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MODELLING INDUCED FIELDS IN THE HUMAN BODY EXPOSED TO ELECTRIC FIELDS FROM HIGH VOLTAGE TRANSMISSION LINES DESIGNED TO MEET 10 kV/m AT GROUND LEVEL

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A dissertation submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree of Master of Science in Engineering.

Johannesburg, February 2017

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LIST OF SYMBOLS

SYMBOLS		UNITS
λ	Wavelength	m
f	Frequency	Hz
$\vec{E}$	Electric field strength vector	V/m
ε_0	Permittivity of free space	F/m
ε"	Imaginary part of the complex relative permittivity	F/m
$\vec{J}$	Current density vector	A/m^2
σ	Conductivity	S/m
ω	Radian frequency	rad
μ_0	Permeability of free space	H/m
B	Magnetic flux density	T
r	radius	m

LIST OF ABBREVIATIONS AND ACRONYMS

ACGIH	American Conference of Governmental Industrial Hygienists
BMI	Body Mass Index
CDEGS	Current Distribution, Electromagnetic Fields, Grounding and Soil Structure Analysis software package
CNS	Central Nervous System
CT	Computed Tomography
ELF	Extremely Low Frequency
EMC	Electro-Magnetic Compatibility
EMF	Electric and Magnetic Fields (Power Frequency)
EQS	Electro-Quasi-Static
Eskom	Eskom Holdings SOC Limited
FDTD	Finite-Difference Time-Domain
FEM	Finite-Element Method
GHz	Giga- Hertz
Hz	Hertz
IARC	International Association of Research on Cancer
ICNIRP	International Commission on Non-Ionising Radiation Protection
IEC	International Electro-technical Commission
IEEE	Institute of Electrical and Electronics Engineers
INIRC	International Non-Ionizing Radiation Committee
IRPA	International Radiation Protection Association
IT'IS	Foundation for Research on Information Technologies in Society
kHz	Kilo-Hertz
MIID	Medical Internal Radiation Dose
MRI	Magnetic Resonance Imagining
NRPB	National Radiological Protection Board
R&D	Research and Development
SES	Safe Engineering Services
SEMCAD	Simulation Platform for Electromagnetic Compatibility, Antenna Design and Dosimetry
SPEAG	Schmid & Partner Engineering
TEMSE	Transmission Energy Management System
WHO	World Health Organisation

DECLARATION

I declare that this dissertation is my own work. It is being submitted for a Master of Science Degree to the University of Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other University.

……..

(Signature of Candidate)

…… day of …… year ……..

day *month* *year*

ABSTRACT

There has been increasing public concern regarding adverse health effects due to power frequency electric and magnetic fields. Safety guidelines/standards for electric and magnetic field exposures have been established by different public organizations. However, the link between low frequency (power frequency) electric and magnetic field exposure and adverse health effects is not yet well established. Limits on human exposure to low frequency electric and magnetic fields are fundamentally specified for *in-situ* fields in tissues/organs. These dosimetric limits are referred to as *Basic Restrictions* for protection against potentially adverse effects from electro-stimulation. In addition, secondary limits, the exposure *Reference Levels* in environmental electric and magnetic fields are also given for practical compliance purposes. These are generally derived from the Basic Restrictions based on uniform-fields with a provision that the Basic Restrictions must be observed for non-uniform cases. In practice, any structure influences the electric fields in High Voltage systems, and thus creates electric field non-uniformity. The human exposure of the general public to electric fields from Eskom's 765 kV transmission network operating at 50 Hz, is addressed through physical measurements, theoretical predictions and 3-D human model dosimetry, which is presented in this dissertation.

ACKNOWLEDGEMENTS

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I wish to express my gratitude to my supervisor and colleagues. First of all, I am very thankful to Professor Ian Jandrell for his guidance, comments and help with the review of the dissertation and my manager Elvis Mathebula and Research Manager Siven Naidoo for support and business contributions related to Eskom Holdings SOC Limited.

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CHAPTER 1: INTRODUCTION

This chapter presents the background and research problem that was hypothesised in this dissertation. It explains the problem and issues that Eskom Holdings SOC Limited is faced with due to the change in the general public electric field exposure reference limit of 5 kV/m in the International Commission for Non-Ionising Radiation Protection (ICNIRP) guidelines. It also presents the outline of the dissertation.

1.1 Background and the Research Problem Formulated

In power transmission technology there is an increasing need for higher power transmission from generating centres to power usage centres, which would either increase the voltage or current of the line to meet the demand. In South Africa, 765 kV has been used in the past and is being expanded at present to meet the country's power demand.

As exposure limits could be legalised in the not too distant future, human exposure to electric and magnetic fields needs to be considered by Eskom Holdings SOC Limited (Eskom) in its drive to expand the 765 kV networks,. This is because acceptable limits, such as international exposure guidelines or standards ought to be adhered to. The International Commission for Non-Ionising Radiation Protection (ICNIRP) [ICNIRP 1998, ICNIRP 2010] and the Institute of Electrical and Electronics Engineers (IEEE) [IEEE 2002], have produced such guidelines and standards relevant to human exposure to low frequency electric and magnetic fields. Over the years, the ICNIRP guideline has been reviewed and updated with the latest findings from research conducted in the field of human exposure to low frequency electric and magnetic fields. In the ICNIRP 1998 version [ICNIRP, 1998], the short-term electric field exposure level of 10 kV/m for the general public was removed from the guideline, thus only allowing exposure levels of 5 kV/m for the general public. Further to the above, the ICNIRP, in its 2010 guideline [ICNIRP 2010], changed the basic restriction of current density to in-situ electric field in the human body. The in-situ electric field means the electric field within the biological tissue of the body. The fields and currents induced in biological tissues could result in a variety of physiological and psychological responses, as mentioned by the World Health Organisation (WHO) [WHO 2007].

Eskom has had an electric and magnetic field (EMF) policy since the early 1990s and this has been reviewed and updated with the latest scientific findings relative to 50 Hz power

frequency exposure limits. The revised policy addresses the information reviewed and states Eskom's policy requirements, which include Eskom's stance on safety, health, the environment and quality (see Appendix D for a copy of the draft policy). The draft policy, which has been developed by the author of this dissertation, states:

"In the absence of national EMF standards and/or regulations in South Africa, Eskom will design overhead transmission lines to meet an electric field exposure design limit of 5 kV/m for power lines ≤ 400 kV, and 10 kV/m above 400 kV within the servitude boundary. Such an approach will be in line with international recommendations [IEEE, 2002 and WHO, 2007]".

The outcomes of the dosimetry study from this dissertation are intended to aid and support Eskom in revising its EMF policy (see Appendix D). It is also intended to further aid in the design and operation of their expanding 400 and 765 kV networks to comply with the basic restrictions of the ICNIRP guidelines [ICNIRP, 1998, ICNIRP, 2010]. The ICNIRP guidelines have been endorsed by the Department of Health of South Africa.

1.2 Outline of the Dissertation

The dissertation will be made up of the following chapters as outlined below:

Chapter 1 gives an introduction to the problem and what will be achieved in the dissertation.

Chapter 2 discusses the research methodology followed to conduct this study for this dissertation as well as the problem statement and research questions and defines the background to the problem.

Chapter 3 discusses the interaction of electromagnetic fields and human exposure. It concludes with the implications Eskom is faced with in the design of the future 765 kV transmission lines.

Chapter 4 discusses the simulation software used to conduct the predictions and the 3D anatomical body dosimetry.

Chapter 5 discusses the use of simple models to validate the software. It further validates the software to similar studies conducted, as well as compares the results obtained to analytical calculations.

Chapter 6 looks at a case study of a 765 kV transmission line with respect to electric field measurements, while Chapter 7 takes the measured data and uses it in the anatomical dosimetry of the human body, to compute the *in-situ* electric field and current densities inside the human body.

Chapter 8 closes with a summary of the dissertation, which draws conclusions and makes reference to future work being considered with respect to electric and magnetic fields within the power network.

CHAPTER 2: THE RESEARCH METHODOLOGY

Chapter 2 presents the research environment followed throughout this dissertation. It presents the research methodology, problem statement, the research questions and the hypothesis. It further discusses the background to the research problem Eskom Holdings SOC Limited is faced with and discusses the anatomical human models that will be used in the dosimetry of this dissertation.

Electric field measurements and dosimetry needed to be investigated and conducted to show compliance to the ICNIRP guideline [ICNIRP, 1998; ICNIRP, 2010] or IEEE standard [IEEE, 2002] when the reference levels/action values have been exceeded but the Basic Restrictions are met. The outcomes of the dosimetry were compared to the ICNIRP guidelines and the IEEE standard to evaluate if the results obtained were compliant. The results of the findings are presented and discussed in Chapter 6 and Chapter 7.

2.1 Methodology

To conduct this study the methodology presented in *Figure 2.1* below was followed.

2.1.1 Electric field measurements and benchmarking

The measurement of electric fields beneath the Mercury – Zeus 765 kV line was conducted using the IEC 62110 and IEEE 644 standards. The CDEGS software package (Current Distribution, Electromagnetic Fields, Grounding and Soil structure analysis) was used to model the unperturbed electric field beneath the transmission line to gain confidence in the electric field measured. This package was chosen as it was available to the author and it can calculate the electric fields quickly and efficiently. Chapter 3 covers a more in-depth explanation of the CDEGS software package.

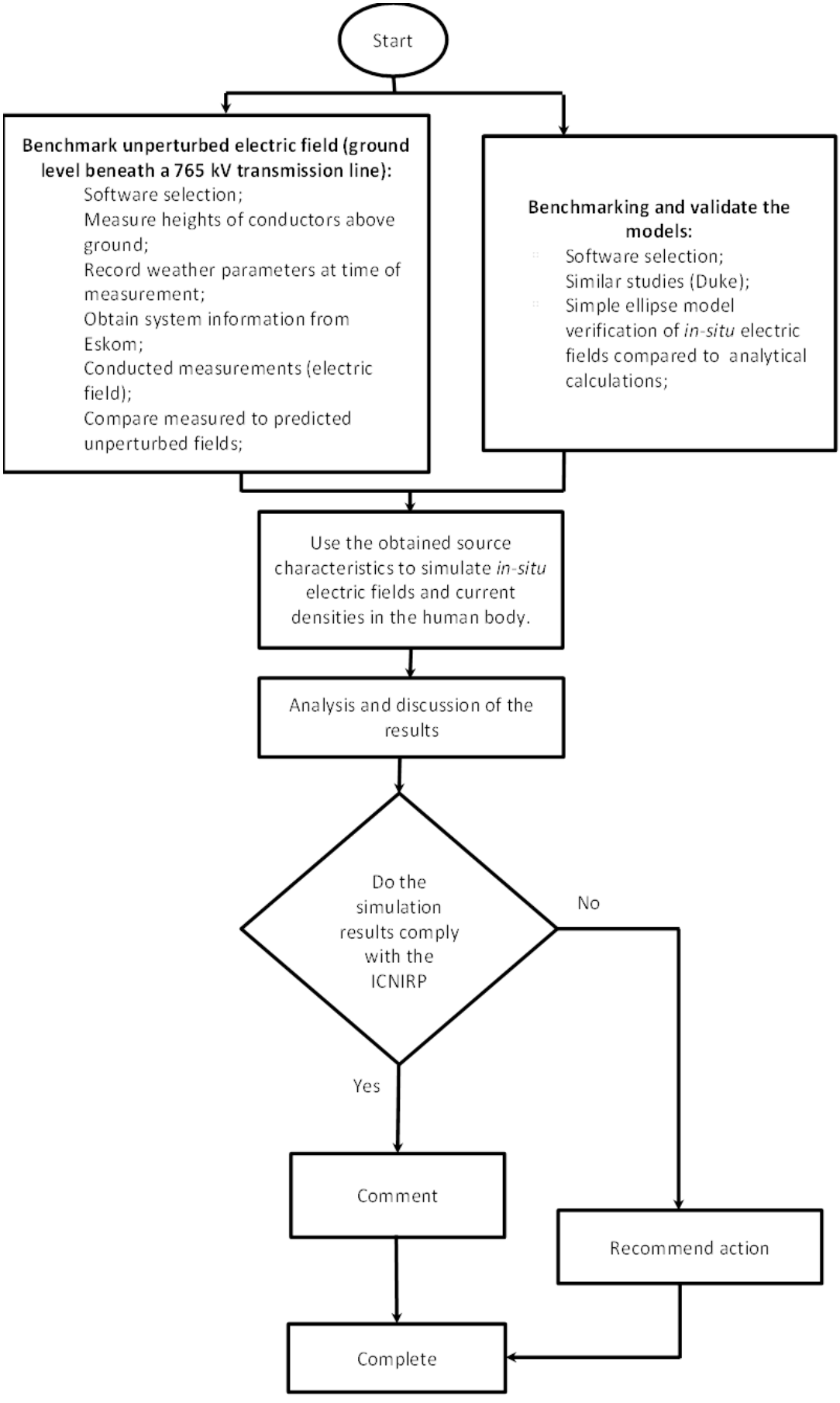


Figure 2.1: The research methodology

2.1.2 Dosimetry of the in-situ electric fields and current densities

Human models were obtained, and modelled using the SEMCAD X software package (see Chapter 3 for an introduction to the SEMCAD X software package). They were benchmarked against similar studies using similar models for confidence in the results obtained. Chapter 4 covers more information on this aspect.

