continuous sinusoidal waveform. This is shown by comparing the assessment of two sinusoidal bursts at different frequencies, 50 Hz and 85 kHz. For each frequency, two limit conditions are considered: 1) finite number of cycles, 2) incomplete cycle at the beginning and at the end, in order to simulate a sharp variation of the field. Fig. 2 shows a sinusoidal burst of four complete periods T (red) and another burst with truncated cycles at the beginning and at the end (blue) that create sharp variations. The peak of the waveforms is always chosen as the ICNIRP limit at the frequency f.

Fig. 3a and Fig. 3b represent the left hand side of (1) for the waveforms at 50 Hz and 85 kHz, respectively. The sharp variation of the field plays a key role because it corresponds to a high frequency spectral line with respect to the fundamental frequency of the field. For the 50 Hz sinusoidal burst it corresponds also to the maximum exposure because the high pass filter emphasizes them as shown in Fig. 3a. Conversely, the exposure to a 85 kHz sinusoidal burst is not affected by sharp variations because the WPM becomes a simple scaling factor as explained earlier and as shown in Fig. 3b. Therefore, the sinusoidal burst of the present application is equivalent to a continuous sinusoidal waveforms at the same frequency. Consequently, the exposure will be assessed by means of a time-harmonic formulation and the weighted peak method is equivalent to the computation of an exposure index defined as the ratio of the maximum value of the E field and the related exposure limit value. This exposure index corresponds to the maximum value of the right hand side of (1).

B. Identification of the worst case scenario

The IPT system studied in this paper is actively controlled on both sides: the power electronics controls and keeps the rms value of the current in the transmitter at 36 A and the current in the receiver at 75 A. This control is possible only when the mutual inductance M is kept to a value higher than 5 μH. For lower coupling, the control system switches the system off. The value of M is mainly affected by the misalignment between transmitter and receiver. The misalignment is defined as the distance between the axes of the two coils. Its influence on M is shown in Fig. 4. The assessment of the human exposure to magnetic fields have to consider the misalignment aspects.

The worst case is identified by computing the magnetic flux density in the region of interest represented in Fig. 5. For every feasible misalignment, the maximum field value in the region of interest and the volume in which the ICNIRP threshold is exceeded are computed. At the frequency of 85 kHz this limit is 27 μT. This procedure makes it possible to identify the worst case not only considering the condition that gives

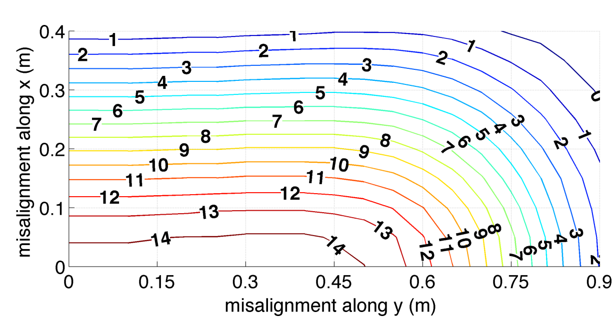


Fig. 4: Contour lines representing the mutual inductance M (in microhenry) versus the misalignment of the coils axes for a gap of 25 cm.

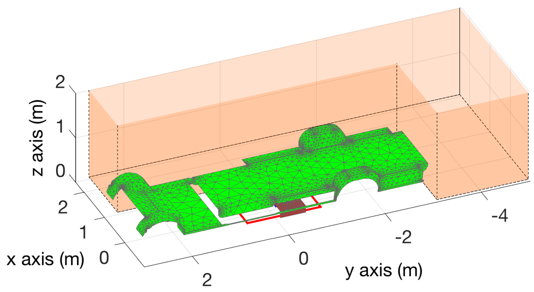


Fig. 5: Region of interest for the evaluation of the magnetic flux density.

place to the maximum magnetic flux density but also the one that presents the larger volume where the limits are exceeded. When the worst case is identified, the dosimetric analysis is carried out, evaluating the induced electric field E in the human body.

