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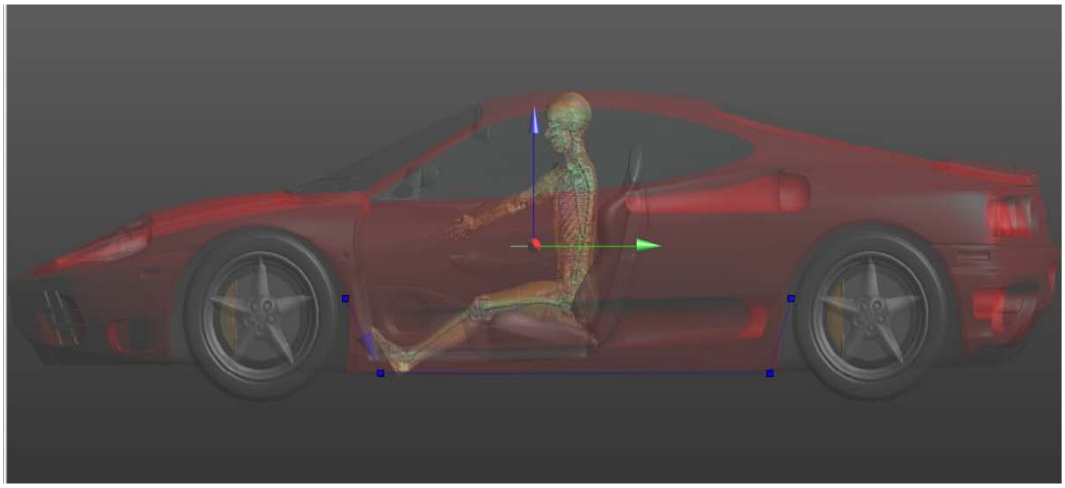
Investigation of Electric/Magnetic fields in the passenger compartment of Volvo cars



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Investigation of Electric/Magnetic fields in the passenger compartment of Volvo cars

Master of Science Thesis in Biomedical Engineering Program

In corporation with

Volvo Car Corporation

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Abstract

The International Commission on Non-Ionizing Radiation Protection (ICNIRP) is established with the main purpose of publishing guidelines for limiting EMF exposure that will provide protection against known adverse health effects.

This guideline contains different information about two main groups, workers and general public.

The aim of this master's thesis is to investigate the electromagnetic fields exposure of the general public in low frequency (up to 100 kHz) and compare the results with the limits in the ICNIRP guidelines, to see whether these limitations are exceeded or not.

This report is mainly focused on two sources which produce low frequency electromagnetic in the car in. These two sources are the cables which connect battery at rear to the motor and headlights that are located in front of the car.

These sources are considered as current source in simulation and the current density which is induced in the Central Nervous System (CNS) is then calculated and compared to the ICNIRP guidelines.

The human body model in this project is a 26 years old women with 170 cm height and 62 Kg weight. This model is placed in two different positions: at the driver seat and bending above the motor when the hood is open.

According to the results, the induced current density in the CNS at both positions is lower than the ICNIRP (1998) exposure limits, however, the current density which is induced in the CNS of the model bending above the motor is higher than when the model is sitting in the car as the distance between the body and the sources becomes less in this position.

The ICNIRP (2010) exposure limits for the internal electric field in the CNS are not exceeded in any of the positions.

Key words: ICNIRP, low frequency, general public, induced current density, electric field, Central Nervous System (CNS)

Acknowledgment

First I would like to express my gratitude to my supervisor at Volvo Car Corporation, Kjell Attback for giving me the opportunity of doing this master thesis at Volvo Car Corporation and giving me great inspiration. I would like to thank him for his invaluable help and guidance.

Secondly I would like to thank my examiner in Chalmers University of technology, Professor Yngve Hamnerius for awaking my interest in area of biological effects and electromagnetic fields. I would like to extend my appreciation for his great knowledge and kind guidance in various problems in my thesis and also for giving me the opportunity of doing this master thesis.

Third I would like to thank my co-supervisor at Volvo Car Corporation, Karl-Gustav Johansson for making me feel welcome at Volvo Car Corporation and supporting me with excellent comments during the thesis.

Finally I would like to thank my family and friends for all their support. A special thanks to my parents for their incredible support and love from a very long distance.

Your support made this thesis possible.

Preface

This report is the master thesis for the Biomedical Engineering program at Chalmers University of Technology in Gothenburg, Sweden. It was conducted at the biomedical group in the Department of Signals and Systems. The work was done from mid April through November in the year 2010. The examiner at Chalmers has been Professor Yngve Hamnerius.

Volvo Car Corporation in Torslanda, Göteborg is sponsoring financially this study for one student. Supervisor at Volvo Car Corporation has been Kjell Attback and the co-supervisor has been Karl-Gustav Johansson.

The task has been to investigate the electromagnetic field in the passenger compartment related to possible human health effects in low frequency (1 Hz to 100 kHz) and comparing the results with ICNIRP guidelines basic restriction.

Simulations in this work have been done by the academic version of Semcad X software with low frequency solver. The signal processing part was done by Matlab.

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1 Introduction

Exposure to electromagnetic fields is not a new phenomenon. However, during the 20th century, environmental exposure to man-made electromagnetic fields has been steadily increasing as growing electricity demand, ever-advancing technologies and changes in social behavior have created more and more artificial sources. Everyone is exposed to a complex mix of weak electric and magnetic fields, both at home and at work, from the generation and transmission of electricity, domestic appliances and industrial equipment, to telecommunications and broadcasting [4].

Exposure to electromagnetic field becomes a concern for public these days as the adverse and long term biological effects of exposure to EMF, are debated.

The International Commission on Non-Ionizing Radiation Protection (ICNIRP) is established with the main purpose of publishing guidelines for limiting EMF exposure that will provide protection against known adverse health effects [1].

There is an interest in Electromagnetic fields, considering the fact that many people spend over several hours per day in the car, including children, infants, and pregnant women. It is the car manufacturer responsibility to make some effort to reduce the levels of EMF inside the passenger area of the car and guarantee their products to be safe to use according to the different exposure limits.

According to some projects which were done based on the measurements of EMF inside the Volvo car compartments and their compliance to the ICNIRP reference levels, there is an essential need to check the ICNIRP basic restriction due to the fact that in some parts of the Volvo cars, the fields are more than reference values. Thus, this project is focused on the compliance with the ICNIRP basic restriction.

In the ICNIRP guidelines, the basic restriction for this frequency range of interest (1 Hz to 100 kHz) is the induced current density, $\boldsymbol{J}$, and internal Electric field, E_i,which have to be calculated in Central Nervous System (CNS) to check whether they exceed the maximum permissible exposure limits.

The thesis consists of an introduction to the basic theory of electromagnetic fields and biological health effects. Then it is continued with a brief information about the low frequency solver which is used to calculate the Maxwell Equation in the software Semcad X. This is followed by introducing two low frequency sources which have more significance among the others in Volvo cars. The measured current data from both of these sources has been processed to make them in such a way that can be inserted in Semcad X as an input source. Simulation has been done for a 26 year-old woman in two different positions inside and outside the car. The results then are compared to the ICNIRP guidelines.

2 Theory

In this chapter electromagnetic fields are introduced, the Maxwell Equations are solved and the appropriate solver is introduced for this specific project. The limitations of exposure to EMF are defined according to the International Commission on Non-Ionizing Radiation Protection, ICNIRP guidelines.

2.1 Electric and magnetic field

An electric field, *E*, of 1 V/m is represented by a potential difference of 1 V existing between two plates that are 1 m apart in the space. The magnitude of the electric field varies inversely with the distance from the source in a free-space. If the distance between the plates doubled, the E-field intensity is cut in half. The strength of electric field between two plates is measured as following equation:

$$E = \frac{\Delta V}{d} \qquad \text{Eq. 2.1}$$

In this equation ΔV is the difference between two plates voltage and *d* is the distance between the plates.

A magnetic field is produced by a magnetic object or particle, or by a time-varying electric current. The magnetic field at any given point is specified by both a direction and magnitude.

Magnetic field strength, *H*, is detected by the force that magnetic materials exert on other magnetic materials and moving electric charges; This is measured in amperes per meter. Eq. 2.2.a and Eq. 2.2.b express the magnetic field strength for an infinite straight conductor and the magnetic field strength at the center of the loop, respectively.

$$H = \frac{I}{2\pi r} \qquad \text{Eq. 2.2.a}$$

$$H = \frac{I}{2r} \qquad \text{Eq. 2.2.b}$$

I is the electrical current in the conductor. Moreover, r is the distance from the conductor and the radius of the loop, respectively in Eq. 2.2.a and Eq. 2.2.b.

Magnetic flux density, *B*, is equal to magnetic field strength times the magnetic permeability in the region in which the field exists. Magnetic flux density's unit is Tesla (T) and the relation between H and B is described in Eq. 2.3:

$$B = \mu \cdot H \qquad \text{Eq. 2.3}$$

Where μ is the constant of proportionality (the magnetic permeability); in vacuum and air, as well as in non-magnetic (including biological) materials, μ has the value $4\pi \times 10^{-7}$when expressed in Henry per meter (H m^{-1}) [3].

2.2 Electromagnetic field and Maxwell equations

The field can be viewed as the combination of an electric field and a magnetic field. The electric field is produced by stationary charges, and the magnetic field by moving charges (currents); these two are often described as the sources of the field. The way in which charges and currents interact with the electromagnetic field is described by Maxwell's equations which can be written in frequency domain as following equations [5]:

$$\nabla \times E = -j\omega B \qquad \text{Eq. 2.4.a}$$

$$\nabla \times H = j\omega D + \boldsymbol{J} \qquad \text{Eq. 2.4.b}$$

$$\nabla \cdot D = \rho \qquad \text{Eq. 2.4.c}$$

$$\nabla \cdot B = 0 \qquad \text{Eq. 2.4.d}$$

Where *E, D, B, H*, and *J* are the phasors of the electric field, displacement current, magnetic flux, magnetic field strength and the current density, respectively. The charge distribution is denoted as ρ. Eq. 2.4.b and Eq. 2.4.c gives the Eq. 2.5 which calls charge continuity equation [5]:

$$\nabla \cdot \boldsymbol{J} + j\omega D = 0 \qquad \text{Eq. 2.5}$$

From the other hand we have these equations:

$$D = \varepsilon E \qquad \text{Eq. 2.6.a}$$

$$B = \mu H \qquad \text{Eq. 2.6.b}$$

$$\boldsymbol{J} = \sigma E + \boldsymbol{J}_0 \qquad \text{Eq. 2.6.c}$$

Where $\epsilon = \epsilon_0 \epsilon_r$ is the electric permittivity and $\mu = \mu_0 \mu_r$ is the magnetic permeability. The Ohmic losses are denoted by the electric conductivity σ and the source current is $\boldsymbol{J}_0$. The complex permittivity would be $\varepsilon^{\sim} = \varepsilon_0 \varepsilon_r + \frac{\sigma}{j\omega}$ [5].