2.2 Problem Statement

Eskom has designed transmission lines to meet internationally accepted EMF limits. Previously, the guideline for the International Radiation Protection Association (IRPA), now known as the International Commission for Non-Ionising Radiation Protection (ICNIRP), allowed a short-term exposure limit of 10 kV/m. In 1998, the ICNIRP revised its guideline and removed the short term exposure level and stated that 5 kV/m for the general public was allowed. Eskom's existing 400 and 765 kV systems have been designed to use an exposure reference limit of 10 kV/m at ground level within the servitude. At that time, this was in accordance to the ICNIRP guideline for the general public, which was endorsed by the South African Department of Health.

To evaluate human exposure to the design of 765 kV transmission lines, designed to meet 10 kV/m within the servitude at ground level, Eskom now needs to comply with the Reference Level (measurable unperturbed electric fields at power frequencies to limit indirect effects of contact with electrical conductors in the field) and Basic Restrictions (based directly on established health effects) of the ICNIRP guideline for the general public. The ICNIRP states that if the 5 kV/m Reference Level of the guideline may be exceeded, as long as compliance to the Basic Restrictions can be shown through 3-D anatomical dosimetry. Through measurement and dosimetry with reference to 765 kV transmission lines this compliance has been conducted through 3-D anatomical dosimetry in this dissertation.

2.3 The Research Questions

The following research questions have been answered in this dissertation:

i. Do the Eskom 765 kV transmission lines, designed to meet 10 kV/m in the servitude, comply with the revised ICNIRP guidelines for the general public in terms of the Reference Levels and Basic Restrictions?

ii. Can 3D anatomical modelling be used to evaluate compliance to electric fields where the Reference Levels of the ICNIRP guidelines have been exceeded? If so, are the Basic Restrictions set by ICNIRP complied with?
iii. What accuracy can be achieved through the use of 3D anatomical modelling?
iv. What benchmarking techniques of the human body models can be used to verify the results of the dosimetry?
v. What effect does the human body posture have on the electrical field exposure?

2.4 The Hypothesis

Transmission lines being designed to meet 10 kV/m exceed the ICNIRP guideline Reference Level of 5 kV/m. With the aid of 3-D anatomical dosimetry and human models, it is hypothesised that it can be proven that the Basic Restrictions of the ICNIRP guidelines [ICNIRP, 1998; ICNIRP, 2010] for the general public are complied with.

2.5 Background to the Research Problem

The problem of evaluating exposure to electric fields and their interaction with the human body in order to find a possible health effect has been studied for the last 60 years. Distinct areas of research have been considered and researched. At first, epidemiology studies looked at the long-term effect of exposure but such studies were costly, involved collecting large amounts of data on complex human populations, and were difficult to control. Secondly, laboratory studies on cells have also been important as their function has been to elucidate the fundamental underlying mechanism that links electric field exposure to biological effects. Thirdly, there have also been experimental studies conducted on rats and mice.

However, despite the large amount of research that has been carried out in this area, possible health effects caused by exposure to electric fields are still open for discussion. Although power frequency electric fields that are commonly accessible by the general public rarely exceed 10 kV/m (and hence the fields induced in an isolated human being are too small to produce any confirmed biological effects) there are concerns that have been raised by some epidemiological studies that link increased rates of certain cancers; specifically childhood leukaemia. An in-depth overview of the studies conducted on human exposure to electric fields is in the WHO environmental health criteria [WHO, 2007] and the IARC monograph [IARC, 2001] documents.

This dissertation focuses on the low-frequency region, where thermal effects are not present. The limits prescribed by ICNIRP [ICNIRP, 1998; ICNIRP, 2010] on health and safety requirements in the frequency range of 1 Hz to 10 MHz are based on established adverse effects on the central nervous system. The types of exposure are acute and its effects are essentially instantaneous [ICNIRP, 1998]. The limits are based on the Basic Restrictions, current density [ICNIRP, 1998] and the in-situ electric field [ICNIRP, 2010].

Following a review of published literature [IARC, 2001; NRPB, 2004; WHO, 2007] the ICNIRP guidelines for limiting exposure to humans have been developed over the years. The criteria applied in the course of the review were designed to evaluate the credibility of the various reported findings as only established effects were used as the basis for the proposed exposure restrictions.

As a result of the ICNIRP 1998, this guideline has been revised; the main changes are the Reference Level from 10 kV/m (short-term) to 5 kV/m for the general public and the Basic Restrictions from current density to the in-situ electric field.

Table 2.1 highlights the main differences in bold italic red. Harmonisation of the international guidelines and standards are being considered at present and is under review.

The guidelines have been based on short-term, immediate health effects. In its 1998 version [ICNIRP, 1998], the ICNIRP states that it has not been considered that long-term electric field exposure causes cancer as there is insufficient data for setting exposure restrictions. Epidemiological studies have provided suggestive, but inconclusive, evidence of an association between possible carcinogenic effects and exposure at levels lower than those recommended in the guideline [ICNIRP, 2010]. The WHO monograph 238 [WHO, 2007] has reviewed the entire published peer reviewed literature on “extremely low frequency fields” and can be consulted for further information.

Table 2.1: ICNIRP Guideline - Electric field reference level and basic restriction comparison

	Reference Level (kV/m)	Basic Restriction
Prior ICNIRP 1998		**Current Density (mA/m^2)**
Occupational	10	10
General public	5	2
	10 (Short-term)	
ICNIRP 1998		**Current Density (mA/m^2)**
Occupational	10	10
General public	5	2
ICNIRP 2010		***In-situ Electric Field (mV/m)***
Occupational	10	***100***
General public	5	***20***

NOTE: 1 kV/m = 1000 V/m

2.5.1 The evolution of standards/guidelines on the exposure limits of human bodies to electric and magnetic fields

The ICNIRP guideline, which is endorsed by the South African Department of Health, has been revised over the years. The review process entailed consulting the new scientific information available, or if no further scientific information was available, the guideline was reaffirmed. The brief history of the guideline development is illustrated in *Figure 2.2* below.

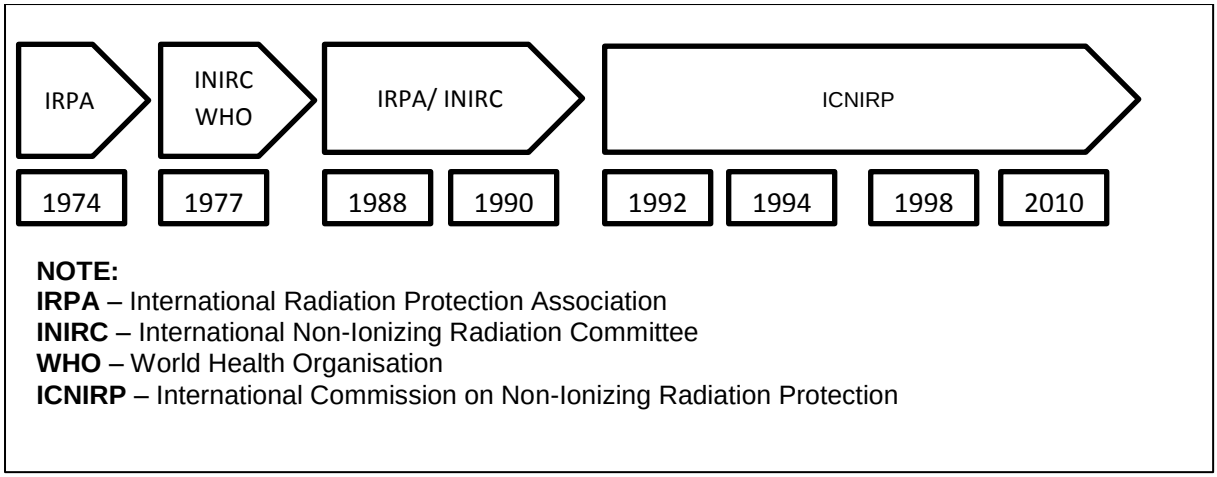


Figure 2.2: History of the development of the ICNIRP Health Exposure Standards

Performance standards are intended to limit electric and magnetic fields (EMF) under specified test conditions. The above guidelines, therefore, do not directly address product performance standards, nor do the exposure guidelines specify how to measure the electric, magnetic and electromagnetic fields. Instead they address the human exposure limits based on basic restrictions and reference levels. Measurements methods and standards are also addressed through the International Electrotechnical Commission (IEC) and IEEE technical bodies.

The guidelines call for exposure Reference Levels for the general public and occupational exposure for electric and magnetic fields at 50 Hz (as shown in *Table 2.2* below). Values are in bold and marked in red to show the difference between the ICNIRP 1998 [ICNIRP, 1998] and ICNIRP 2010 [ICNIRP, 2010] Reference Levels. The *Table 2.3* that follows highlights the change to the Basic Restrictions being applied in the two guidelines. It must be noted, that *Table 2.2* presents the magnetic field Reference Levels, but this will not be focused on in this dissertation. It is only presented here due to the change in the reference levels between the guidelines.

Table 2.2: ICNIRP Guideline Reference Level comparison: 1998 [ICNIRP 1998] vs 2010 [ICNIRP 2010]

	REFERENCE LEVEL	
	Electric field (kV/m)	**Magnetic field (μT)**
1998		
Occupational	10	**500**
General public	5	**100**
2010		
Occupational	10	**1000**
General public	5	**200**

NOTE: 1 kV/m = 1000 V/m
μT = micro-tesla
Reference levels are defined as a level that can be used for practical exposure assessment purposes to determine whether the Basic Restrictions are likely to be exceeded.

Table 2.3: ICNIRP Basic Restrictions: 1998 [ICNIRP, 1998] vs 2010 [ICNIRP, 2010]

BASIC RESTRICTIONS	
1998 Current Density (mA/m^2)	
Occupational	10
General public	2
2010 Internal Electric Field (mV/m)	
Occupational	100
General public	20

NOTE: Basic Restrictions are defined as a level of exposure to time-varying electric fields that are based directly on established health effects

The contact current of 1 mA for occupational exposure and 0.5 mA for the general public exposure remains the same in both guidelines. However, this will not be addressed in this dissertation as it forms a topic for discussion on its own.

In the case where the Basic Restriction of the ICNIRP guidelines [ICNIRP, 1998: ICNIRP, 2010] has been exceeded, dosimetry needs to be conducted, to show compliance to the

Basic Restrictions. This entails using anatomical human body models. The following section discusses these models.