C. Problem formulation

The typical distances between the coils and the space around the vehicle where people could stay is in the order of some meters. For this reason it is necessary to use a suitable formulation of the 3D electromagnetic problem that does not require to mesh the air and that simplifies the computation of the induced phenomena on the vehicle chassis. The selected formulation relies on the surface impedance boundary conditions (SIBC) applied to the vehicle chassis coupled with the boundary element formulation to account for the magnetic field in the open space [5]. The magnetic flux density is evaluated in the region of interest represented in Fig. 5. This region has a fixed relative position with respect to the chassis. Preliminary evaluations indicated the possibility to restrict the modeling of the vehicle chassis to the bottom part only. The dosimetric analysis makes use of the human model Duke, a 34-year-old male from the Virtual Population [6]. The voxel resolution of $2 \times 2 \times 2\ \mathrm{mm}^3$ is used. Since the presence of the human body does not modify the external magnetic field, the exposure is assessed by means of the scalar potential finite difference technique expressed in its algebraic form [7]:

$$\mathbf{G}^{\mathrm{T}}\mathbf{M}_{\sigma}\mathbf{G}\boldsymbol{\varphi} = -\mathrm{j}\omega\mathbf{G}^{\mathrm{T}}\mathbf{M}_{\sigma}\mathbf{a}_{\mathrm{S}} \tag{2}$$

where σ is the electric conductivity, φ is the electric scalar potential, $\mathbf{a}_{\mathrm{S}}$ is the magnetic vector potential integrated along the mesh edges due to the sources and $\mathbf{M}_{\sigma}$ is the constitutive conductance matrix.

III. Results

The receiver can be mounted in two positions: a central position, between the axle shafts, and a rear position, as illustrated in Fig. 6. Both cases have been analyzed. When the receiver is mounted at the center, the active transmitter is always covered by the body of the vehicle. Fig. 7 shows that the worst case condition in terms of maximum B occurs for

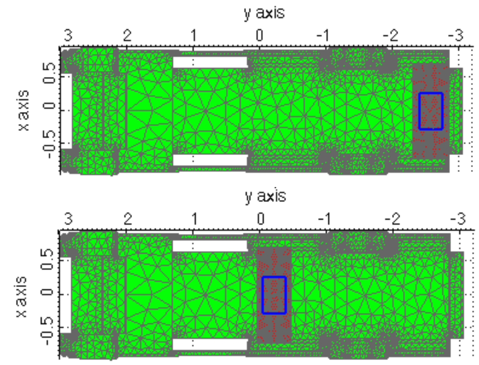


Fig. 6: Mounting positions for the receiver. Receiver structure in red, coil in blue.

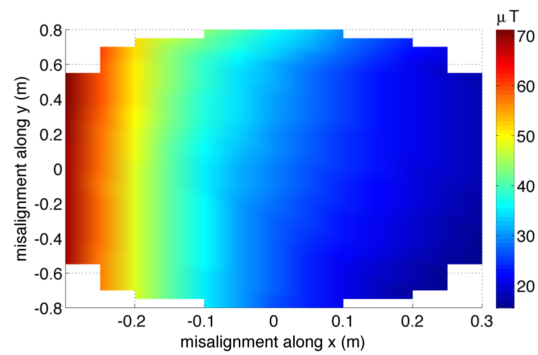


Fig. 7: Maximum value of the magnetic flux density versus the misalignment in the case of receiver mounted on the center. Missing points correspond to a weak coupling condition where the mutual inductance M is lower than 5 μH.

a misalignment of -0.3 m along x and 0.55 m along y. The corresponding B value is 72 μT. When the receiver is mounted in the rear part of the vehicle, the transmitter may be uncovered during the movement of the vehicle. When the misalignment exceeds about 30 cm the value of the magnetic flux density B remains practically constant at the value of 1.4 mT, Fig. 8. Hence, the worst case is identified calculating the volume in which B goes beyond the limit of 27 μT, represented in Fig. 9.

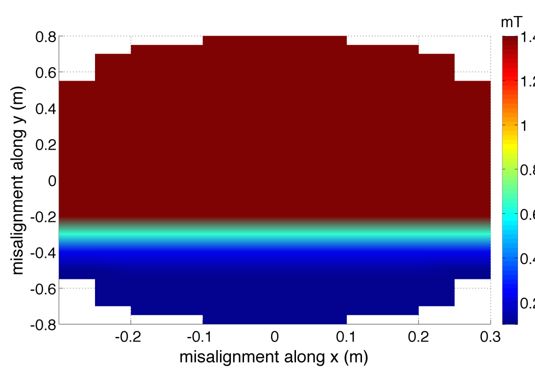


Fig. 8: Maximum value of the magnetic flux density versus the misalignment in the case of receiver mounted on the rear. Missing points correspond to a weak coupling condition, where the mutual inductance M is lower than 5 μH.