Introducing the vector potential A with $\nabla \times A = B$, ($\nabla \cdot A = 0$), solves Eq. 2.4.a and Eq. 2.4.d and leads to Eq. 2.7 [5]:

$$E = -j\omega A + \nabla\emptyset = E_s + E_i \qquad \text{Eq. 2.7}$$

Where $\emptyset$ is a scalar potential and $\nabla \cdot E_s = j\omega\nabla \cdot A = 0$, $\nabla \cdot E_i = \nabla \times \nabla\emptyset = 0$ so rewriting Eq. 2.7 with the new potentials would gives Eq. 2.8 [5]:

$$\nabla \times \frac{1}{\mu} \nabla \times A = \omega^2 \varepsilon^{\sim} A + j\omega\varepsilon^{\sim}\nabla\emptyset + \boldsymbol{J}_0 \qquad \text{Eq. 2.8}$$

And Eq. 2.5 becomes:

$$\nabla \cdot \varepsilon^{\sim} \nabla \emptyset = j\omega \nabla \cdot \varepsilon^{\sim} A \qquad \text{Eq. 2.9}$$

With some mathematical approximations Eq. 2.8 can be rewritten as (to get more details about the equations you can refer to the Semcad X 14.4 reference guide) [5]:

$$\nabla \times \frac{1}{\mu} \nabla \times A = \boldsymbol{J}_0 \qquad \text{Eq. 2.10}$$

The vector potential A is the magneto static vector potential A_0 which is calculated by law of Biot-Savart [5]:

$$A_0(r) = \frac{\mu_0}{4\pi} \int \frac{\boldsymbol{J}_0(\mathrm{r}')}{r - \mathrm{r}'} \, \mathrm{dr}' \qquad \text{Eq. 2.11}$$

Using again Eq. 2.9 and the fact that $\nabla . \boldsymbol{J}_0 = 0$ (closed currents loops) we yield to Eq. 2.12 which is Magneto Quasi-Static (M-QS) equation [5]:

$$\nabla \cdot \varepsilon^{\sim} \nabla \emptyset = j\omega \nabla \cdot (\varepsilon^{\sim} A_0) \qquad \text{Eq. 2.12}$$

Again, this complex valued equation might be further simplified, when the condition holds for all materials in the computational domain [5]:

$$\text{if } \sigma \ll \omega\epsilon \quad \nabla \cdot \varepsilon \nabla \emptyset = j\omega \nabla \cdot (\varepsilon A_0) \qquad \text{Eq. 2.12.a}$$

$$\text{if } \sigma \gg \omega\epsilon \quad \nabla \cdot \sigma \nabla \emptyset = j\omega \nabla \cdot (\sigma A_0) \qquad \text{Eq. 2.12.b}$$

According to the equations, in this project the electrical conductivities of different parts of human body is much lower than the relevant permittivities so the low frequency solver which is implemented, is Magneto Quasi-Static (Biot-Savart) which uses the Eq. 2.12.a [5].

In Magneto Quasi-Static (Biot-Savart) solver, all boundary conditions are neglected. The low frequency current sources cannot be part of the lossy computational domain, due to field singularity. This model uses the real-valued solver. The E field is only calculated in the lossy ($\sigma \neq 0$) domain whereas the H-field is calculated overall. Therefore, the default grid covers only the lossy domain [5].

2.3 ICNIRP definitions and limits

The main objective of ICNIRP is to establish guidelines for limiting EMF exposure that will provide protection against known adverse health effects. Two classes of guidance are presented in frequency between 1 Hz to 10 GHz [1]:

- Basic restrictions: Restrictions on exposure to time-varying electric, magnetic, and electromagnetic fields that are based directly on established health effects. Depending upon the frequency of the field, the physical quantities used to specify these restrictions are current density (***J***), specific energy absorption rate (SAR), power density (*S*) and internal electric field strength (E_i) which is the electric field affects the nerve cells and other electrically sensitive cells [1].

- Reference levels: These levels are provided for practical exposure assessment purposes to determine whether the basic restrictions are likely to be exceeded. Most reference levels are derived from relevant basic restrictions using measurement and/or computational techniques but some address perception (electric field) and adverse indirect effects of exposure to EMF. The derived quantities are electric field strength (*E*), magnetic field strength (*H*), magnetic flux density (*B*) and currents flowing through the limbs (I_L). The quantity that addresses indirect effects is the contact current (I_C). In any particular exposure situation, measured or calculated values of any of these quantities can be compared with the appropriate reference level. Compliance with the reference level will ensure compliance with the relevant basic restriction. If the measured or calculated value exceeds the reference level, it does not necessarily follow that the basic restriction will be exceeded. However, whenever a reference level is exceeded it is necessary to test compliance with the relevant basic restriction and to determine whether additional protective measures are necessary [1],[3].

A general summery of EMF and dosimetric quantities and units is provided in table 2.1.

Quantity	Symbol	Unit
Conductivity	**σ**	Siemens per meter (S m^{-1})
Current	I	Ampere (A)
Current density	**J**	Ampere per square meter (A m^{-1})
Frequency	*f*	Hertz (Hz)
Electric field strength	**E**	Volt per meter (V m^{-1})
Magnetic field strength	**H**	Ampere per meter (A m^{-1})
Magnetic flux density	**B**	Tesla (T)
Magnetic permeability	μ	Henry per meter (H m^{-1})
Permittivity	ε	Farad per meter (F m^{-1})
Power Density	**S**	Watt per square meter (W m^{-1})
Specific energy absorption	SA	Joule per kilogram (J Kg^{-1})
Specific energy absorption rate	SAR	Watt per kilogram (W Kg^{-1})

Table 2.1. *Electric, magnetic, electromagnetic, and dosimetric quantities and Corresponding SI units [1].*

In this project the focus is on general public in low frequency between1 Hz to100 kHz. According to ICNIRP (1998), basic restriction for this particular frequency range is induced current density which is derived from table 2.2. However, according to the new ICNIRP (2010), the basic restriction for frequency between 1 Hz to 100 kHz is internal electric field (E_i) which is indicated in table 2.3. Thus, both restrictions from ICNIRP (1998) and ICNIRP (2010) are studied in this project.

Exposure Characteristics	Frequency	Current density for head and trunk (m A m^{-1}) (rms)	Whole body average SAR (W Kg^{-1})	Localized SAR (head and trunk) (W Kg^{-1})	Localized SAR (limbs) (W Kg^{-1})
Occupational exposure	Up to 1 Hz	40	-	-	-
	1-4 Hz	40/f	-	-	-
	4 Hz-1 kHz	10	-	-	-
	1-100 kHz	f/100	-	-	-
	100 kHz-10 MHz	f/100	0.4	10	20
	10 MHz-10 GHz	-	0.4	10	20
General public exposure	Up to 1 Hz	8	-	-	-
	1-4 Hz	8/f	-	-	-
	4 Hz-1 kHz	2	-	-	-
	1-100 kHz	f/500	-	-	-
	100 kHz-10 MHz	f/500	0.08	2	4
	10 MHz-10 GHz	-	0.08	2	4

Table 2.2 *Basic restrictions for time varying electric and magnetic fields for frequencies up to 10 GHz from 1998 ICNIRP guidelines, f is the frequency in Hz [1].*

Exposure Characteristics	Tissue	Frequency	Internal Electric Field (Vm^{-1})
Occupational exposure	CNS tissue of the head	1-10 Hz	$0.5/f$
		10 Hz-25 Hz	0.5
		25 Hz-400 Hz	$2 \times 10^{-3}f$
		400 Hz-3 kHz	0.8
		3 kHz-10 MHz	$2.7 \times 10^{-4}f$
	All tissues of head and body	1 Hz-3 kHz	0.8
		3 kHz-10 MHz	$2.7 \times 10^{-4}f$
General public exposure	CNS tissue of the head	1-10 Hz	$0.1/f$
		10 Hz-25 Hz	0.01
		25 Hz-1000 Hz	$4 \times 10^{-4}f$
		1000 Hz-3 kHz	0.4
		3 kHz-10 MHz	$1.35 \times 10^{-4}f$
	All tissues of head and body	1 Hz-3 kHz	0.4
		3 kHz-10 MHz	$1.35 \times 10^{-4}f$

Table 2.3 *Basic restrictions for time varying electric and magnetic fields for frequencies up to 10 MHz from 2010 ICNIRP guidelines, f is the frequency in Hz [3].*

3 Exposure to EMF

We are all surrounded by both natural and man-made electromagnetic fields. Therefore, it becomes a considerable tissue to be focused on in order to see how these fields effect the human health. In this chapter, there is a summarized review of coupling mechanisms between fields and the body. It is then followed by a brief introduction to the health effects caused by the exposure to EMF in low frequency range between 1 Hz to 100 kHz.

3.1 Coupling mechanisms between fields and the body

There are two established basic coupling mechanisms through which time-varying electric and magnetic fields interact directly with living matter :

- Coupling to low-frequency electric fields
- Coupling to low-frequency magnetic fields

3.1.1 Coupling to low-frequency electric fields

Actually human and animal bodies significantly affect the spatial distribution of a low frequency electric field. At low frequencies, the body is a good conductor, and the field lines external to the body are nearly perpendicular to the body surface. Electric field outside the body produces the electric charges on the surface of the exposed body. Therefore, these electric charges produce currents inside the body. The interaction of time-varying electric fields with the human body results in the flow of electric charges (electric current), the polarization of bound charge (formation of electric dipoles), and the reorientation of electric dipoles already present in tissue. The relevant magnitudes of these different effects depend on the electrical properties of the body which are electrical conductivity and permittivity. Electrical conductivity is a measure of material's ability to conduct an electric current. The permittivity of a substance shows how an electric field is affected by the substance, and is determined by the ability of material to polarize in response to the field, and thereby reduce the field inside the material. A high permittivity tends to reduce any field present. Thus, permittivity relates to a material‘s ability to permit an electric field. These parameters depend on the type of body tissue and the frequency of the applied field. Main features of dosimetry for exposure of humans to low frequency electric fields consist of [1],[3]:

- The induced electric field inside the body is considerably lower than the external electric field, e.g., five to six orders of magnitude at 50–60 Hz [3].
- For a given external electric field, the highest fields are induced when the human body is in perfect contact with the ground through the feet (electrically grounded), and the lowest induced fields are when the body insulated from the ground (in free space) [3].
- The total induced current going through the body depends on the body size, shape and posture rather than tissue conductivity [3].
- Distribution of induced current inside different tissues and organs depends on the electrical conductivity of different types of tissues.

3.1.2 Coupling to low-frequency magnetic fields

For magnetic fields, the permeability of body is the same as that of air, so the field inside the body is the same as the external field. Therefore, human and animal bodies do not significantly perturb the magnetic field. The main interaction of magnetic fields with the human body is according to Faraday's law which says any time-varying magnetic field induces electric field and associated electric currents in the substance. Electric fields may also be induced by movement in a static magnetic field. Main features of dosimetry for exposure of humans to low frequency magnetic fields consist of [3]:

- For a given magnetic field, greater electric fields are induced in the bodies of larger people because the conduction loops are larger [3].
- The induced electric field and current depend on the orientation of the external magnetic field to the body. Generally induced fields in the body are highest when the field is aligned from the front to the back of the body. However, for some organs the highest values are for different field alignments [3].
- The lowest electric fields are induced by a magnetic field oriented along the principal body axis [3].
- The distribution of the induced electric field is affected by the conductivity of the various organs and tissues [3].

3.2 Biological and health effects of electromagnetic fields and epidemiological studies (up to 100 kHz)

It is important to distinguish between biological effects and health effects in general. Biological effects are measurable responses to a stimulus or to a change in the environment. These changes are not necessarily harmful to our health. An adverse health effect causes detectable impairment of the health of the exposed individual or of his or her offspring; a biological effect, on the other hand, may or may not result in a n adverse health effect [4].