2.6 Anatomical Human Models

High resolution anatomical models provide a detailed geometric representation of biological tissues and organs. Furthermore, they allow assignment of distinct dielectric properties for body tissues. The anatomical models from the "Virtual Family" package [Christ et al., 2007] were used in this dissertation and study. The CAD models were derived from high resolution MRI scans and consist of approximately 200 organs and 80 tissue types. The virtual models that were evaluated are Duke (adult male), Ella (adult female), Bille (girl) and Thelonious (boy). These models were selected to represent a family of different ages and gender. The specifications of the models, as shown in *Table 2.4* below, include other models which were not covered or used in this study.

Table 2.4: Virtual family model specifications

Name	Sex	Age (years)	Height (m)	Weight (kg)	BMI
Duke	Male	34	1.77	72	23.1
Ella	Female	26	1.63	59	22.0
Bille	Female	11	1.47	35	16.5
Thelonious	Male	6	1.17	19	14.0
Louis	Male	14	1.69	50	17.7
Eartha	Female	8	1.36	31	16.7
Dizzy	Male	8	1.39	26	13.4
Roberta	Female	5	1.09	18	14.9

NOTE: BMI – Body Mass Index

The body posture could affect the perturbation of the incident electric field distribution and result in a difference in the induced fields within a human body. In the past, most research on electric field exposure of the human body was based on fixed-posture body models that are inadequate for modelling the real-life scenario and environment.

2.7 Implications for Eskom's 765 kV Line Design and the Revised ICNIRP Guidelines

Taking cognisance of the above, Eskom is faced with the following situations:

- All Eskom's lines of 275 kV and below meet the presently recommended limits of 5 kV/m and 100 μT for public exposure to electric and magnetic fields respectively.
- Most of the current 400 kV lines comply, the exceptions being the maximum electric field of the following lines:
  - Two double circuit 400 kV lines (Ariadne-Hector and Acacia-Phillipi)
  - 275 kV lines up-rated from 275 to 400 kV (Glockner-Lethabo, Minerva-Vulcan and Apollo-Pluto)
- The existing 765 kV line (Alpha-Beta) was designed for 10 kV/m exposure limit and therefore does not meet the electric field limit for the general public.

Without any regulation of ELF EMF exposure, Eskom currently designs, constructs and operates lines within this framework using an electric field level of 10 kV/m, which is currently presented by international standards (IEEE) [IEEE, 2002] and guidelines [ICNIRP 1998, ICNIRP, 2010]. This compliance will be shown through 3-D anatomical dosimetry in this dissertation.

2.8 Conclusion

The research methodology, problem statement, the research questions and the hypothesis have been presented and discussed.

The history of the development of the ICNIRP guidelines from a health standard point of view was discussed and the changes highlighted, which has an impact on the design standards that Eskom Holdings SOC Limited uses in its present and future line design. It further presented the background to the problem Eskom Holdings SOC Limited is faced with and discusses the anatomical human models that will be used in the dosimetry of this dissertation outlined in Chapter 5 and Chapter 6.

CHAPTER 3: ELECTROMAGNETIC FIELDS AND HUMAN EXPOSURE

The interaction of the human body to electric fields is presented in this chapter. It discusses the external electric field to the human body and how it perturbs the electric field around the human body. The geometry of the human body is presented and the modelling associated with it is presented. The calculation methods that are used are also discussed, as well as how to measure the unperturbed electric fields. It closes with a discussion on the implications Eskom Holdings SOC Limited is faced with in the present and future 765 kV line design.

3.1 General

The total field produced by any electrical device when operating is made up of the electric field and the magnetic field and when combined, is called the **electromagnetic field**. It is characterised by its frequency *f* or its wavelength λ. The wavelength is the ratio of the velocity of light in a vacuum (*c*) divided by its frequency: $\lambda = c/f$.

Where the wavelength is large compared to the distance of the object (human body) from the equipment and the size of the object (human body), the exposure to the fields is defined as “near field exposure“. Under these conditions, electric and magnetic fields are independent and can be studied separately. In practice this is valid for the frequency spectrum of low and intermediate frequencies.

3.2 Interaction between External Electric Fields, Currents and the Human Body

A stimulation of nerve or muscle tissue can occur when the current (density) inside the body reaches a certain threshold [ICNIRP, 1998]. This threshold depends on the shape of the waveform and duration of the current. The stimulation follows an all-or-none law. Once the threshold is exceeded, higher currents cannot increase the response. When the human body comes into contact with energised conductors at an electric potential, a current flow in the body will occur [ICNIRP 1998]. The effect of such a contact current can range from a perception of the current, muscle contractions, to severe injury, depending on the magnitude of the current [Barchanski, 2007]. A substantial amount of experimental data for this scenario has been studied [Barchanski, 2007]. The results have been made available and the

threshold values have been summarised in *Table 3.1*. They are valid for a male person with his skin in contact with the potential difference of the source at 50 Hz.

There is a need to set up some limits of exposure for the general population to internal current density or *in-situ* electric fields produced by an external electric field. In the ICNIRP guidelines accepted by many countries worldwide, especially in the European Union, Reference (restriction) Levels are defined for occupational exposure and the general public. Since the occupational exposed population comprises mainly adults, exposed to known conditions, they can be trained to be aware of the risk. The Reference Levels for occupational exposure are higher than those for the general public.

Table 3.1: Experimental thresholds for the effects of 50 Hz contact currents on male persons [Barchanski, 2007]

Effect	**Current (mA)**
Perception threshold finger/grasp	0.36/ 1.1
Painful sensation for finger contact	1.8
Painful sensation for grasp (release possible)	9
Painful sensation for grasp (release partially possible)	16
Strong shock (release not possible)	23
Possible ventricular fibrillation	100

Current densities above 100mA/m^2 can result in acute changes in the central nervous system. In view of safety considerations for all, the ICNIRP guideline has applied a safety factor of 10 to the basic restriction limit for occupational exposure in the frequency range from 4 Hz to 1 kHz, and a further 5 for the general public. This results in a 10mA/m^2 and a 2mA/m^2 Basic Restriction for occupational and general public exposure respectively.

Since current density and in-situ electric fields inside the human body cannot be easily measured, Reference Levels for the applied external fields have been defined. The in-situ electric field or current density can be obtained using the Basic Restrictions and the use of mathematical modelling. Restrictions on the effects of exposure to electric, magnetic and

electromagnetic fields are based on established health effects and are termed “Basic Restrictions”.

Reference Levels of exposure for ease of measurement are provided for comparison with values of physical quantities; that is, compliance with all Reference Levels given in the ICNIRP guidelines will ensure compliance with the Basic Restrictions. If measured values are higher than the Reference Levels, it does not necessarily follow that the Basic Restrictions have been exceeded, but a more detailed analysis is necessary to assess compliance with the Basic Restrictions. The Basic Restrictions form the basis for the Reference Levels and are achieved through mathematical modelling and extrapolation from laboratory investigations at the defined frequency of interest. This has been conducted in this dissertation, as the Reference Level of 5 kV/m for the general public has been exceeded and through dosimetry, compliance with the Basic Restrictions was needed.

3.3 Geometrical Modelling of the Human Body

The dielectric properties of different biological tissues differ. At a specific frequency, the conductivities of biological tissues can have a spread of three orders of magnitude (such as, at 50 Hz, blood 0.7 S/m, bone marrow 0.0016 S/m). This variation seen in the dielectric properties of biological tissues resulted in realistic body models being developed. These models reflect the heterogeneity of the human body for electric, magnetic and electromagnetic field simulations. Published works on using human-body phantoms were initially for nuclear radiation safety.

The available phantoms used in the past can be divided into two groups. The first available phantoms consisted of simplified geometries. For example, a 30 cm thick slab 30 cm circular cylinder 30 cm in diameter and 60 cm high. Secondly, Fisher and Snyder from Oak Ridge National Laboratory in 1966 developed a more detailed phantom that was revised in 1969 [Snyder et al., 1969]. The human body model was based on data obtained from modern medical imaging techniques, such as Magnetic Resonance Imaging (MRI) or the Computed Tomography (CT) and represents the human body by means of sampled volume pixels, the so-called voxels. The revised model in accordance with the reference data published by the International Commission on Radiological Protection (ICRP) was called the Medical Internal Radiation Dose (MIRD) 5 phantom [Snyder et al., 1969]. The MIRD 5 phantom was then revised several times. Three phantoms consisting of a male, female and pregnant female were constructed and used to calculate the internal dosimetry of the body. Since the

dimensions of the body and organs differ from child to adult, as well as the position of the organs within the body, special effort was made to obtain paediatric phantoms at various ages [Christy, 1980]. In recent times, most publications make use of the tomographic phantoms, while the stylised phantoms have also been improved by several authors [Farfan et al., 2004; Han et al., 2006].

Advances made in computer technology and medical imaging has made it possible to obtain images of the human body in slices. In 1989, the United States National Library of Medicine (NLM) conducted a programme to construct a high-resolution, tomographic phantom of the human body in the framework of the so-called 'Visible Human Project' as follows:

> "NLM should undertake a first project building a digital image library of volumetric data representing a complete, normal adult male and female. This Visible Human Project will include digitalized photographic images from cryosectioning, digital images derived from computerized tomography and digital magnetic resonance images of cadavers."

The results of the outcome of this programme were made available in 1994 [ECOLE, 1994]. The outcomes of this programme created a large amount of data. As a result, the Visible Human has been made available in coarser resolutions, up to an edge length of 8 mm. Several anatomically developed tomographic phantoms are used in the area of electric, magnetic and electromagnetic field dosimetry. Some of these phantoms have been normalised to match the reference human model data, while others are unmodified. A selection of the phantoms, along with a reference to the publication is listed in *Table 3.2*. A more complete list can be found in Lee and Lee [Lee and Lee 2006].

The majority of the available tomographic phantoms have represented the body in a lying position, as this is how they were scanned. In the Visible Human phantom, the hands were placed alongside the body, with the fingers touching the upper thighs, connecting the arms and legs electrically. Extensive efforts were made to obtain a flexible (posable) phantom after the Visible Human model that could represent the body in any posture.

More recently, the limitations of stylised and tomographic phantoms were addressed and a hybrid phantom was developed. It combined the mathematical equations used in the stylised phantoms with the anatomical realism of the tomographic phantoms. The organs and body contours were segmented using medical images. The organ position and shape could easily be transformed to match the reference data.

Tomographic phantoms or segmented MRI data offers a fine spatial resolution for electric, magnetic and electromagnetic field calculations. However, each voxel of a given tissue type will always be assigned one conductivity value. This does not allow for the heterogeneity of the same tissue type.

Table 3.2: A selection of available tomographic phantoms

Phantom	**Image type**	**Subject**	**Race**	**Age and gender**	**Reference**
Zubal	CT	Diffuse melanoma	Caucasian	Adult male	[Zubal et al. 1994]
Norman	MRI	N/A	Caucasian	Adult male	[Jones 1999]
Naomi	MRI	Volunteer	Caucasian	23-year-old female	[Dimbylow 2005]
Korman	MRI	Volunteer	Korean	30-year-old male	[Lee et al.2004]
Taro	MRI	Volunteer	Japanese	22-year-old male	[Nagaoka et al. 2004]
Hanako	MRI	Volunteer	Japanese	23-year-old female	[Prakash 1998]
Duke	MRI	Volunteer	European	34-year-old male	[Christ et al. 2007]
Ella	MRI	Volunteer	European	26-year-old female	[Christ et al. 2007]
Bille	MRI	Volunteer	European	11-year-old female	[Christ et al. 2007]
Thelonious	MRI	Volunteer	European	6-year-old male	[Christ et al. 2007]

At the stage of conducting the studies for this dissertation, no such software and posable models were available to the author. All whole-body calculations presented in this dissertation have been performed using the “Virtual Family Models” developed by IT’IS [Christ et al., 2007].