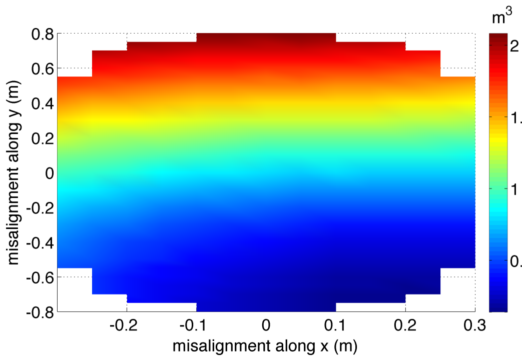


Fig. 9: Volume having magnetic flux density higher than the reference level of 27 μT. Missing points correspond to a weak coupling condition, where the mutual inductance M is lower than 5 μH.

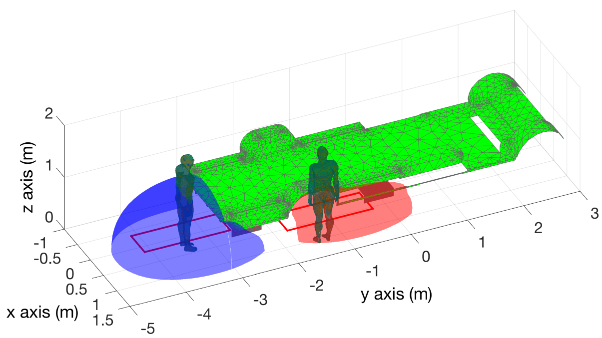


Fig. 10: Boundary of the volumes having magnetic flux density higher than the reference level of 27 μT and position of the Duke model for the exposure assessment. Both cases are represented with the related relative position of the coils. The red volume refers to the case with the receiver mounted on the center. The blue volume refers to case with the receiver mounted on the rear.

The worst case occurs for a misalignment of 0.1 m along x and 0.8 m along y. Fig. 10 summarizes the two worst cases that are considered for the calculation of the exposure index based on the basic restrictions and the corresponding volumes where the magnetic flux density is not compliant with the reference level. The human model is placed at the point corresponding to the maximum intersection between this volume and the body, as shown in Fig. 10. The electric field is calculated at all voxels of the human model, then the 99th percentile is evaluated for all tissues [2]. Fig. 11 shows the exposure indexes at the tissues usually identified as critical [8]. It is apparent that (1) is satisfied at all tissues when the receiver is placed in the center of the vehicle, whereas the exposure index is overreached when the receiver is installed at the back of the vehicle. In order to be compliant with the ICNIRP guidelines, a clearance distance of 75 cm must be guaranteed. This is a conservative distance because it is referred to the reference levels.

IV. Conclusion

This paper focuses on the assessment of the human exposure to magnetic fields generated by dynamic inductive power transfer systems for automotive applications. Pulsed magnetic fields often require the use of time-domain approaches to determine the peak exposure. This paper shows that the complex analysis in time-domain may be avoided because the peak exposure can be accurately evaluated using a time-harmonic formulation. Furthermore, the weighted peak method turns into the computation of a simple exposure index provided that the frequency of the system is higher that 10 kHz. Two indicators are proposed to characterize the worst case scenario: the maximum field value and the volume of the region where the limit is exceeded. It is shown that the two indicators are particularly useful when the receiver is on the vehicle rear. The application studied in this paper is always compliant with the ICNIRP guidelines when the receiver is on the center of the vehicle. Conversely, when the receiver is on the vehicle rear, a clearance distance of 75 cm from the transmitter is required. Finally, it is worth noting that the proposed methodology is also suitable for static IPT systems.

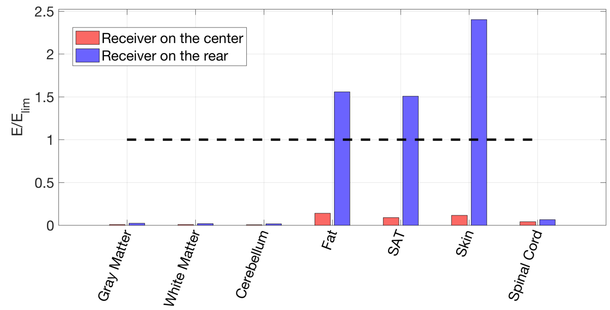


Fig. 11: Exposure index on the selected tissues for the analyzed worst cases.

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