Biological effects of exposure to low frequency electromagnetic fields have been reviewed by the International Agency for Research on Cancer (IARC), ICNIRP, and the World Health Organization (WHO) (IARC 2002; ICNIRP 2003a; WHO 2007a) and national expert groups [3].

According to the ICNIRP (2010), the health effect of exposure to low frequency Electromagnetic field is divided into acute and chronic effects.

3.2.1 Acute effects

There are many acute effects of exposure to low-frequency EMFs on the nervous system including direct stimulation of nerve and muscle tissue and the induction of retinal phosphenes which is the feeling of flashing light when there is actually no lights coming through the eyes. There is also an indirect effect on brain functions such as visual processing and motor co-ordination that can be transiently affected by induced electric fields. All these effects have thresholds below which they do not occur and can be prevented by meeting appropriate ICNIRP basic restrictions [3].

ICNIRP (2003) notes that there is a relatively narrow margin between peripheral nerve perception and pain thresholds. For both types of nerves, thresholds increase above around 1–3 kHz because of the very short membrane time constants resulting from myelination, and below about 10 Hz due to the accommodation to a slowly depolarizing stimulus [2].

ICNIRP reference levels are defined to prevent the painful effects of surface electric charges produced on the body as a result of exposure to low-frequency electric field.

3.2.2 Chronic effects

The research on chronic effects of low frequency electromagnetic fields has been evaluated by many scientists. WHO's cancer research institute and IARC (International Agency for Research on Cancer), evaluated low frequency magnetic fields in 2002 and classified them in category 2 B, which translates to "possibly carcinogenic to humans". The basis of this classification was the epidemiologic results on childhood leukemia [3].

ICNIRP judged the scientific evidence for a causal relationship between childhood leukemia and exposure to low-frequency magnetic field to be too weak to form the basis for guidelines. Therefore, the ICNIRP guidelines are not based on this hypothesis [3].

4 Low Frequency Electromagnetic Sources in the Car

In the low frequency range (1 Hz to 100 kHz) which is the frequency range of interest in this project there are many sources which produce electromagnetic field in the car compartments.

Electric motor, headlight switch, ignition, alternators, air conditioning system and magnetized steel belts in the tires are some of the sources which exist in the car [8].

In this project the first two sources mentioned above, start motor and headlights are studied and the relevant measurements are evaluated.

4.1 Start motor pulse

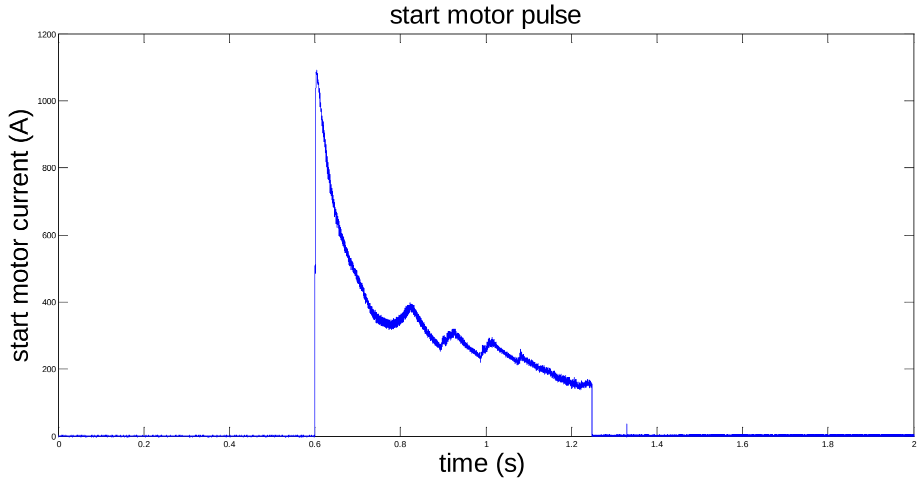

Figure 4.1 Start motor current pulse.

Figure 4.1 illustrates the initial start motor current in 2 sec which is measured with 200 kHz sampling rate. Measurements are done on C30 5 cylinder Diesel Volvo car under cold start condition in room temperature, with a Yokogawa DL750 oscilloscope.

Semcad X software has the possibility to get input as a single frequency pure sine. Thus, to make this signal appropriate for this simulation software, Fast Fourier Transform is done and those particular frequencies with higher amplitude are selected to be inserted as input data to the simulating program.

Figure 4.2 and figure 4.3 indicate the FFT amplitude and phase of the start motor signal, respectively.

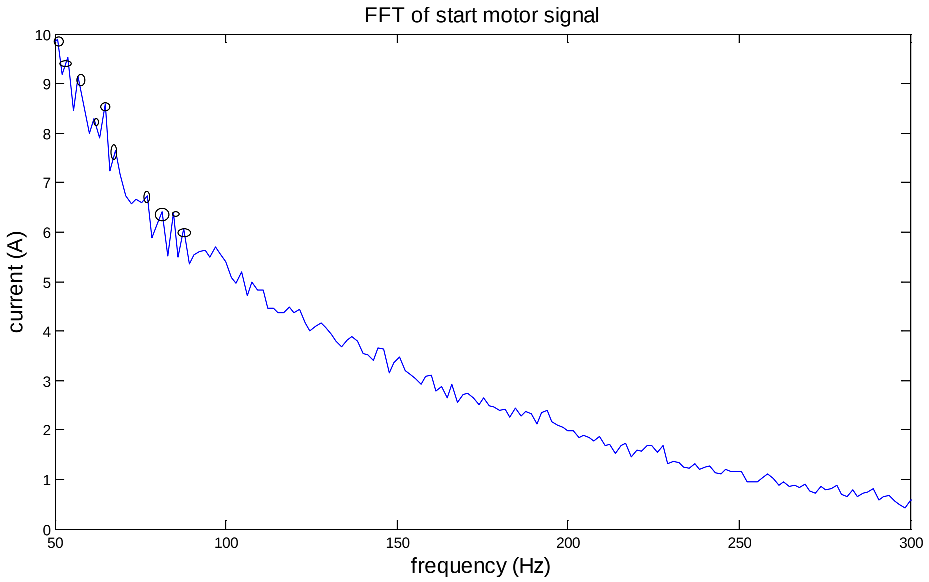

Figure 4.2 FFT (amplitude) of start motor signal.

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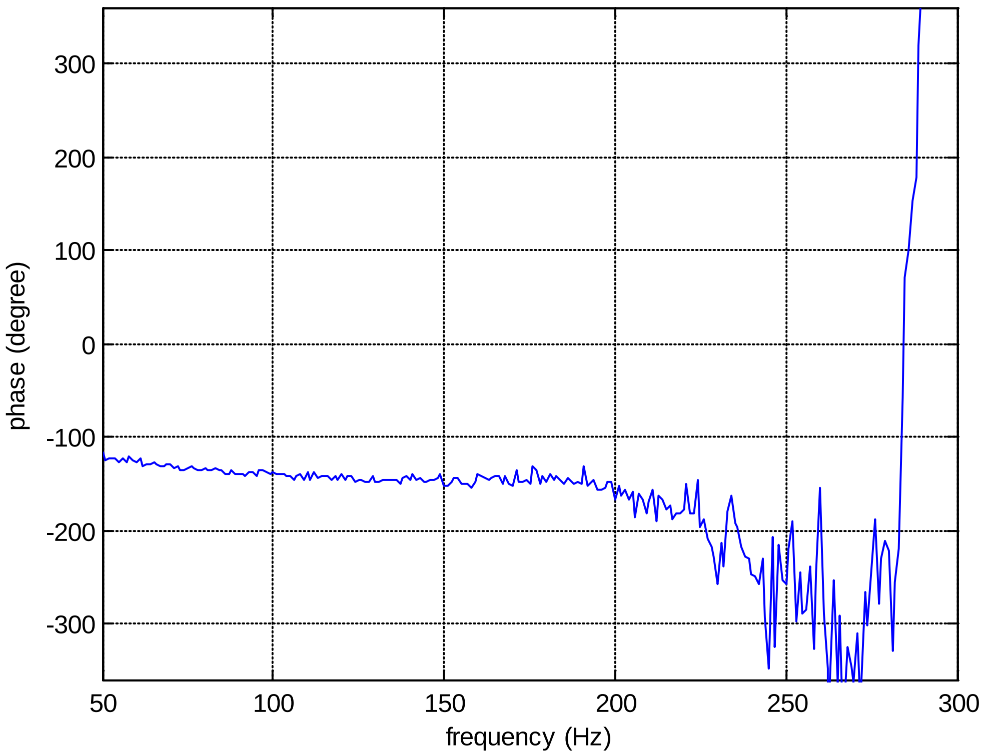

Figure 4.3 FFT (phase) of start motor signal.

Frequency	Amplitude (Ampere)	Phase (degree)
53	9.5	-123
56	9.14	-123
61	8.2	-123
64	8.58	-123
67	7.6	-130
73	6.6	-135
76	6.7	-130
81	6.4	-135
84	6.4	-136
87	6.05	-139

Table 4.1 *10 particular frequencies with the highest amplitude and their relevant phases of start motor signal.*

4.2 Headlight signal

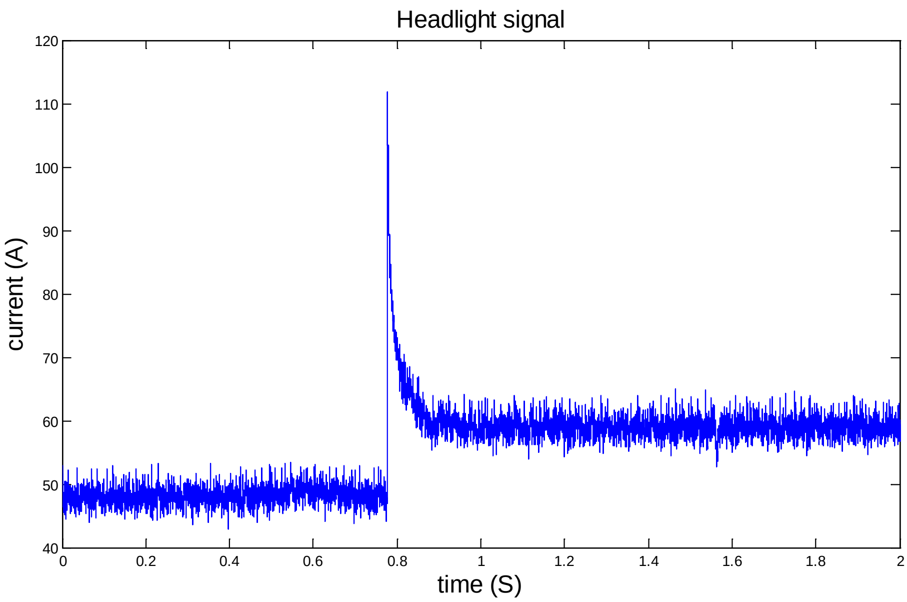

Figure 4.4 Headlight current signal.

Figure 4.4 shows the initial current goes through the cable from the battery to the headlights when they are turned on. These measurements are done on V50 Volvo car at idle mode with Yokogawa DL750 oscilloscope.

Similar procedure as start motor signal should apply to the headlight signal to change it into frequency domain. Figure 4.5 and figure 4.6 shows the FFT amplitude and phase of headlight signal, respectively.