3.4 Current Density and In-situ Electric Field Calculation Methods

Several methods have been developed to study electric fields, current densities and in-situ electric fields induced in anatomic models of the human body for low frequency exposure [Dawson & Stuchly, 1998; Dimbylow, 1998]. Some of these methods use equivalent body models (spheroid, space potential). Most of these methods are based on macroscopic Maxwell's equations. The choice is based on the precise method for the resolution, including time of calculation. These numerical methods are:

- **Spheroid model**. This model assumes the human body to be a spheroid with dimensions similar to the human body. This computation is used to assess an analytical formula of the induced current density in the human body taking into account the geometrical properties of the spheroid and the external electrical field.
- **Space potential method**. In this method the equivalent capacity of the head of the body (equivalent to a spheroid) is determined. The potential of the head is calculated and the current coming from the head is then calculated. This method is easy to use but is imprecise and not frequently used.
- **Charge simulation method.** This method simulates an actual electric field with a field formed by a finite number of imaginary charges situated inside the body. The values of simulation charges are determined by satisfying the boundary conditions at a number of contour points selected at the body surface. Once the values of simulation charges are determined, the potential and electric field at any point in the region outside the body (air) can be calculated using the superposition principle.
- **Finite element method**. In this method, a physical equation is solved using finite element equations.
- **Impedance method**. In this method, the induced current distribution inside the body is determined by supposing that the body is equivalent to an impedance network. The methodology splits the human body into a grid of elements and then calculates the equivalent impedance of each element.
- **Hybrid method.** This method needs two successive calculations. The first calculation determines the external field at the surface of the body by solving Laplace's equation and assuming an equipotential surface. The distribution of surface charge densities is then obtained. The second calculation determines the internal field and potential distribution in a human body model. This human body model is composed of many small blocks of a few millimetres in size.

- **Finite Difference Time Domain (FDTD) method.** Arguably the most popular numerical method used for the solution of problems in electromagnetics in the high frequency range. Although the FDTD method has existed for over 30 years, its popularity continues to grow as computing costs continue to decline. This dissertation is based on this method.

While the computational strategies of the above methods may differ with its application, the results obtained are reasonably similar. The choice of method depends on:

a) the size and shape of the specimen to be modelled;
b) the field exposure to be simulated;
c) the specimen resolution, determined by the size of modelling element (voxel);
d) computational efficiency; and
e) memory requirements of the computer.

The resolution of these methods mentioned above, lie between 1 mm and 1.31 cm. At cellular level, FEM has been used with higher resolution down to 1μm for computation of the induced electric fields. This dissertation is based on the FDTD method and did not develop the code used in the dosimetry of the human body models. The mathematics associated with the FDTD method can be found in Appendix E, which has been applied in the anatomical dosimetry in this dissertation using the SEMCAD X software package [SPEAG] and the virtual family models, Duke, Ella, Billie and Thelonious [Christ et al., 2007]. The following section discusses the anatomical body model and the dielectric composition of the internal body part used in the 3D anatomical body dosimetry.

A. Anatomical whole body model.

In a high resolution anatomical model, biological tissues and corresponding organs are assigned distinct dielectric properties. The Duke, Ella, Billie and Thelonious anatomical models from the Virtual Family package [Christ et al., 2007] have been used in this dissertation. The CAD models were derived from high resolution MRI scans and consist of approximately 200 organs and 80 tissue types.

One of the investigated human models used (Duke) represents an adult, 34-year-old male, 1.77 m tall and weighing 72 kg. The anatomical structure is shown in *Figure 3.1* below. It is well-known that body posture could affect the perturbation of incident electric and

electromagnetic field distributions and result in a vast difference in induced fields within the human body.

In the past, most research on electric, magnetic and electromagnetic exposure of the human body has been based on fixed-posture body models that are inadequate for modelling the real life scenario and environment.

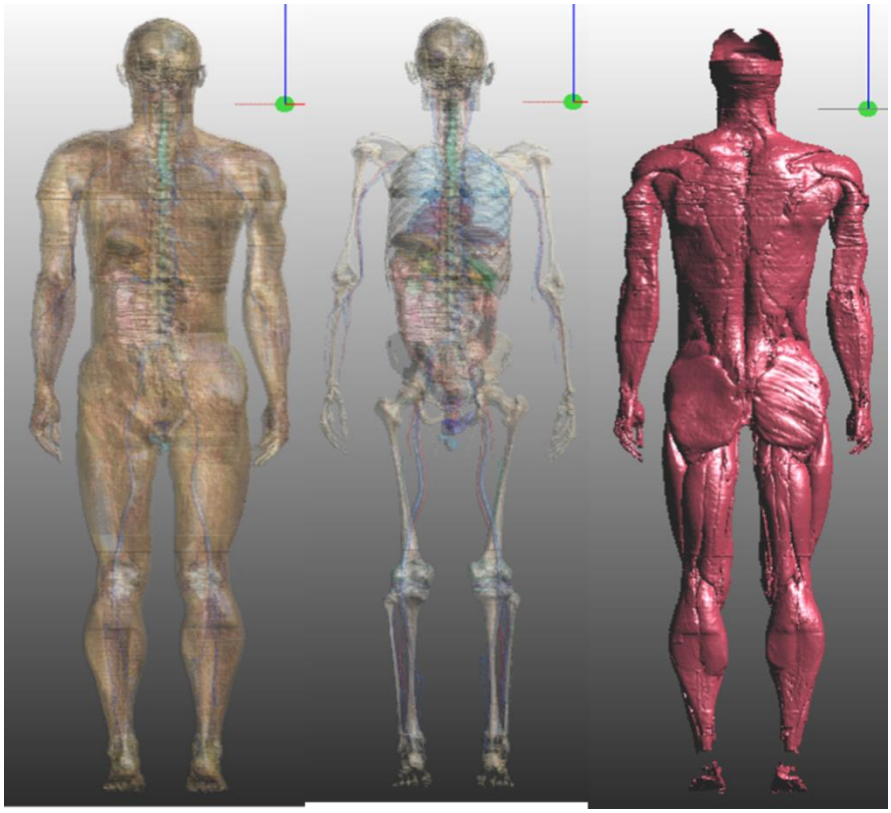


Figure 3.1: High resolution MRI scan-based anatomical model of Duke with detailed organs, skeleton and tissues

B. Dielectric properties of body tissues.

The dielectric properties of biological tissues vary significantly with respect to frequency. In the low frequency spectrum, biological tissues are mostly diamagnetic ($\mu=\mu_0$), and display high relative permittivity with low conductivity. The values of the tissue conductivity and permittivity used in this dissertation were obtained from [Gabriel et al. 1996]. A list of some of the basic dielectric properties for some of the organ tissues at 50 Hz used in this study is given in *Table 3.3*.

Table 3.3: Tissue conductivity and permittivity values at 50 Hz [abriel et al., 1996]

Tissue	**Relative Permittivity (ε_r)**	**Conductivity, σ (*S/m*)**
Bladder	481636	0.205
Blood	5260	0.7
Bone	8867.8	0.02
Brain white matter	5.29×10^6	0.053
Brain grey matter	1.21×10^7	0.075
Cartilage	1.64×10^6	0.17
Fat	1.14×10^6	0.019
Heart	8.66×10^6	0.083
Kidney	1.01×10^7	0.089
Liver	1.83×10^6	0.037
Lung (inflated)	5.75×10^6	0.068
Muscle	1.77×10^7	0.23
Nerve	1.61×10^6	0.027
Skin (dry)	1136	2×10^{-4}
Small intestine	2.03×10^6	0.52
Spinal cord	1.6×10^6	0.027

3.5 Numerical Dosimetry

The interaction of low frequency (0 Hz - 100 Hz) electric fields with humans and other living systems has become increasingly important. The driving factor behind this is the potential health hazards due to the electric fields emitted by extremely high voltage power lines and high voltage equipment. This subject has been investigated experimentally or empirically by numerous researchers [Chen et al., 1986; Karanikolos et al., 1995; Kaune et al., 1980; Kauneet et al., 1984].

Electric field dosimetry studies the physical aspects of the coupling between an electric field (unperturbed) and a biological object exposed to it. This is the first step of the interaction process. *Figure 3.2* shows this process.

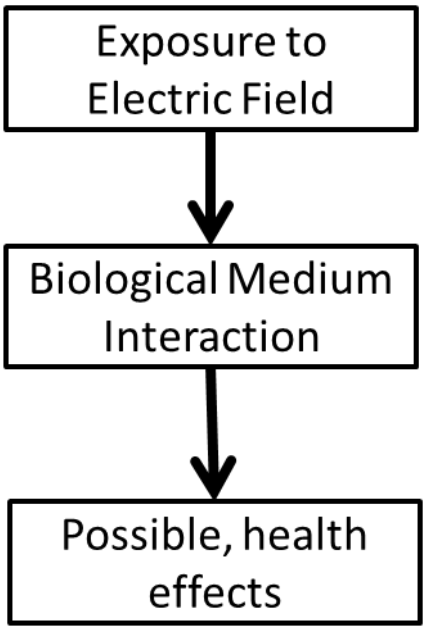


Figure 3.2: Dosimetry process for electric field exposure and biological medium

This interaction process is fundamentally multidisciplinary as it includes physics, biology and medicine. The coupling itself is merely a physical process. It involves the laws of interaction between electric fields and complex-shaped objects made with heterogeneous, glossy materials. Electric field dosimetry applies the methods of physics to the study of this coupling. The relationships between the field intensities of the impressed electric field and the values of the physical quantities (charges, currents, power) which the field induces in the tissues of the exposed body are calculated.

The application of the quasi-static approach to numerical dosimetry follows a simple approach, such as:

- Calculating the impressed (unperturbed) electric fields.
- The object/subject exposed is subdivided (segmented/voxel) into small homogeneous elements with the corresponding dielectric properties assigned to them.
- A set of differential or integral equations is then solved.
- The current densities or in-situ electric fields are then compared to the guidelines or standards to verify compliance.

CHAPTER 4: ELECTRIC FIELD SIMULATION SOFTWARE SELECTION

This chapter discusses the simulation software and applicable modules used to conduct the comparison of the exposure measurements and the human exposure dosimetry. The two software packages selected for use in this dissertation are:

- SEMCAD X [SPEAG]
- CDEGS [CDEGS]

Each of the above packages is critically discussed explaining why they were chosen for use. For more in-depth information, consult the relevant software manuals.

4.1 SEMCAD X

4.1.1 Introduction

The SEMCAD X is a 3-D full wave simulation environment based on the finite-difference time domain (FDTD) method, developed and provided by Schmid & Partner Engineering [SPEAG]. It was developed to be used in electromagnetic technology applications such as:

- electromagnetic compatibility (EMC)
- dosimetry
- radio frequency solvers
- low frequency solvers.

In addition, a multi-parameter, multi-goal optimisation engine based on genetic algorithms allows for importing complex CAD structures for use in the software.

Since mid-2009, SEMCAD X has been interfaced with the newly introduced aXware accelerator card and the aXware Cluster In A Box, which allows for further reducing the runtime by at least 25 times. This dedicated hardware has specifically been optimised for use with FDTD and high bandwidth accelerator memory, which has proven to be more efficient and cost-effective than multiprocessor workstations or multi node clusters by decreasing initial and long-term maintenance costs.

4.1.2 Electromagnetic simulation theory - F*inite-difference, time-domain formulation [SPEAG]*

The finite-difference, time-domain (FDTD) method is multipurpose and can be used for solving bioelectromagnetic problems. The FDTD has been used for modelling whole-body or partial-body exposures due to spatially uniform or non-uniform, near- or far-fields that are sinusoidally varying or transient in nature.

Using the FDTD method, it is necessary to represent the scattered/absorber (human body) or a part thereof, as well as the electromagnetic sources. This includes their shapes, excitations, and so forth, if these sources are in the near-field region. In the far-field, sources are described by means of incident plane-wave fields. They are specified on a three-dimensional source 'box' located typically 6 to 10 cells away from the exposed body. A cell is defined as either a wavelength or distance from the object. The interaction space consists of several hundred thousand to several million cells. They are truncated by means of absorbing boundaries. The fields penetrating the object cells are tracked in time in the total interaction space. The computation is considered to be completed when convergence occurs. This occurs when either both the **E** and **H** fields have died off for an impulsive excitation or when the sinusoidal steady-state is observed for all cells within the interaction space for sinusoidal steady-state.

4.1.2.1 Conformal FDTD formulation

The SEMCAD X features a powerful enhancement which reduces computational resources while maintaining its accuracy. This is achieved through using a conformal mesh with coarser spatial resolution to produce the same accuracy as a fine staircasing mesh results with a reduction in memory requirements (fewer cells) and simulation time (larger time step).

Conformal FDTD is based on its formulation similar to conventional FDTD, but makes use of more geometrical details. For example, one cell can represent more than one single dielectric material in contrast to the conventional FDTD algorithm. The error caused by the staircasing is subsequently largely reduced.

In SEMCAD X, two algorithms of treating conformal FDTD have been incorporated, depending on what type of material is involved. These models are defined as follows:

- **Dielectric model.** This is the area perpendicular to the edge that is used to average the electromagnetic parameters. The method is always stable without any necessary reduction of the time step determined by the Courant-Friedrich-Levy (CFL) stability criterion.

- **PEC (perfect electric conductor) model.** In this algorithm the effective PEC-free edge length and the PEC-free area are taken into account while time updating. In general, the improvement in accuracy is much more significant than for dielectric models. Furthermore, there is no need to reduce the conventional time step in order to guarantee numerical stability, i.e., the method is always stable. However, the algorithm's accuracy can be improved with a slightly reduced time step: therefore, the user can put a specific focus on either speed or accuracy. The time step reduction benefit can be dependent on the example.

4.2 CDEGS Software

The CDEGS software package (**C**urrent **D**istribution, **E**lectromagnetic Fields, **G**rounding and **S**oil Structure Analysis) is a powerful set of integrated engineering software tools designed to accurately analyse problems involving grounding/earthing, electromagnetic fields, electromagnetic interference, including AC/DC interference mitigation studies. The CDEGS computes conductor currents and electromagnetic fields generated by an arbitrary network of energised conductors. These conductors can be positioned above or below ground for normal, fault, lightning and transient conditions. The CDEGS models can consist of simple or multi-component conductors. These can include bare conductors, coated pipes and pipe-enclosed cable systems buried in complex soil structures. The CDEGS package consists of numerous sub-packages, which provide an array of cost-effective solutions for problems ranging from simple earthing/grounding grid designs to the behaviour of complex networks. These networks can consist of above-ground and buried conductors, which could be energised by steady-state voltages or currents, lightning or other transients. Data reporting and graphing utilities allow the collection and illustration of any aspect of the results.

Validation of the software using field tests and comparisons with analytical or published research results has been conducted for more than 30 years. The validation, conducted by Safe Engineering Services (SES) as well as other independent researchers, is documented

in numerous technical papers published in reputable international journals. The module used to compare the measured and predicted electric fields is SES-EnviroPlus.

4.2.1 SES-EnviroPlus

SES-EnviroPlus is used to analyze power line cross-sections to determine line parameters, capacitive and magnetic induction, as well as electrostatic potentials, gradients and corona parameters for AC/DC overhead transmission systems. The program can be used to analyze complex corridors containing any combination of transposed and non-transposed transmission lines (see *Figure 4.1* below).

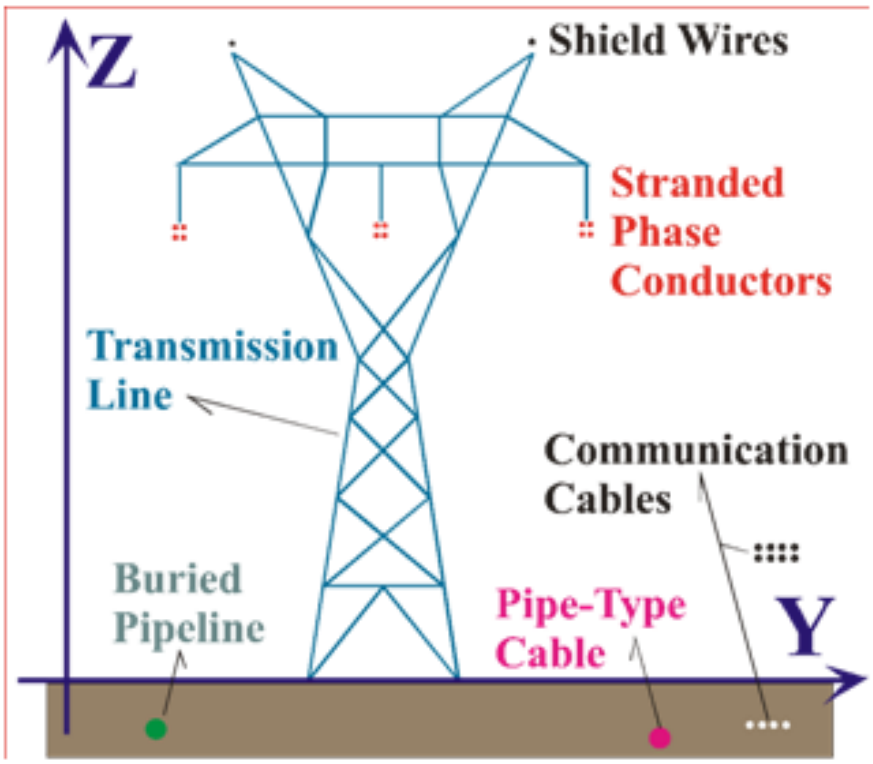


Figure 4.1: Cross-section of transmission line used in SES-EnviroPlus

The following input data was required to compute the results:

- Coordinates and physical characteristics of the transmission line conductors and their insulation being modelled. SES-EnviroPlus uses overhead bare single core cables with a mix of transposed and/or un-transposed circuits.

- Physical characteristics of the medium surrounding the conductors. This can be air and/or a multi-layered soil model. SES-EnviroPlus uses one uniform layer in the computation.
- Line voltages and currents of the transmission line conductors and their frequencies. These voltages and currents are optional, depending upon the desired output required.
- Coordinates and physical characteristics of nearby conductors that do not form part of the transmission line(s). These are normally specified when induction effects are to be calculated.
- Specification of output data format that would be required.
- Calculations required need to be selected; e.g., at which points to evaluate gradients, whether or not to carry out these calculations, as well as the accuracy that is desired.
- SES-EnviroPlus allows the user to select the required calculations (radio interference, audible noise, corona losses, magnetic fields, etc.) which the user has specified.

The output data is made up of the following:

- Electrostatic potentials and gradients at any location around the transmission lines, which includes the surface gradient of the conductors. The calculations optionally include the effects due to the presence of “space charge" around the lines in the DC case.
- For magnetic fields, induced currents, line parameters and environmental parameters (radio interference, audible noise, and corona losses).

4.3 Conclusion

The selection of available software for the ground level electric field modelling has been discussed and will be validated in Chapter 5. The CDEGS software will be used to check the measured and predicted electric fields (Chapter 6), while the SEMCAD X software will be utilised for the dosimetry of the human models (Chapter 7) in this dissertation for a case study of a 765 kV transmission line.

CHAPTER 5: 765 kV TRANSMISSION LINE MODEL SELECTION AND SOFTWARE VALIDATION OF GROUND LEVEL ELECTRIC FIELDS

Simple models were used to check the electric field exposures at ground level. This was conducted, to ensure that the electric field at ground level in Chapter 6 can be validated between the two software packages discussed in Chapter 4 which will be used in the 3D anatomical dosimetry for human exposure presented in Chapter 7.

5.1 Verification of Fields

A verification of two software packages available in Eskom's Research, Testing and Development Department, namely CDEGS and SEMCAD X, was conducted to validate the electric fields computed between them are similar to each other. The error between them should be negligible for the unperturbed electric field.

The model used to validate the electric fields comparison, is shown in *Figure 5.1*. The three circles are the phase conductors above the ground level (solid line) and the dotted line 1m above ground level, where the unperturbed electric field will be measured and predicted.

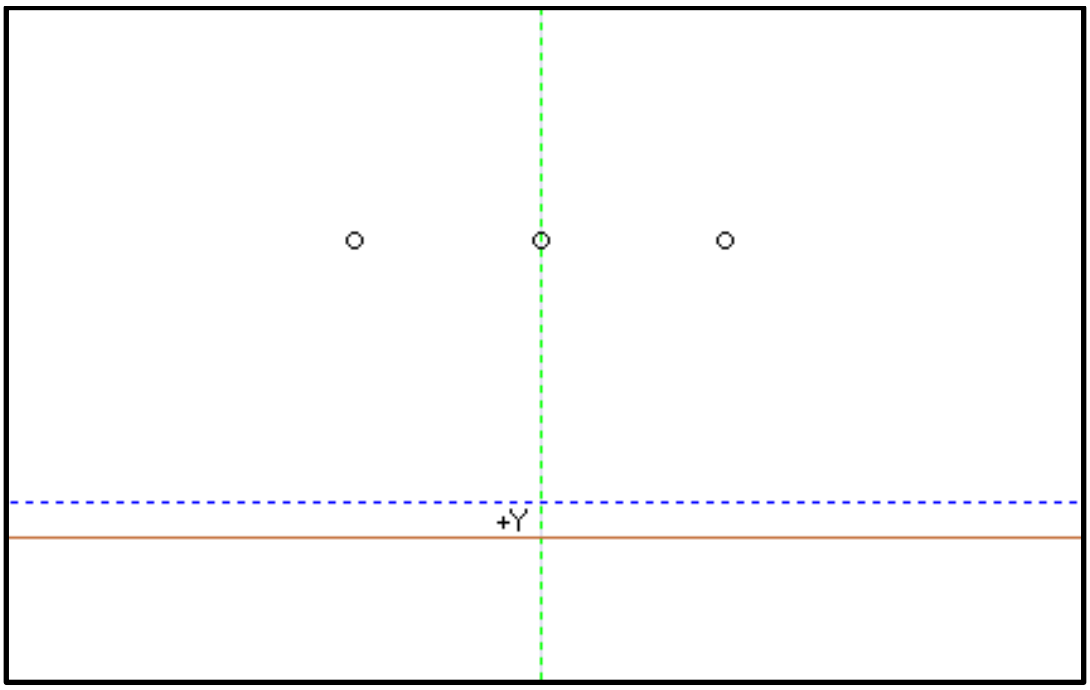


Figure 5.1: Cross-section of transmission line used for comparison

The model parameters used in the comparison are shown in *Table 5.1* below, with a nominal supply voltage of 400 kV phase to phase being used.

Table 5.1: Model Parameters used for validation of CDEGS and SEMCAD X

PARAMETER	VALUE
Phase conductor radius (cm)	38
Number of conductors per phase	1
Earth resistivity (Ohm-m)	100
Electric and magnetic field computed and measurement height (m)	1
Phase orientation (left to right) (°)	0, 120, 240
Phase height from ground level (m)	8
Phase separation (m)	5

Figure 5.2 below presents the electric field comparison. Measurements conducted in the field have also been compared with the predictions and have shown a good correlation with the predictions (see Chapter 6). The magnetic field showed similar results and are not shown in this dissertation.