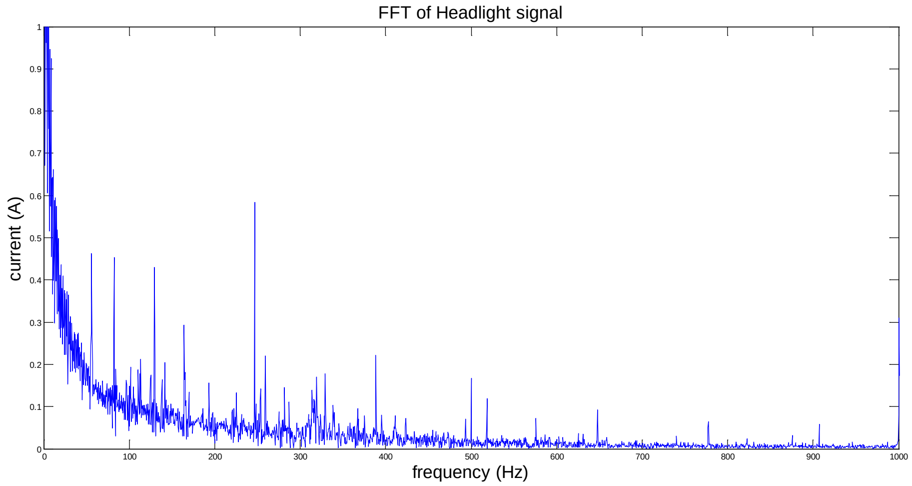

Figure 4.5 FFT (amplitude) of headlight signal.

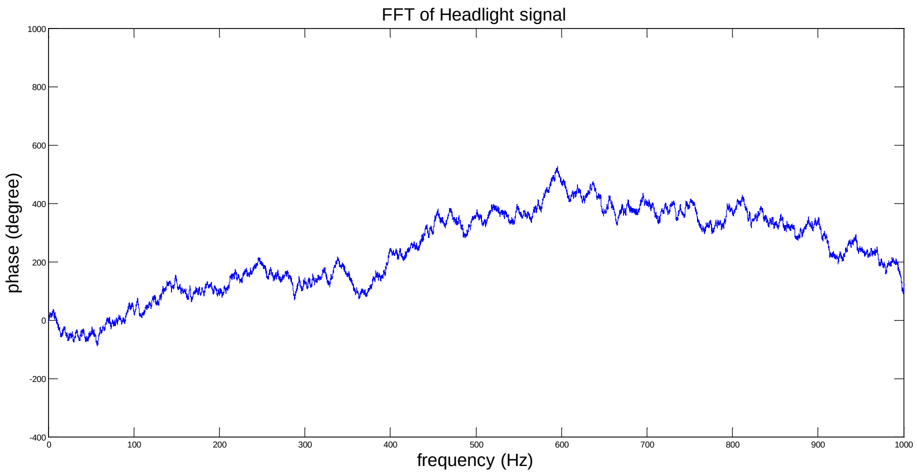

Figure 4.6 FFT (phase) of headlight signal.

Table 4.2 shows the 10 particular frequencies with highest amplitude and their relevant phases which are inserted into Semcad X as an input data.

Frequency	Amplitude (Ampere)	Phase (degree)
56	0.46	80
82	0.45	10
129	0.43	-110
164	0.29	140
246	0.58	40
259	0.22	-150
319	0.17	-10
329	0.17	120
388	0.22	170
500	0.16	-10

Table 4.2 *10 particular frequencies with the highest amplitude and their relevant phases of headlight signal.*

5 Simulation with Semcad X

This chapter is divided into two parts. The first part contains the 26 year-old women model sitting in the driver seat and both the start motor and the headlight signals are considered at the same time. In the second part the worst case is studied which happens when a woman is bending over the motor and the hood is open. In this case, there is the minimum distance between the source and the body and the maximum current is induced in CNS.

5.1 Sitting at the driver side

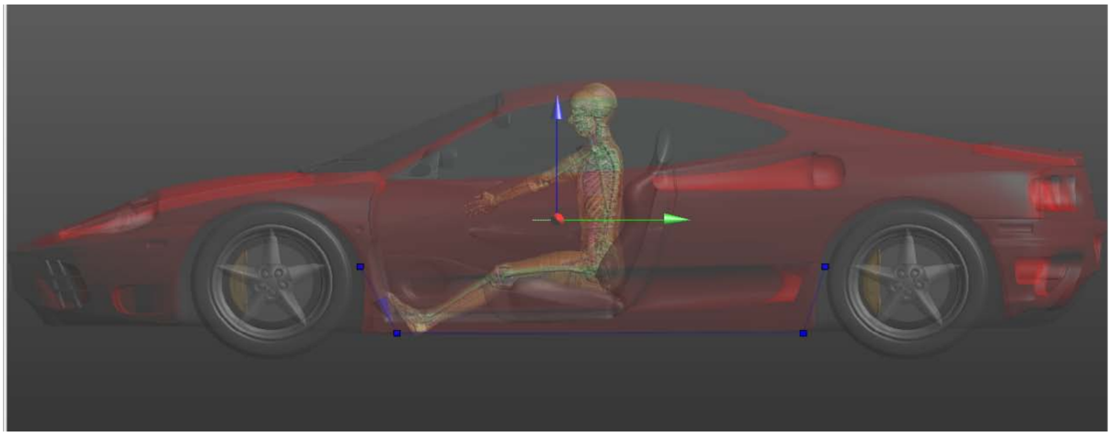

Figure 5.1 Semcad x interface, sitting at the driver side.

This part contains 10 different simulations with 10 different frequencies which are explained in chapter 4. In each simulation several parameters have to be set. The electrical parameters of the whole body, the phase and amplitude of the current sources, and the type of the low frequency solver which is explained in chapter 2. The electrical properties of car materials are skipped due to the lack of information about these properties in this particular frequency range. Before running the simulation, the voxels are made for the whole body, at least two voxels for each part according to the especial gridding rules of low frequency solver.

Actually there is a current loop from the battery to the motor and also from the battery to the headlights. Battery is connected to the motor and to the headlights separately with cables. The returning current of the loop goes through the chassis while the chassis acts as a ground. In this project the returning current is skipped because we cannot figure out where it exactly goes and which return path the electrical current uses through the chassis. From the other hand according to the field measurements, the worst case which means the maximum induced electric field is when the cable is assumed as a finite straight conductor. According to these two reasons in this project, the cable is placed under the chassis in the middle of the car as indicated in figure 5.1.

The radius of cables connecting the battery to the motor and to the headlights are 4 mm and 0.7 mm, respectively.

Central Nervous System (CNS)		
Brain	Spinal cord	Retina
Brain-Gray, Brain-White, Cerebellum, Thalamus, Hypothalamus and Hippocampus		

Table 5.1 *CNS different parts.*

Central Nervous System (CNS) contains brain, spinal cord and retina. Different parts of CNS is indicated in table 5.1. In different frequencies each part has its own electrical properties which are summarized in table 5.2, 5.3 and 5.4. These data are taken from Camelia Gabriel and the precision of the digits are just as in [6]. The frequency components are selected according to the Fourier Transform of start motor and headlights which were explained in chapter 4 [6].

tissue	F = 53 Hz		F = 56 Hz		F = 61 Hz	
	Electrical conductivity (s/m)	Permittivity (F/m)	Electrical conductivity (s/m)	Permittivity (F/m)	Electrical conductivity (s/m)	Permittivity (F/m)
Brian gray	0.076918	11115000	0.078399	10230000	0.080526	8958700
Brain white	0.053863	4820300	0.054382	4410300	0.055121	3834700
Cerebellum	0.096918	11115000	0.09899	10230000	0.10053	8959000
Hypothalamus	0.52151	1474100	0.52159	1334900	0.5217	1145400
Hippocampus	0.52151	1474100	0.52159	1334900	0.5217	1145400
Spinal Cord	0.027491	1445300	0.27491	1306300	0.027675	1117100
Thalamus	0.52151	1474100	0.52159	1334900	0.5217	1145400
Retina	0.50271	272330	0.50272	254770	0.50274	230800

tissue	F = 64 Hz		F = 67 Hz		F = 73 Hz	
	Electrical conductivity (s/m)	Permittivity (F/m)	Electrical conductivity (s/m)	Permittivity (F/m)	Electrical conductivity (s/m)	Permittivity (F/m)
Brian gray	0.081628	8300500	0.082619	7709100	0.08432	6695000
Brain white	0.0055501	3542200	0.055843	3282400	0.05643	2843200
Cerebellum	0.10163	8300800	0.10262	7709400	0.10432	6695300
Hypothalamus	0.52176	1051600	0.52181	969760	0.52189	834510
Hippocampus	0.52176	1051600	0.52181	969760	0.52189	834510
Spinal Cord	0.027727	1023500	0.027773	1306300	0.027849	806920
Thalamus	0.52176	1051600	0.52181	969760	0.52189	834510
Retina	0.50275	218910	0.50276	208520	0.50277	191280

Table 5.2 *CNS different parts and their corresponding electrical properties [6].*

tissue	F = 76 Hz		F = 81 Hz		F = 84 Hz	
	Electrical conductivity (s/m)	Permittivity (F/m)	Electrical conductivity (s/m)	Permittivity (F/m)	Electrical conductivity (s/m)	Permittivity (F/m)
Brian gray	0.085051	6259400	0.086125	5620600	0.086694	5282600
Brain white	0.056684	2656700	0.057058	2385400	0.057258	2242800
Cerebellum	0.10505	6259700	0.10613	5620900	0.522	655490
Hypothalamus	0.52192	778270	0.52197	697720	0.522	655990
Hippocampus	0.52192	778270	0.52197	697720	0.522	655990
Spinal Cord	0.02788	750850	0.027925	670590	0.027949	629040
Thalamus	0.52192	778270	0.52197	697720	0.522	655990
Retina	0.50278	184080	0.50279	173730	0.5028	168350

tissue	F = 87Hz		F = 129 Hz		F = 164 Hz	
	Electrical conductivity (s/m)	Permittivity (F/m)	Electrical conductivity (s/m)	Permittivity (F/m)	Electrical conductivity (s/m)	Permittivity (F/m)
Brian gray	0.0787214	4973900	0.091429	2496700	0.092938	1641600
Brain white	0.057442	2113200	0.059021	1083500	0.059674	726810
Cerebellum	0.10721	4974200	0.11143	2497000	0.11294	1641900
Hypothalamus	0.52202	618400	0.52223	333060	0.52234	240060
Hippocampus	0.52202	618400	0.52223	333060	0.52234	240060
Spinal Cord	0.02797	591630	0.28135	308760	0.028193	217830
Thalamus	0.52202	618400	0.52223	333060	0.52234	240060
Retina	0.5028	163490	0.50288	125480	0.50294	111900

tissue	F = 246 Hz		F = 259 Hz		F = 319 Hz	
	Electrical conductivity (s/m)	Permittivity (F/m)	Electrical conductivity (s/m)	Permittivity (F/m)	Electrical conductivity (s/m)	Permittivity (F/m)
Brian gray	0.094517	836700	0.094667	771889	0.095219	565460
Brain white	0.060484	381820	0.06057	353160	0.060896	260270
Cerebellum	0.11452	836990	0.11467	772170	0.11522	565760
Hypothalamus	0.52254	152740	0.52257	145500	0.52271	121620
Hippocampus	0.52254	152740	0.52181	145500	0.52271	121620
Spinal Cord	0.028262	135260	0.2827	128760	0.028303	108210
Thalamus	0.52254	152740	0.52181	145500	0.52271	121620
Eye-Sclera	0.5031	96493	0.50313	94890	0.50326	88756

Table 5.3 *CNS different parts and their corresponding electrical properties [6].*

tissue	F = 329 Hz		F = 388 Hz		F = 500 Hz	
	Electrical conductivity (s/m)	Permittivity (F/m)	Electrical conductivity (s/m)	Permittivity (F/m)	Electrical conductivity (s/m)	Permittivity (F/m)
Brian gray	0.095288	543530	0.095701	432630	0.096349	317730
Brain white	0.060937	250220	0.06118	198720	0.061535	143940
Cerebellum	0.11529	543820	0.1157	432930	0.11635	318030
Hypothalamus	0.52273	118970	0.52288	104950	0.52315	88440
Hippocampus	0.52273	118970	0.52288	104950	0.52315	88440
Spinal Cord	0.028308	106050	0.02834	95188	0.028403	84130
Thalamus	0.52273	118970	0.52288	104950	0.52315	88440
retina	0.50328	87963	0.50342	83212	0.50368	75939

Table 5.4 *CNS different parts and their corresponding electrical properties [4].*

From the table 5.2, 5.3 and 5.4 it can be seen that as frequency increases the electrical conductivity increases and the permittivity decreases in the CNS.

5.1.1 Induced current density inside the body in driver seat

Concerning the ICNIRP (1998) basic restriction for general public in the frequency range between 4 Hz to 1000 Hz, the maximum induced current in head and trunk should not exceed 2 mAm^{-2}.

Tissue	J (μAm^{-2}) in f = 53 Hz	J (μAm^{-2}) in f = 56 Hz	J (μAm^{-2}) in f = 61 Hz
Brain-Gray	5.6	4.3	4.14
Brain-White	1.5	1.56	1.5
Cerebellum	5.6	6.1	5.8
Hypothalamus	3.16	3.2	3.2
Hippocampus	2.5	2.7	2.57
Spinal cord	0.73	0.75	0.72
Thalamus	3.7	3.6	3.14
Retina	13.8	14.4	13.7

Table 5.5 *RMS values of induced current density in CNS in three sample frequencies (at driver seat).*

Table 5.6 summarizes the rms value of current density induced in the CNS as a result of the internal electric field in three sample frequencies of start motor signal. It indicates that for instance, in f = 53 Hz, the induced current in the brain-gray is more than the current induced in f = 56 Hz while in the same frequencies, induced current in retina increases as the frequency changes from 53 Hz to 56 Hz. This is due to the fact that the induced current density is affected by two factors, internal electric field and electrical conductivity of the material according to the Eq2. 6.c. However, internal electric field itself is affected by frequency, amplitude and phase of the current source, distance and the permittivity of the substance in which electric field penetrates.

Among the CNS different parts, retina has the maximum induced current density. This is because the electric conductivity of retina is higher than the other parts.

While the aim of this project is to find the maximum induced current in the entire CNS, for the rest of the frequencies we just study the current which induced in retina that has the maximum value among the other CNS parts.

Frequency (Hz) of start motor signal	J (μAm^{-2}) in retina
53	13.8
56	14.4
61	13.7
64	14.8
67	13.9
73	12.2
76	13.9
81	14.2
84	14.7
87	14.4

Table 5.6 *RMS values of induced current density in retina with start motor signal (at driver seat).*

Frequency (Hz) of headlight signal	J (μAm^{-2}) in retina
56	0.7
82	1.01
129	1.5
164	1.3
246	3.9
259	1.55
319	1.48
329	1.7
388	2.3
500	2.18

Table 5.7 *RMS values of induced current density in retina with headlight signal (at driver seat).*

Table 5.7 shows that the highest induced current density is in f = 246 Hz to compare with the other frequencies. The reason is that this frequency component has the maximum current amplitude according to the table 4.2.

Induced current density which is summarized in Table 5.6 and 5.7 are quite lower than the ICNIRP (1998) basic restriction, that means the basic restriction for the induced current density is not exceeded in any of these frequencies.

According to the ICNIRP (1998), in situations of simultaneous exposure to fields of different frequencies, these exposures are additive in their effects [1].

For electrical stimulation, relevant for frequencies up to 10 MHz, induced current densities should be added according to the Eq. 5.1 [1]:

$$\sum_{i=1Hz}^{10\,MHz} \frac{J_i}{J_{L,i}} \leq 1 \qquad \text{Eq. 5.1}$$

J_i is the current density induced at frequency i; $J_{L,i}$ is the induced current density restriction at frequency i as given in table 2.2.

To calculate the combined induced current density in retina both when the motor starts and the headlights switched on, Eq. 5.1 should be applied. $J_{L,i}$ is 2 mAm^{-2} for this frequency range.

$$\sum_{i=1Hz}^{10\,MHz} \frac{J_i}{J_{L,i}} = \frac{13.8+14.4+13.7+14.8+13.9+12.2+13.9+14.2+14.7+14.4}{2000} + \frac{0.7+1.01+1.5+1.3+3.9+1.55+1.48+1.7+2.3+2.18}{2000} = \frac{157.62}{2000} \leq 1$$

The total induced current density is less than the restrictions and it ensures that the there is no risk of adverse health effect when the motor starts and simultaneously the headlights turned on for a person sitting in the driver seat.

Figure 5.2 indicates the total induced current in the head along the x axis. The coordinates for the maximum current inside retina is in x equals to 36 cm. From the figure the total current is around 28 μAm^{-2} which is less than what we calculated from Eq. 5.1. The reason is that the induced current density has a complex value including both real and imaginary part. From the other hand, the components of current sources have different phases as summarized in table 4.1 and 4.2. Thus, the total rms induced current obtained from the simulation is less due to the fact that some of these components are anti-phase and when they are adding as complex number, they cancel each other.

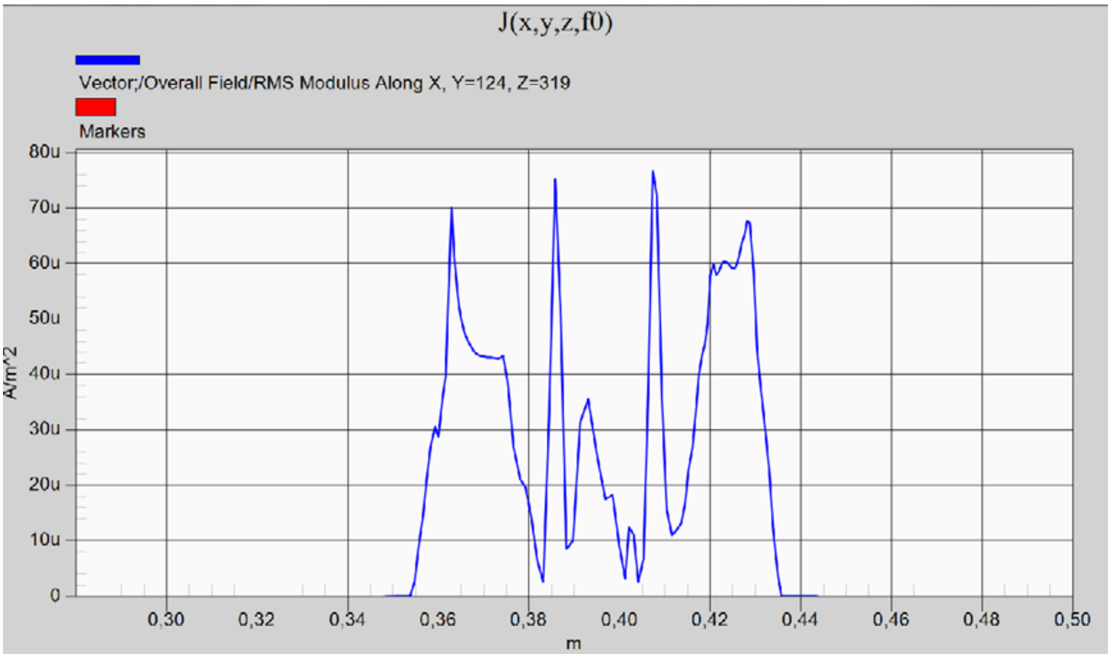

Figure 5.2 Distribution of total induced current density in the head along the X axis (max at x = 0.36 m in retina).

In figure 5.3, the distribution of total induced current density in the whole body is indicated. According to the scale it can be figured out that the highest value is in the head. Moreover, the quite high induced current in the legs is because of high electrical conductivity of muscles and the shorter distance from the legs to the source.

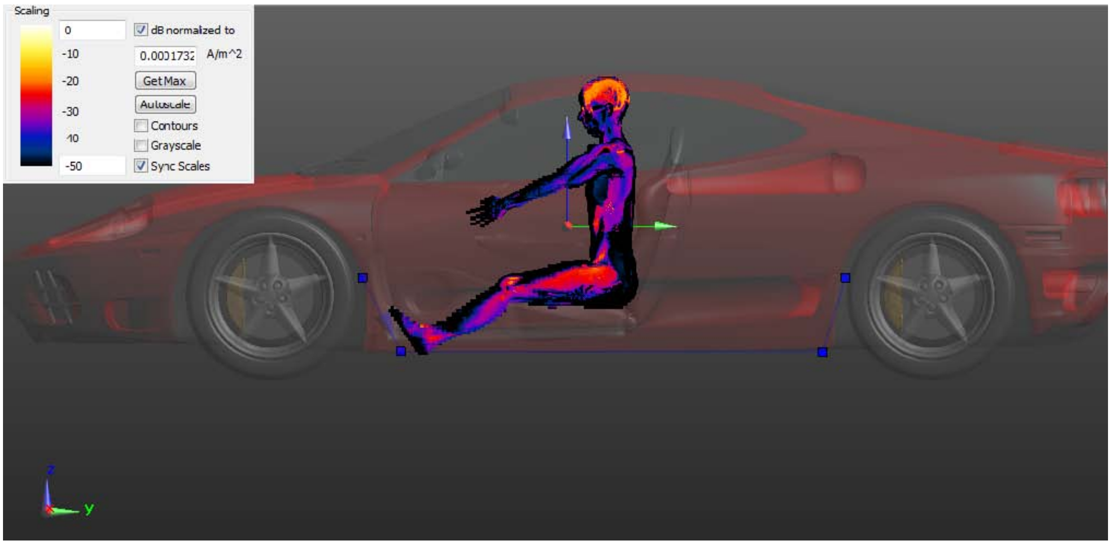

Figure 5.3 Distribution of total induced current density in the whole body.

5.1.2 Internal electric field inside the CNS in driver seat

In general, the maximum electric field is induced in the body when the external fields are homogeneous and directed parallel to the body axis (E-field) or perpendicular (H-field) [4].

To ensure that the basic restriction is not exceeded when a model is sitting at driver seat with both motor and headlights start simultaneously, the internal electric field should be calculated in CNS according to the ICNIRP (2010).

Tissue	E ($\mu V m^{-1}$) in f = 53 Hz	E ($\mu V m^{-1}$) in f = 56 Hz	E ($\mu V m^{-1}$) in f = 61 Hz
Brain-Gray	73	66	62.7
Brain-White	32.2	29.6	27.8
Cerebellum	60.1	64.7	60.6
Hypothalamus	7.2	7.05	7.2
Hippocampus	10	10.5	9.9
Spinal cord	26.7	27.3	25.9
Thalamus	15.4	15.1	14.2
Retina	59.2	62.4	59.19

Table 5.8 *RMS values of induced electrical field in CNS at three sample frequencies (at driver seat).*

Table 5.8 shows that the brain-gray matter has the highest internal electric field among the CNS. Thus, for the rest of frequencies we only study the brain-gray matter.