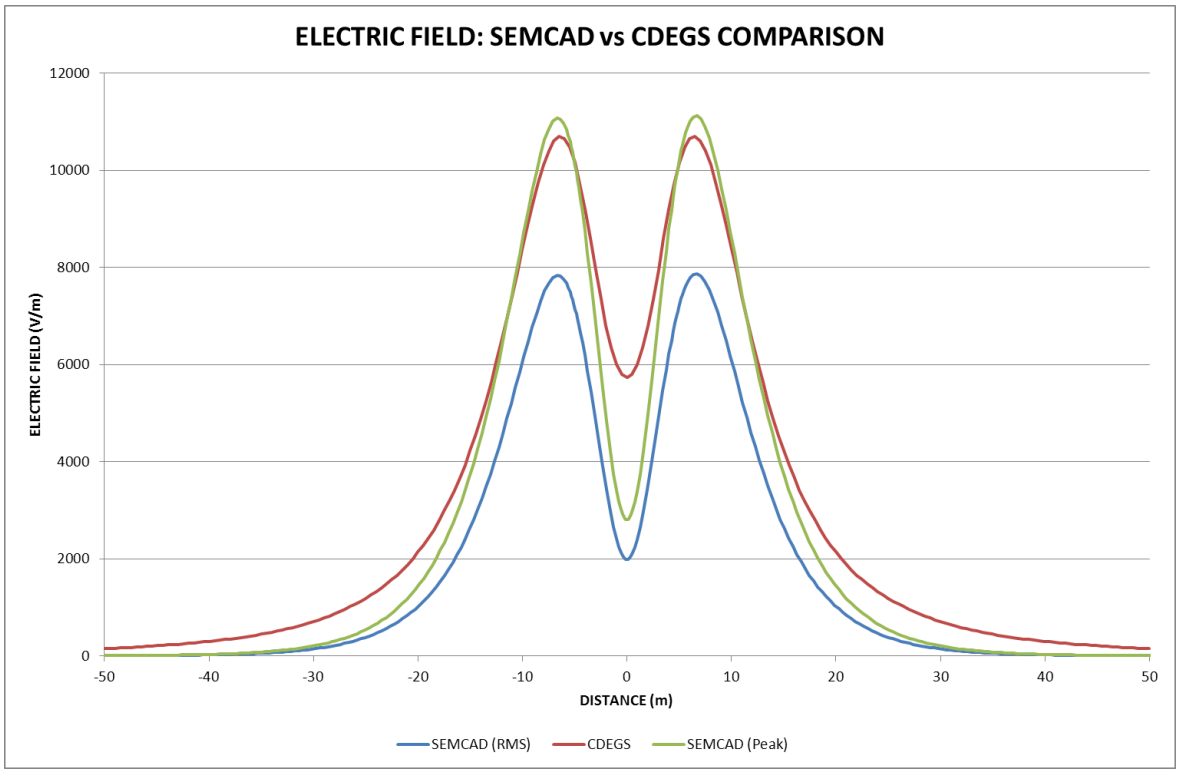


Figure 5.2: Electric field comparison of CDEGS and SEMCAD X

From *Figure 5.2*, it is clear that the electric fields at 1 m from ground level are similar in both the CDEGS and SEMCAD X software packages. The differences in the roll-off on either side of the centre line is due to the accuracy of the step size between the prediction points of the two packages and the boundary conditions set in SEMCAD X.

The electric field is a vector field and at any point is defined by its space components in three dimensions. The electric field produced from a transmission line can be considered to be two-dimensional (vertical and horizontal).This means it has an elliptical polarisation. This electric field polarisation under the transmission line depends on the distance from the conductors, magnitude and direction. The direction of the electric field vector rotation depends on the phase arrangement. An electric field at a height of 1 m from ground is nearly vertically polarised. This leads to the specific 'M' like shape as shown in *Figure 5.2*.

5.2 Model Validation of SEMCAD X Software – Electric Field

The dissertation focuses on human exposure to extremely low frequency (ELF) electric fields. In particular, current densities and in-situ electric fields induced in realistic models of the human body standing beneath 765 kV transmission lines are studied.

In order to test the validity and approach with previously tested examples, an ellipsoidal model proposed by King [King, 2004] has been solved and the results have been compared with the analytical calculations.

Time harmonic Maxwell's equations for imperfect conductors in the ELF electric field at distances smaller than the propagation wavelength can be written as:

$$\nabla \cdot [(\sigma + i\omega\epsilon)E] = 0 \qquad (5.1)$$

Where $\omega = 2\,\pi\,f$, $i = \sqrt{-1}$, $E = -\nabla\varphi$ is the electric field, σ is the electrical conductivity of the body/ medium and ε the permittivity. The model representing a homogenous biological tissue in air exposed to an ELF vertical electric field (unperturbed electric field without the object) consists of an ellipsoid centred at the origin, defined by the following equation:

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = 1 \qquad (5.2)$$

With a = 0.3 m, b = 0.15 m and c = 0.875 m, σ = 0.5 S/m and negligible permittivity, immersed in air with zero conductivity and ε = 8.854 x 10^{-12} F/m, the body is exposed to an incident electric field in the z-plane direction $E^{inc} = E_{0Z}$.

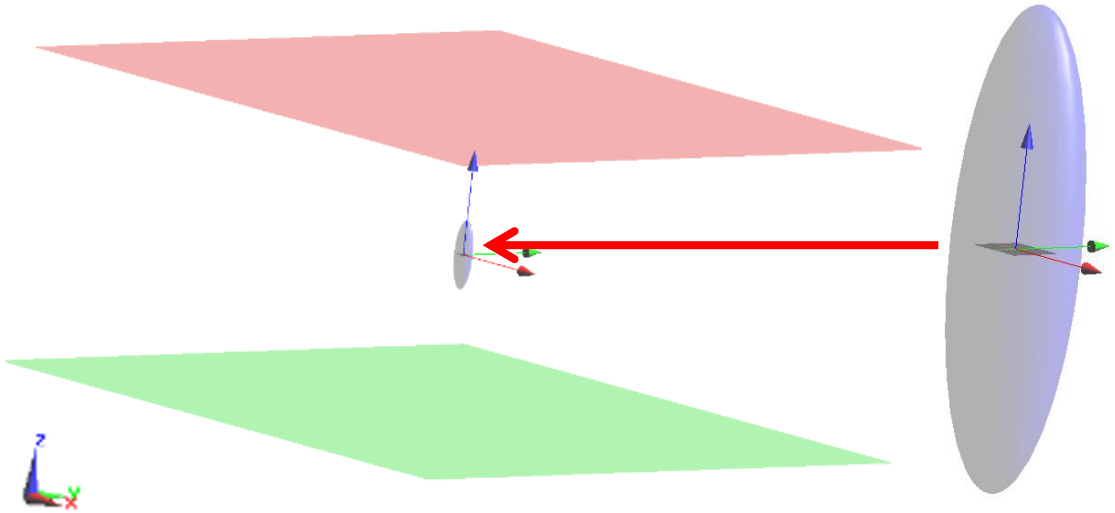


Figure 5.3: Elipsoid model between two parallel plates (left); the ellipsoid (right)

The boundary conditions applied to the bounding box are: U and –U at the top and bottom plate surfaces respectively, with U = 8 V so that it produces E_0 = 1 V/m (see *Figure 5.3*).

The electric field obtained inside the ellipsoid with a discretised resolution of 20 mm using SEMCAD X software is 9.63 x 10^{-8} V/m and the corresponding current density obtained was 4.608 x 10^{-8} A/m^2. The results are comparable with the analytical calculations obtained in reference [King, 2004] as shown in *Table 5.2*.

Table 5.2: Comparison of electric field and current density results obtained with the FDTD approach and the corresponding analytical solution [King, 2004]

	Analytical	**FDTD**	**Error (%)**
E (V/m)	9.545 x 10^{-8}	9.63 x 10^{-8}	0.89
J (A/m^2)	4.77 x 10^{-8}	4.608 x 10^{-8}	3.396

Figure 5.4, below highlights the electric field predictions used in the SEMCAD X model.

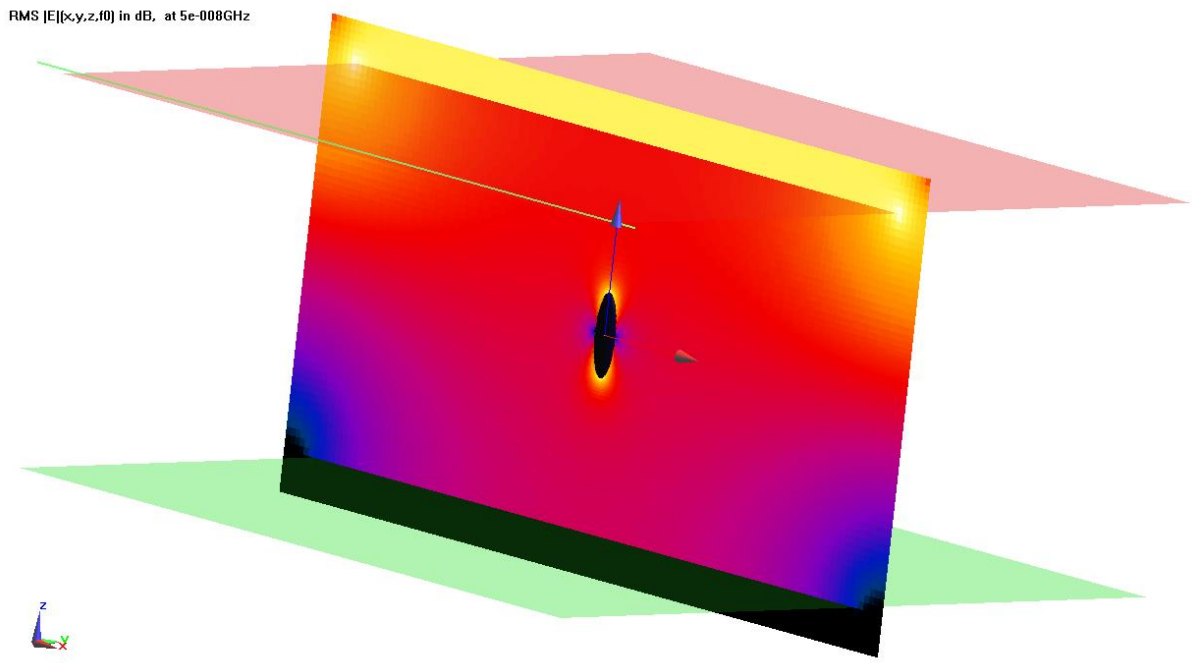


Figure 5.4: Electric field plot of the model with the ellipsoid inserted in the centre of the parallel plates along the X-axis.

It can be noted from *Figure 5.4* that the high electric fields are produced at the upper and lower points of the ellipsoid. This is due to the ends being closer to the supply voltage plates where the electric fields are at the maximum around the ellipsoid.

5.3 765 kV Transmission Line Exposure Comparison

Figure 5.5 shows a two-dimensional plot of a cross-section of a 765 kV transmission line electric field strength (V/m), while *Figure 5.6* shows the same plot in three dimensions above a perfect ground plane (0 ohm-m) in the Y-axis of the 765 kV model in SEMCAD X. The electric field values are shown in dB, referenced to the scale (5.26 x 10^5V/m) shown in the right bottom corner, to give a better resolution of the electric fields.

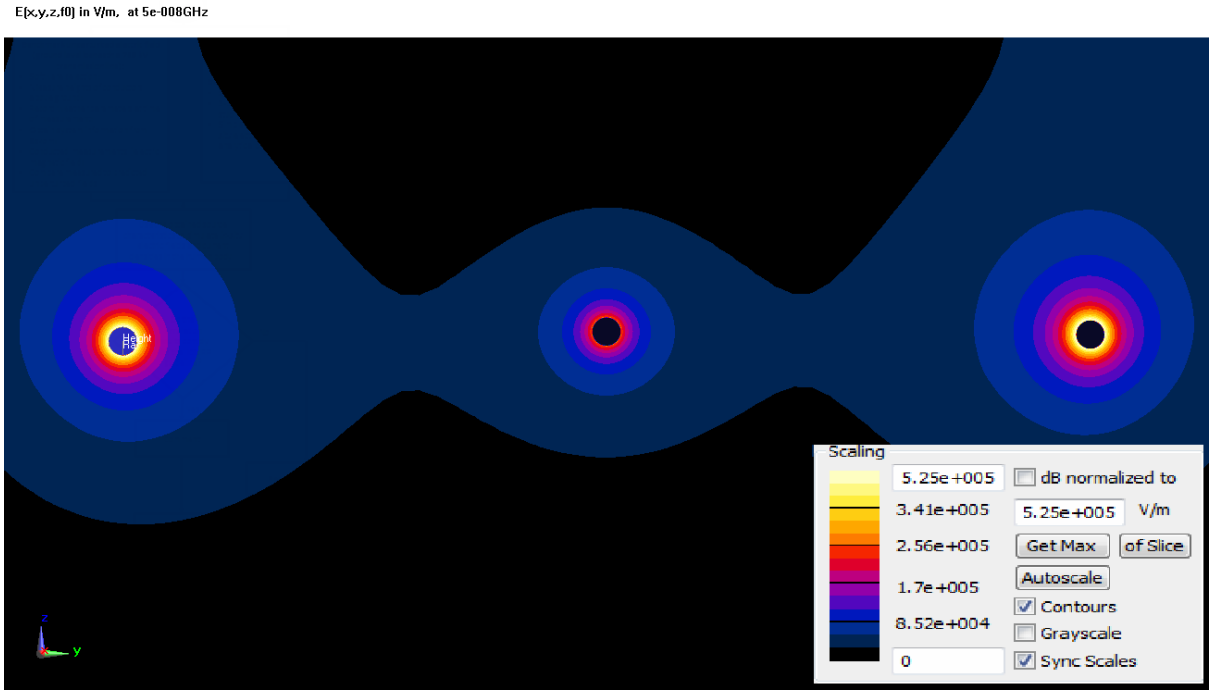


Figure 5.5: Sliced electric field plot of a 765 kV line displayed in electric field strength referenced to 5.25 x 10^5 V/m