According to the ICNIRP (2010) basic restriction in table 2.3, for the frequency range between 25 Hz to 1000 Hz, internal E-field should not exceed $4 \times 10^{-4} f$ ($V m^{-1}$). For the frequency components of start motor and headlights, these limits are calculated as seen it table 5.9 and table 5.10.

Frequency (Hz) of start motor signal	E ($\mu V m^{-1}$) in brain-gray	ICNIRP basic restriction E($\mu V m^{-1}$)
53	73	21200
56	66	22400
61	62.7	24440
64	111	24400
67	63.4	26800
73	72	29200
76	62.8	30400
81	63.7	32400
84	65.9	33600
87	64.4	34800

Table 5.9 *RMS values of internal electric in the brain-gray with the start motor signal and ICNIRP relevant restriction (at driver seat).*

Frequency (Hz) of headlight signal	E ($\mu V m^{-1}$) in brain-gray	ICNIRP basic restriction E($\mu V m^{-1}$)
56	3.2	22400
82	4.5	32800
129	6.68	51600
164	5.7	65600
246	17	98400
259	6.8	103600
319	6.4	127600
329	6.6	131600
388	10.1	155200
500	9.4	200000

Table 5.10 *RMS values of internal electric in the brain-gray with the headlight signal and ICNIRP relevant restriction (at driver seat).*

For each frequency this restriction is not exceeded. However, similar to the summation for the induced current density according to the ICNIRP, relevant for frequencies up to 1 MHz, for electrical stimulation, internal E-field should be added according to the Eq. 5.2 [4]:

$$\sum_{i=1Hz}^{10\,MHz} \frac{E_{i,j}}{E_{L,j}} \leq 1 \qquad \text{Eq. 5.2}$$

$E_{i,j}$ is the internal electric field strength induced at frequency j, and $E_{L,j}$ is the induced electric field strength restriction at frequency *j* as given in table 2.3.

To calculate the combined internal E-field in brain-gray both when the motor starts and the headlights switched on, Eq. 5.2 should be applied.

$$\sum_{i=1Hz}^{10\ MHz} \frac{E_{i,j}}{E_{L,j}} = \left[\frac{73}{21200} + \frac{66.5}{22400} + \frac{62.7}{24440} + \frac{111}{24400} + \frac{63.4}{26800} + \frac{72}{29200} + \frac{62.8}{30400} + \frac{63.7}{32400} + \frac{65.9}{33600} + \frac{64.4}{34800} + \frac{3.2}{22400} + \frac{4.5}{32800} + \frac{6.7}{51600} + \frac{5.7}{65600} + \frac{17}{98400} + \frac{6.8}{103600} + \frac{6.4}{127600} + \frac{6.6}{131600} + \frac{10.1}{155200} + \frac{9.4}{200000}\right] = 0.02 \leq 1$$

Combiled internal E-field is much lower than the ICNIRP basic restriction. Figure 5.4 shows the combined internal E-field in the brain-gray along the x axis. The maximum of internal E-field estimated in the software for the brain-gray matter is around 43 $\mu V m^{-1}$. Software use the complex summation for the combined electric field.

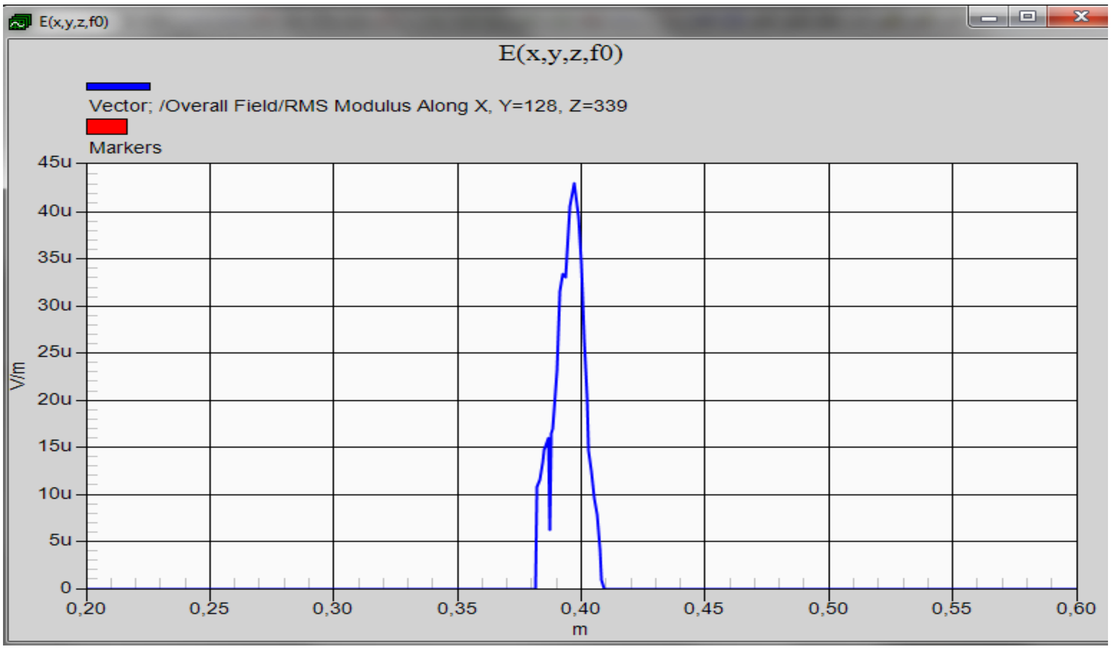

Figure 5.4 Distribution of total internal E-field in the brain-gray matter along the X axis (max at x = 39 cm).

Distribution of E-field in both the brain-gray matter and in the whole body is indicated in figure 5.5 and 5.6, respectively.

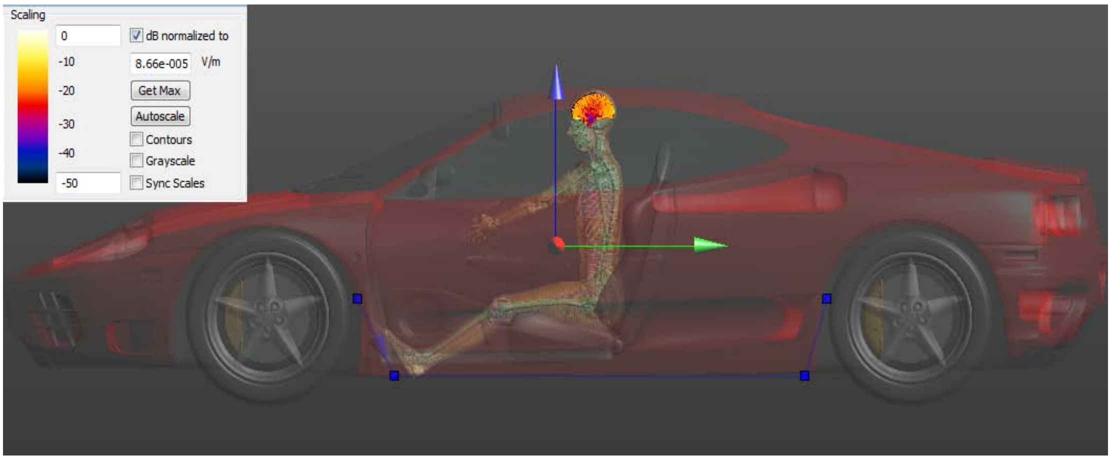

Figure 5.5 Distribution of total induced E-field in the brain-gray matter.

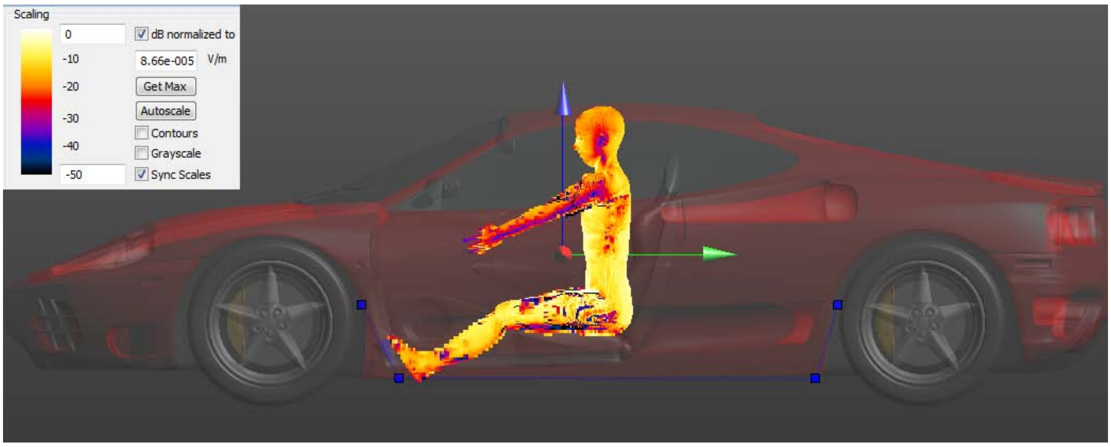

Figure 5.6 Distribution of total induced E-field in the whole body.

5.2 Bending over the motor with the hood open

In this part, another position which can be considered as a worst case, is studied. The model is bending over the motor while the hood is open and both motor and headlights start simultaneously. It is expected to get more internal E-field and induced current inside the body since the distance between the source and the body is too close in this position. The cable is located almost 10 cm from the head in simulation as indicated in figure 5.7.

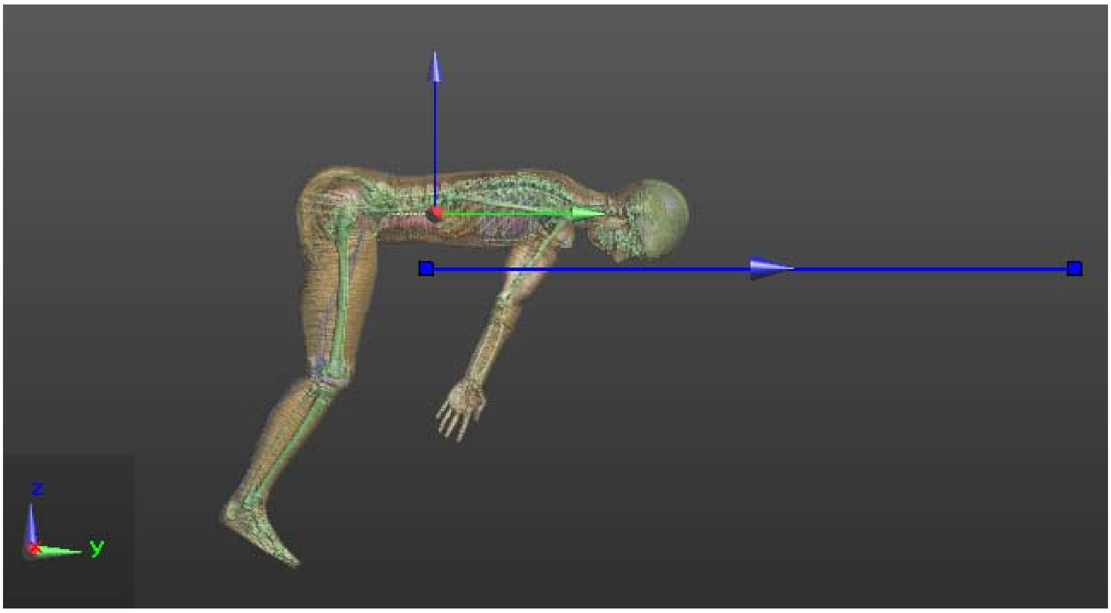

Figure 5.7 Semcad X interface, bending over the motor with the open hood.

5.2.1 Induced current density inside the CNS while bending over motor

It is expected to have more induced current inside the CNS in this position to compare with sitting at driver seat because the head is close to the source and consequently the internal electric field will be more. To show the compliance with the ICNIRP (1998) basic restriction, the induced current density should be calculated inside the CNS. Table 5.11 summarizes the induced current inside the CNS different parts in three sample frequencies.

Tissue	J (μAm^{-2}) in f = 53 Hz	J (μAm^{-2}) in f = 56 Hz	J (μAm^{-2}) in f = 61 Hz
Brain-Gray	95.5	97.8	96.8
Brain-White	23.7	24.2	23.9
Cerebellum	56.9	57.8	56.9
Hypothalamus	35.1	36.7	35.8
Hippocampus	30	38.3	37.1
Spinal cord	5.18	5.19	5.08
Thalamus	60.2	56	54.45
Retina	187	190	185.6

Table 5.11 *RMS values of induced current density in the CNS in three sample frequencies (bending over motor).*

The results show that the induced current in the retina has the highest value among the other parts of CNS as expected, it is due to the highest electrical conductivity of retina among the other parts of CNS. Moreover, the Brain-gray matter has almost high value of induced current as a reason of high internal E-field which is induced in this tissue.

We know that the highest current would be induced inside the retina. Therefore for the rest of frequency components, the retina is studied instead of the whole CNS.

The results from the simulation of retina induced current in this particular frequency range are summarized in table 5.12 and 5.13.

Frequency (Hz) of start motor signal	J ($\mu V m^{-1}$) in retina
53	187
56	190
61	185.6
64	201
67	188
73	168
76	188
81	192
84	199
87	194

Table 5.12 *RMS values of induced current density in retina with start motor signal (bending over the motor).*

Frequency (Hz) of headlight signal	J ($\mu V m^{-1}$) in retina
56	9.55
82	13.6
129	20.5
164	17.5
246	52.6
259	21
319	20
329	20.7
388	31.7
500	29.8

Table 5.13 *RMS values of induced current density in retina with headlight signal (bending over the motor).*

According to the ICNIRP (1998), the restriction for the induced current in the frequency range between 4 Hz to 1 kHz is 2 mAm^{-2}. Therefore, results indicate that for every single frequency, the basic restriction is not exceeded.

To get the total induced current inside retina, Eq. 5.1 should be applied.

$$\sum_{i=1Hz}^{10\,MHz} \frac{J_i}{J_{L,i}} = \frac{187+190+185.6+201+188+168+188+192+199+194}{2000} + \frac{9.5+13.6+20.5+17.5+52.6+21+20+20.7+31.7+29.8}{2000} = \frac{2129}{2000} \nleq 1$$

Since 1.064 is not less than 1, this is a critical situation and needs more accurate calculation. ICNIRP (2003) defies a summation formula in which the phases of the induced current density in each particular frequency is taken into account.

$$\sum_{i=1Hz}^{10\,MHz} \frac{J_i}{J_{L,i}} \cos\left(2\pi f_i t + \theta_i + \varphi_i\right) \leq 1 \qquad \text{Eq. 5.3}$$

J_i is the current density induced at frequency *i*; $J_{L,i}$ is the induced current density restriction at frequency i as given in table 2.2; θ_i is a phase angle of the induced current and φ_i is the phase angle of the filter at the harmonic frequencies which is set as zero for frequencies lower than 1000 Hz according to the ICNIRP (2003) for general public [2].

To calculate θ_i in each particular frequency, The Imaginary part of the current vector should be divided by the Real part of it. The result is the arctangent of θ_i. Table 5.14 summarizes θ_i in all frequency components of two signals.

frequency	Real part (μAm^{-2})	Imaginary part (μAm^{-2})	θ_i(degree)	Cos (θ_i)
53	222	144	33	0.84
56	225	146	33	0.84
61	220	142	32.8	0.84
64	238	155	33.7	0.83
67	204	171	40	0.76
73	168	168	45	0.7
76	204	171	40.4	0.76
81	192	192	45	0.7
84	195	202	46	0.69
87	180	208	49	0.65
56	1.33	0.23	10	0.98
82	0.33	1.9	80	0.17
129	2.7	0.99	20	0.93
164	1.6	1.9	50	0.64
246	4.78	5.7	50	0.64
259	1.48	2.57	60	0.5
319	0.49	2.8	80	0.17
329	2.53	2.53	30	0.86
388	0.77	7.78	80	0.17
500	0.73	7.3	80	0.17

Table 5.14 *Real part, Imaginary part, phase and cos(θ_i) for induced current vector in retina (bending over the motor).*

$$\sum_{i=1Hz}^{10\,MHz} \frac{J_i}{J_{L,i}} \cos(2\pi f_i t + \theta_i + \varphi_i) = [187 \times 0.84 + 190 \times 0.84 + 185.6 \times 0.84 + 201 \times 0.83 + 188 \times 0.76 + 168 \times 0.7 + 188 \times 0.76 + 192 \times 0.7 + 199 \times 0.69 + 194 \times 0.84 + 9.5 \times 0.98 + 13.6 \times 0.17 + 20.5 \times 0.93 + 17.5 \times 0.64 + 52.6 \times 0.64 + 21 \times 0.5 + 20 \times 0.17 + 20.7 \times 0.86 + 31.7 \times 0.17 + 29.8 \times 0.17]\,/2000 = \frac{1594.34}{2000} \leq 1$$

In Eq. 5.3, t is set to zero because Semcad X simulation is based on t = 0. The results show that by applying this formula, the ICNIRP (1998) basic restriction is not exceeded. Thus, the total induced current density inside the CNS is still below the exposure limit.

Figure 5.9 illustrates the induced current density inside the head along the X axis. The maximum current induced in retina is at x= -32.2 cm. The result is around 1575 μAm^{-2} which is a little bit less than what is calculated from the Eq. 5.3.

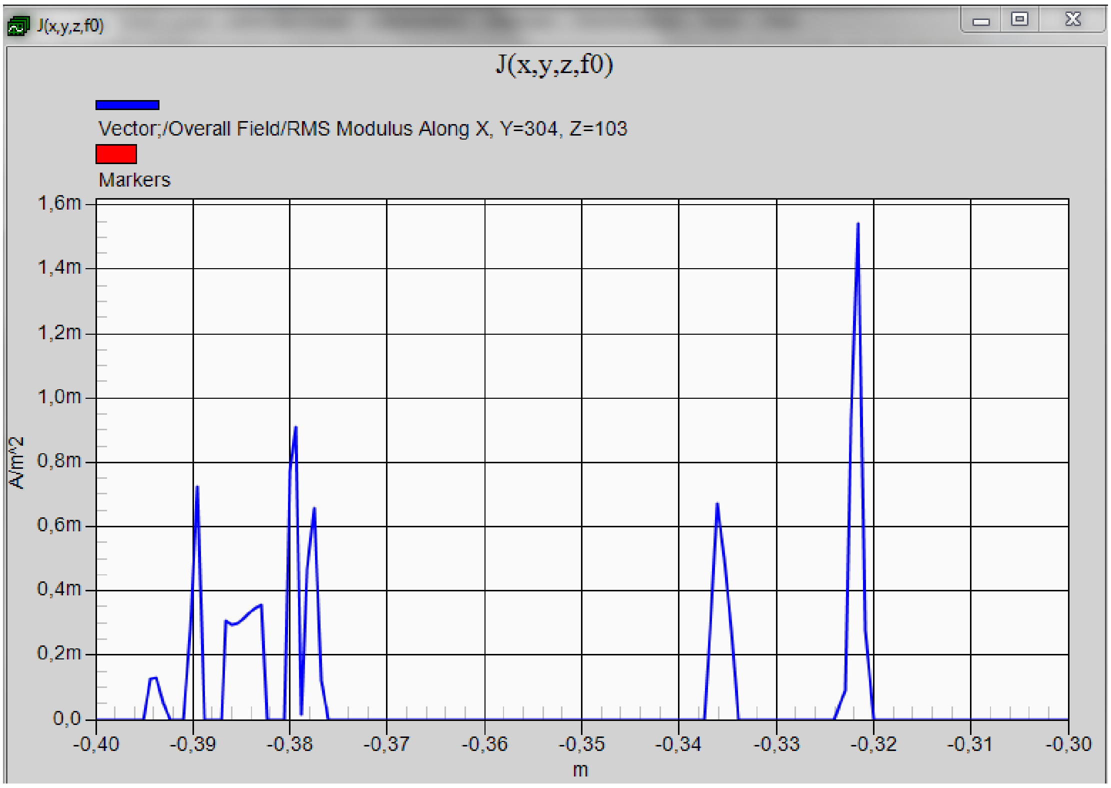

Figure 5.8 Distribution of total induced current density in retina along the X axis (max at x = -0.322 m).

Distribution of total induced current inside the whole body is indicated in figure 5.9. However, there is a black spot inside the brain which means there is no induced current inside the brain according to the scale. This is probably the program fault since it is not reasonable that no current flow through the brain as its electrical conductivity and internal electric field is not zero.

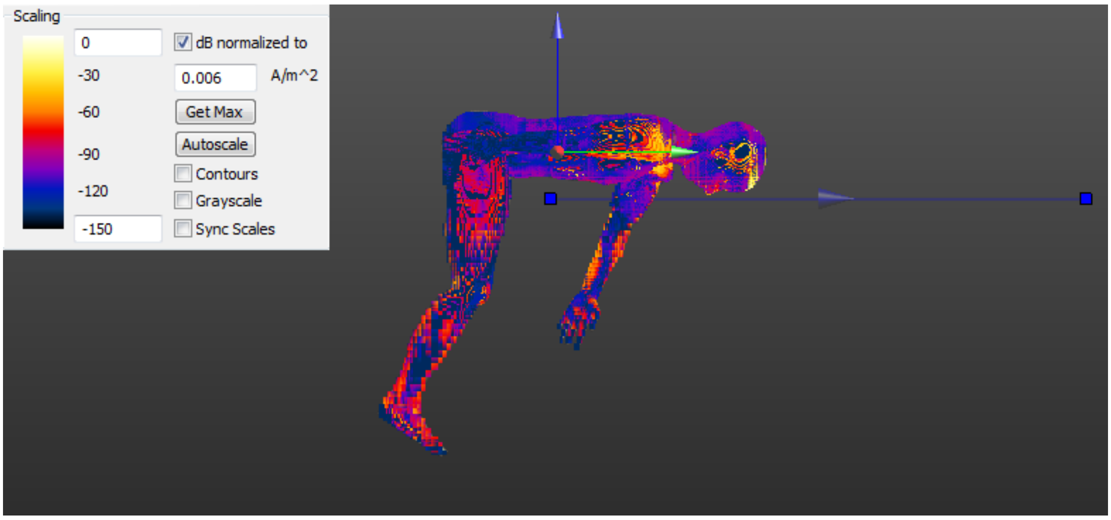

Figure 5.9 Distribution of total induced current density inside the whole body.

5.2.2 Internal electric field inside the CNS while bending over the motor

In this position, it is expected that more internal electric field induced in the CNS as the distance between head and the electric current source is close.

Table 5.15 summarizes the internal electric field results from Semcad X inside the CNS. As expected, the brain-gray matter has the maximum electric field due to its lower electrical conductivity among the other parts of CNS.