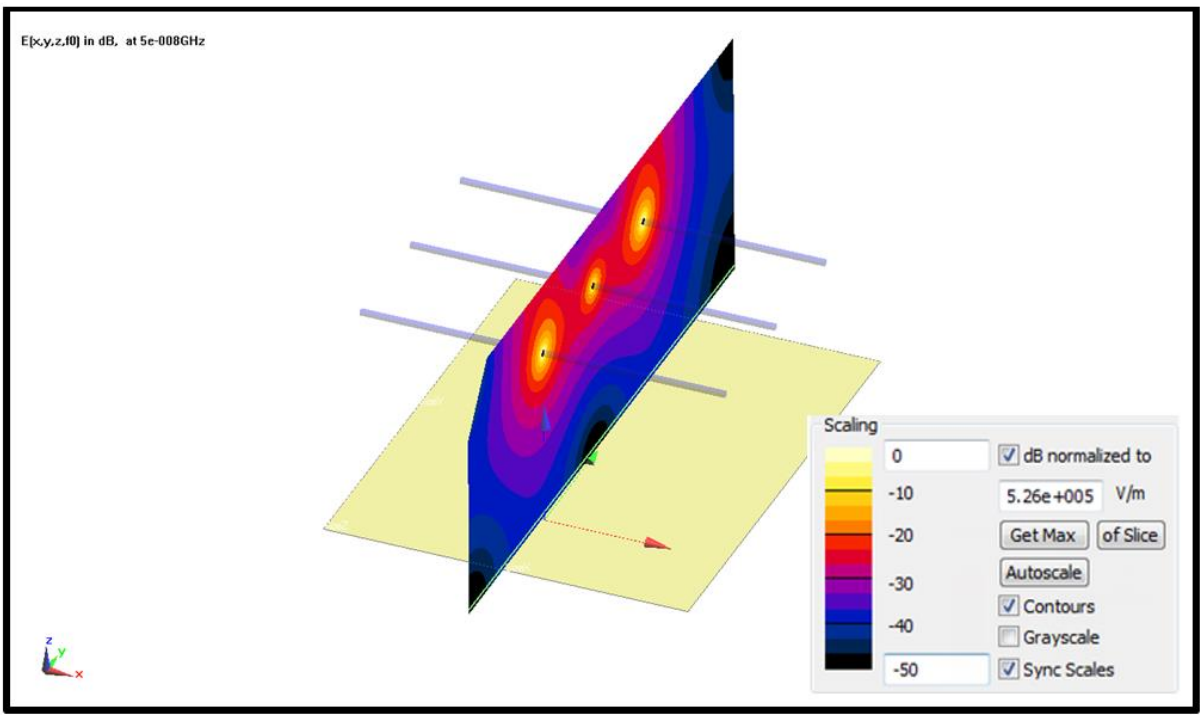


Figure 5.6: Sliced electric field plot with perfect ground plane (765 kV, displayed in dB Referenced to 5.26 x 10^5 V/m)

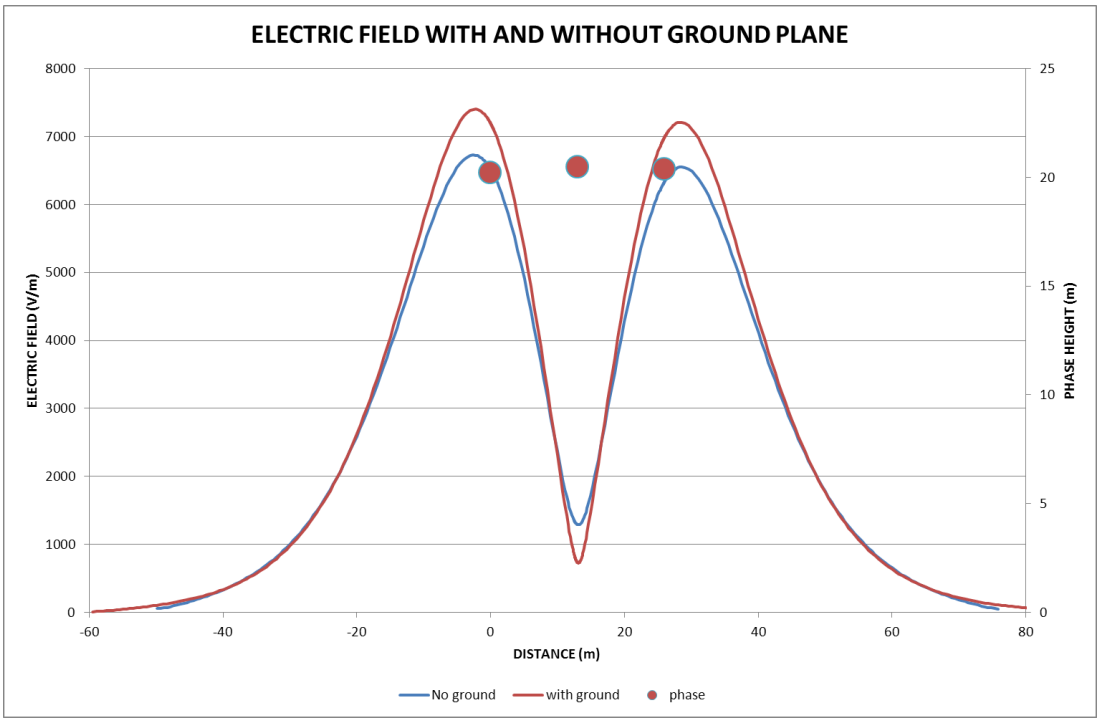


Figure 5.7: Electric field comparison with and without ground plane

From *Figure 5.7* it is shown that the ground plane does not increase the overall electric field further away from the 765 kV transmission line centre. The maximum is higher by approximately 9.1 % with the added ground plane.

A comparison of the model is shown in *Figure 5.8* using the CDEGS software module SES-EnviroPlus for the prediction at 730 kV nominal system voltages (obtained from Eskom system data *Figures 6.3 and 6.4*). It must be noted, that the CDEGS electric field values (RMS), need to be converted to peak values (ground to line) by dividing the 730 kV by $\sqrt{3}$ and then multiplying the electric field by $\sqrt{2}$ for comparison, as SEMCAD displays peak values.

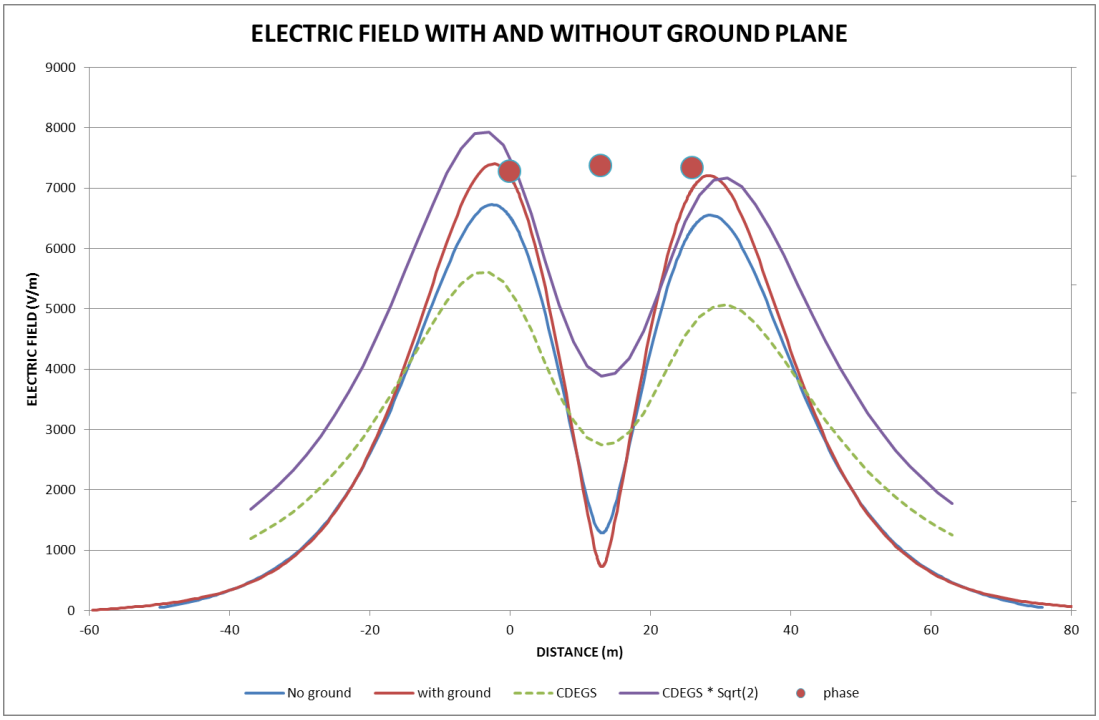


Figure 5.8: Electric field comparison with CDEGS

5.4 Anatomical Model Verification and Comparison

With respect to more standard numerical problems, when dealing with dosimetry in the human body one is concerned with the problem of obtaining a model of the human body. Therefore, not only the numerical method, but also the model of the body by itself has to be evaluated. From the current literature, many human body models exist [Dimbylow, 1998], most of which are based on voxels. Regrettably, there are only a few inter-laboratory and inter-model comparisons that exist.

Results obtained from the computation were compared with results found in [Hart, 1988], which have been obtained with different computational methods (Scalar Potential Finite Difference—SPFD) and models (named “AF,” “UVic,” and “NORMAN”). The study by Hart focused on magnetic field exposure, thus the electric field (E) is equal to zero. The exposure conditions are: E = 0, B = 1 μT uniform, orientated in the direction back/front, frequency 60 Hz. The comparison of some of the body parts is shown in *Table 5.3* below. The last column shows the results obtained using the SEMCAD X software and the Duke model.

Table 5.3: Comparison of the induced electric field (mV/m)in a few organs for the various models at a resolution of ~2 mm voxels

TISSUE	NRPB	UVic	AF	DUKE (% Error) [1]
Blood/ vessels	23.1	20.5	35.6	22.6 (2.17)
Brain	30.7	26.5	21.4	
Brain grey matter	-	-	-	51.1 (-66.4)
Brain white matter	-	-	-	30.8 (-0.36)
Cerebrospinal fluid	11.9	13.9	11.9	15.1 (-26.89)
Kidneys	42.7	50.2	31.7	39.2 (8.20)
Lungs	59.2	46.4	35.8	54.3 (8.28)
Testes	26.2	32.9	32.6	28.2 (7.63)

NOTE: 1: SEMCAD - E field E(x,y,z,f0) with the % Error referenced to the NRPB model, as it is the closest to the DUKE model.

The electric fields induced in several tissues are reported in Table 5.3. As a first observation, the orders of magnitudes obtained are similar. A deeper analysis shows large difference in some tissues (brain) as well as close values for other tissues (kidneys). Some of these differences can be explained by size and shape differences between the models (AF is bigger than NORMAN and UVic). The most troubling point concerns the AF model, which in principle is derived from the same anatomical data. For instance, in some models the grey matter, white matter and CSF are not distinguished, whereas they are in other models, and muscle anisotropy is not taken into account. Moreover, the discretization of the different models is not the same: this parameter has a major impact on maximum values [Hart, 1998].