Tissue	E ($\mu V m^{-1}$) in f = 53 Hz	E ($\mu V m^{-1}$) in f = 56 Hz	E ($\mu V m^{-1}$) in f = 61 Hz
Brain-Gray	1241	1246	1202
Brain-White	561	555	538
Cerebellum	611	612	590
Hypothalamus	120	124	120
Hippocampus	79.3	98.5	95.3
Spinal cord	220	223	217
Thalamus	199	184	179.3
Retina	798	807	786

Table 5.15 *RMS values of induced electric field in the CNS (bending over motor).*

For the rest of frequencies, only brain-gray matter is studied because we are interested in the maximum internal electric field in the entire CNS.

Table 5.16 and 5.17 summarize the internal E-field inside the brain-gray matter. Frequency, amplitude of the applied source and the permittivity of the brain affect the amount of induced E-field at different frequencies.

The maximum internal E-field is in f = 64 Hz due to the high amplitude of the current source at this particular frequency.

Frequency (Hz) of start motor signal	E ($\mu V m^{-1}$) in brain-gray	ICNIRP basic restriction E ($\mu V m^{-1}$)
53	1241	21200
56	1246	22400
61	1202	24440
64	2258	24400
67	1210	26800
73	1281	29200
76	1195	30400
81	1209	32400
84	1250	33600
87	1221	34800

Table 5.16 *RMS values of electric field in brain-gray with start motor signal and the relevant ICNIRP restriction (Bending over the motor).*

Frequency (Hz) of headlight signal	E ($\mu V m^{-1}$) in brain-gray	ICNIRP basic restriction E ($\mu V m^{-1}$)
56	62.7	22400
82	86.12	32800
129	126	51600
164	107	65600
246	319	98400
259	127	103600
319	121	127600
329	124	131600
388	190	155200
500	177	200000

Table 5.17 *RMS values of electric field in brain-gray with headlight signal and the relevant ICNIRP restriction (Bending over the motor).*

Relevant ICNIRP (2010) restriction for each of the frequencies in table 5.16 and table 5.17 are calculated based on $4 \times 10^{-4} f\,(V m^{-1})$ expression.

These results imply that for each particular frequency, the ICNIRP basic restriction is not exceeded. However, the total E-field inside the brain-gray matter should be added according to Eq. 5.2.

$$\sum_{i=1Hz}^{10\ MHz} \frac{E_i}{E_{L,i}} = \left[\frac{1241}{21200} + \frac{1246}{22400} + \frac{1202}{24440} + \frac{2258}{24400} + \frac{1210}{26800} + \frac{1281}{29200} + \frac{1195}{30400} + \frac{1209}{32400} + \frac{1250}{33600} + \frac{1221}{34800} + \frac{62.7}{22400} + \frac{86.12}{32800} + \frac{126}{51600} + \frac{107}{65600} + \frac{319}{98400} + \frac{127}{103600} + \frac{121}{127600} + \frac{124}{131600} + \frac{190}{155200} + \frac{177}{200000}\right] = 0.508 \leq 1$$

Summation indicates that the ICNIRP (2010) basic restriction for internal electric field is not exceeded in this position. However, we have to check the simulation results too.

Figure 5.10 shows that the maximum combined electric field in the brain-gray matter is at x= -36 cm which is around 2500 $\mu V m^{-1}$. This value for the total internal electric field inside the CNS is less than each of the ICNIRP (2010) restriction in single particular frequencies considering the table 5.16 and table 5.17.

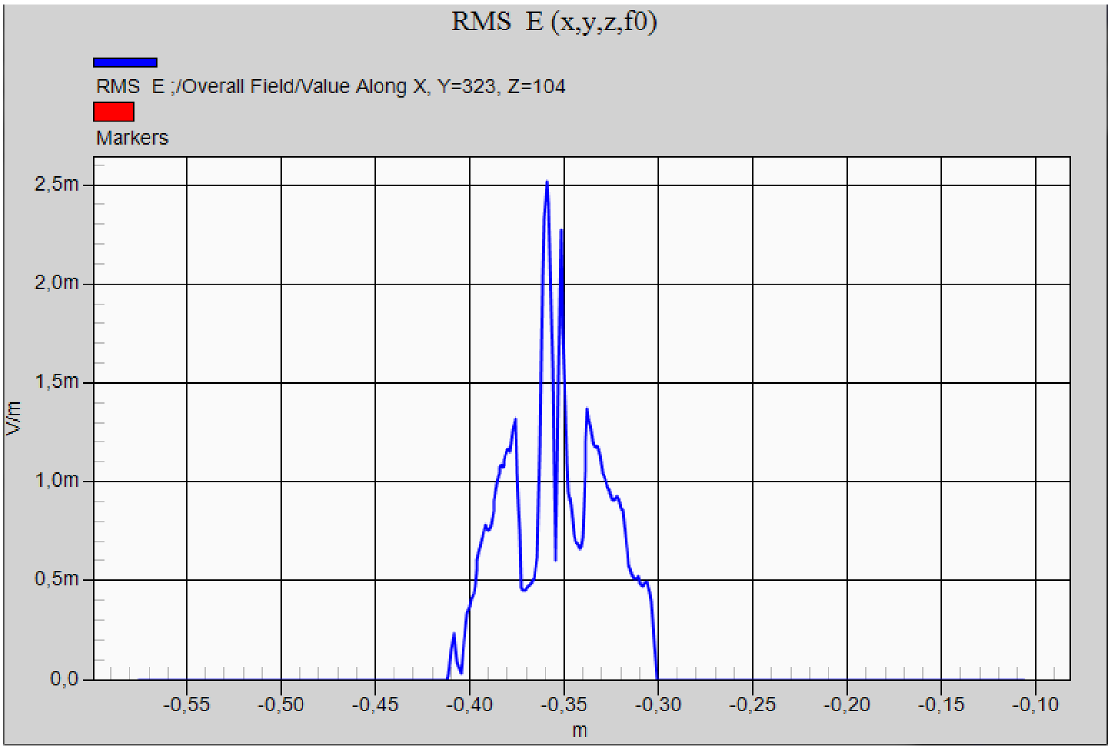

Figure 5.10 Distribution of total internal electric field in the brain along the X axis (max at x = −0.36 m).

Distribution of total internal electric field particularly inside the brain and also inside the whole body is indicated in figure 5.11 and figure 5.12, respectively.

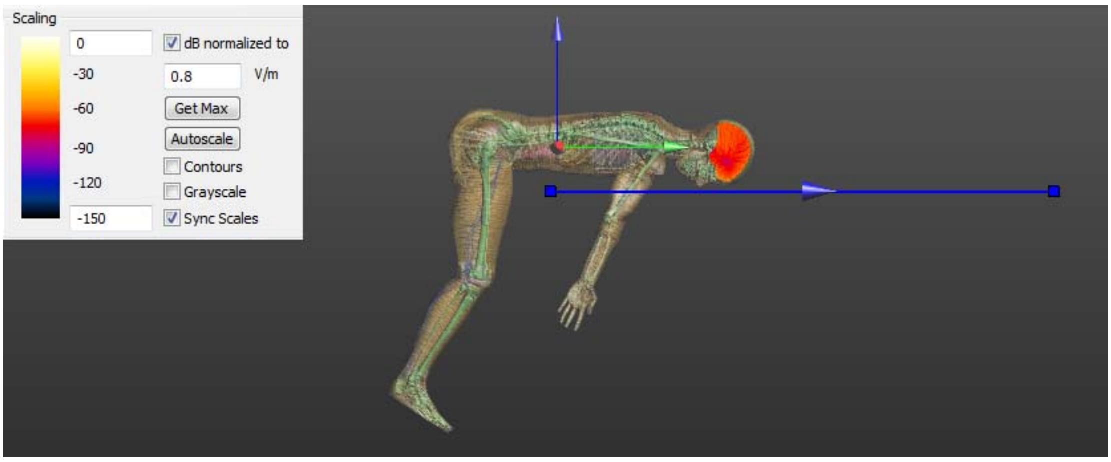

Figure 5.11 Distribution of total induced E-field in the brain-gray matter.

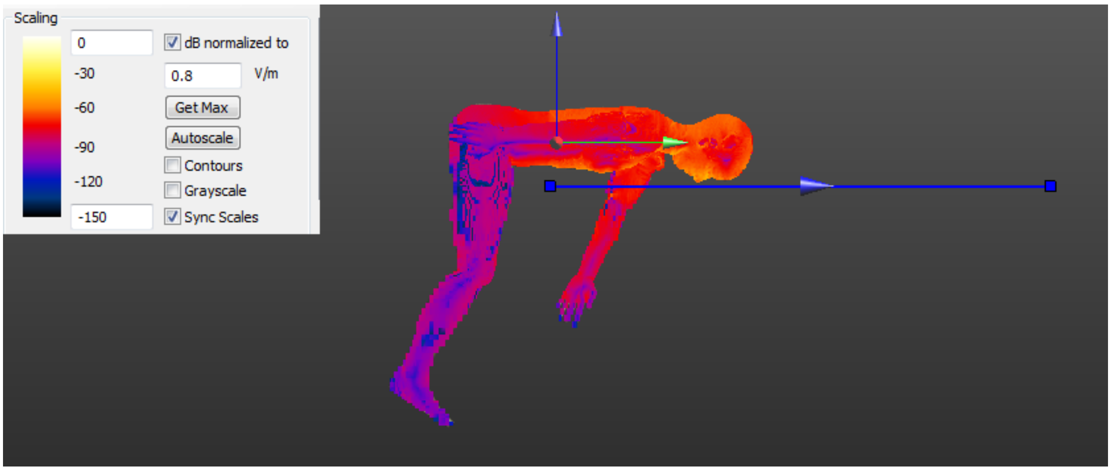

Figure 5.12 Distribution of total induced E-field inside the whole body.

6 Discussion and Conclusion

Regarding the results from both simulation and calculation, in both positions when a man is sitting in the driver seat and when he is bending over the motor with an open hoot, while the motor starts and the headlights turned on, the total induced current density inside the CNS is not exceeded the ICNIRP (1998) basic restriction in the frequency range between 1 Hz to 100 kHz.

Total internal electric field in the CNS does not exceed the ICNIRP (2010) basic restriction both when a man is sitting in the car and when he is bending over the motor with an open hood, while the motor and the headlights start simultaneously in the low frequency range between 1 Hz to 100 kHz, according to the results both from simulation and calculations.

Biological tissues are inhomogeneous and show significant variability in structure and composition and hence in dielectric properties. Such variations are natural and may be due to physiological processes or other functional requirements. The spread of electrical properties of different body tissues and organs range from about +/− 5% above 100 MHz to +/− 15% at the very low frequencies [6].

The model which is used in Semcad X is a Ferrari that probably has different shape from the Volvo cars. The shape and size of each part of the car affects the fields inside the car; therefore, to get more accurate results, more similar models should be used.

The electric current source is considered as a finite straight conductor in this simulation. However, we know that these sources are conducting as a loop and the returning current goes through the chassis. Thus, to get an accurate results, these loops should be taken into account and the fields inside the body should be calculated based on these loops.

In this project according to the software limitations including the memory needed, only 10 frequencies are picked for each source. However, to get more accurate results, more frequency components should be taken into account.

From the other hand, as frequency increases, the ICNIRP basic restriction increases. It means that if more frequencies picked in the higher range, the ICNIRP limits will increase for these frequencies.

The different materials in the car, including dielectric and PEC/metal, affect the induced field inside the body. Therefore, the electrical properties of each material should be considered in order to get more accurate results.

7 References

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