Further to the above, the Duke model in an unperturbed electric field (see Appendix C) when compared to data presented in the IARC monograph (Table 10, page 83) [IARC, 2001], compares favourably to the results obtained through the modelling in this dissertation with the use of SEMCAD X software. The differences between the two results are shown in *Table 5.4.* The IARC Table 10 from the monograph [IARC, 2001] has been reproduced in *Figure 5.9* and is compared to the SEMCAD X modelling conducted in this dissertation.

Table 5.4: Main difference between IARC modelling and SEMCAD X modelling

IARC	Dissertation
Unperturbed vertical electric field	
60 Hz	50 Hz
1 kV/m	5 and 10 kV/m

Table 10. Calculated electric fields (mV/m) in a vertical uniform electric field (60 Hz, 1 kV/m) induced in a model of a grounded adult human body[a]

Tissue/organ	E_{avg}	$E_{99\ percentile}$	E_{max}
Blood	1.4	8.9	24
Bone marrow	3.6	34	41
Brain	0.86	2.0	3.7
Cerebrospinal fluid	0.35	1.0	1.6
Heart	1.4	2.8	3.6
Kidneys	1.4	3.1	4.5
Lungs	1.4	2.4	3.6
Muscle	1.6	10	32
Prostate	1.7	2.8	3.1
Spleen	1.8	2.6	3.2
Testes	0.48	1.2	1.6

Modified from Kavet *et al.* (2001)

[a] Corresponding current densities can be computed from tissue conductivity values (see Table 2, General Introduction)

Figure 5.9: Reproduction of Table 10 of the IARC monograph [IARC, 2001]

Table 5.5: In-situ electric field of various body organs (Duke) in V/m

E(x,y,z,f0) Volume-Average [ICNIRP-2010]				
Body organ	**Field applied (kV/m)**			
	5		**10**	
	Real Modulus (V/m)	**RMS Modulus (V/m)**	**Real Modulus (V/m)**	**RMS Modulus (V/m)**
Body	**3.40E+00**	**1.05E+02**	**6.80E+00**	**2.10E+02**
Brain (grey and white)	5.85E-03	1.10E-02	1.17E-02	**2.20E-02**
Cerebrospinal fluid	1.41E-03	5.57E-03	2.81E-03	1.11E-02
Cornea	8.93E-05	9.84E-04	1.79E-04	1.97E-03
Heart (lumen and muscle)	9.15E-03	1.97E-02	1.83E-02	**3.94E-02**
Kidney (cortex and medulla)	3.75E-03	9.66E-03	7.50E-03	1.93E-02
Liver	5.61E-03	1.83E-02	1.12E-02	**3.66E-02**
Lung	4.51E-03	1.30E-02	9.03E-03	**2.61E-02**
Nerves	6.89E-03	**3.30E-02**	1.38E-02	**6.59E-02**

Comparing the results of the in-situ electric fields, it is noted, that similar organs have been shown in *Figure 5.9* and *Table 5.5*, which are similar in value. The following comparison can be made as shown in *Table 5.6* below.

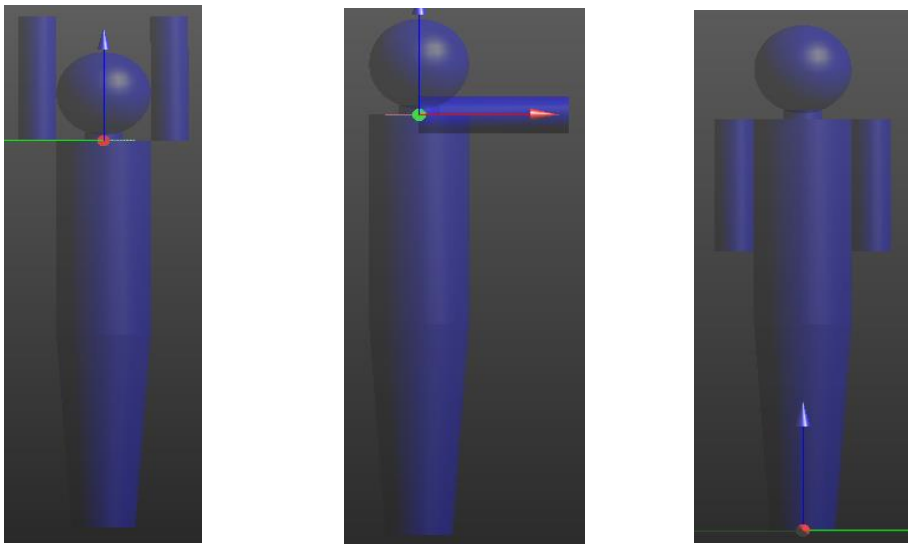
Table 5.6: Comparison of internal body organs from the IARC monograph [IARC, 2001] and modelling conducted by SEMCAD X

BODY PART	IARC (mV/m)	SEMCAD X (mV/m)	% DIFFERENCE
Heart	2.8	3.94	-29.68
Kidneys	3.1	1.93	40.52
Lungs	2.4	2.61	-7.1

From *Table 5.6*, it is noted that the error is better than 50%, which is reasonable as the models used in both predictions are not the same as size and shape are different as well as the placement of the internal organs,.

5.5 Model Perturbation of the Electric Field

Three simple models have been used to show how the electric field is perturbed by the introduction of the human body in different posture positions using SEMCAD X. These models of the human are shown in *Figure 5.10*, while the dimensions of the model are given in *Table 5.7*.



(a) Arms above head (b) Arms in front (c) Arms at side

Figure 5.10: ***Three human body positions used in the comparison of electric field perturbation; (a) Arms raised above the head; (b) Hands raised in-front of the body; (c) Arms at the side of the body***

The electric field generated around the body consisted of a ground plate below the body, which was used as the reference plane and represents the earth surface. An energised plate positioned 10 m above the ground plane was energized at 50 kV, which relates to a 5 kV/m unperturbed vertical electric field between the plates. Each model of the human consists of a head, neck, body, arms and legs (see *Table 5.7* for dimensions), which is positioned in contact with a ground plane at the bottom of the feet at the centre of the ground plane.

Table 5.7: Model dimensions used in the electric field exposure model

BODY PART	LENGTH (mm)	RADIUS (mm)
Head	300	150
Neck	30	60
Body	700	150
Legs	700	150 (top)/ 100 (bottom)
Arms	450	60

The predictions are then conducted using SEMCAD X and the sliced field view of the electric field produced for each of the models in the three body postures. The three electric field plots of the different body postures are shown in *Figure 5.11*.

Figure 5.11 shows how the posture of human body perturbs the electric field around the human body. Depending on the position of the arms, the electric field on the human body has different electric field strengths on the surface of the body. This affects the current density and in-situ electric field within the human body, as well as in the internal organs.

Considering these three models and using a conductivity of 0.2 S/m for the body, *Table 5.8*, highlights the difference computed for the current density and in-situ electric field with an unperturbed electric field of 10 kV/m produced between two parallel plates.

Table 5.8: In-situ electric field and current density computed in the human body in different postures in a 10 kV/m electric field

BODY POSTURE	IN-SITU ELECTRIC FIELD (V/m)	CURRENT DENSITY (A/m^2)
Arms above head	0.118	0.01636
Arms in-front of body	0.129	0.0118
Arms at the side	0.0272	0.00422

From the information presented in Table 5.8, it is shown that the posture of the body influences both the in-situ electric fields and current densities of the human body. The differences are large, in excess of 200%, depending on which model is used as reference. Similar studies to exposure of electric field has been noted in the literature [IARC, 2001; ICNIRP, 1998; ICNIRP, 2010; WHO, 2007], where the electric field is perturbed by the object (human body) when placed in an unperturbed electric field. This can be seen in *Figure 5.11* below.

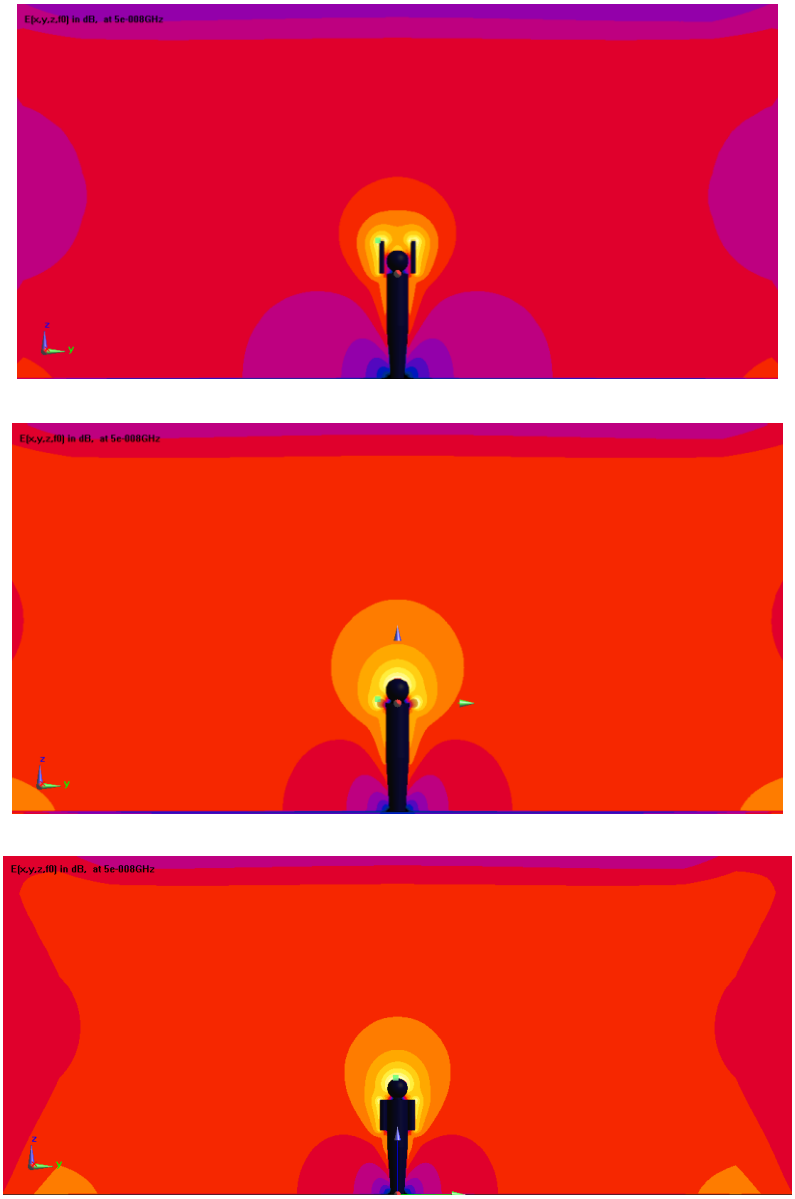


Figure 5.11: Electric field comparison (Top: Arms raised above the head; Middle: Hands raised in-front of the body; Bottom: Arms at the side of the body)

The comparison of the results with existing data found in the literature provided a partial validation of the modelling. In particular, the obtained values are reasonably close to existing data (differences rarely exceed 50%) and the largest differences can be at least partly explained by known features of the models, like size effects. However, this analysis highlights the difficulties in comparing different models and methods. The development of methods to handle this complexity is a major challenge in numerical dosimetry.

5.6 Conclusions

In this section, a formulation and a geometrical model of the human body is presented, which together allow computing in-situ electric field and current density induced in the human body by low-frequency electric fields. These computations using CDEGS and SEMCAD X have been compared to the literature and a good agreement is shown.

CHAPTER 6: HUMAN EXPOSURE TO A 765 kV POWER LINE: A CASE STUDY - MEASUREMENTS

An electric field is discussed in detail as well as the measurement procedures to be followed as per international standards to measure the ground level electric fields. The measured electric field of a typical 765 kV transmission line case study have been presented and predictions using the Eskom monitoring system to measure the line parameters have been discussed.

6.1 Introduction

The case study makes reference to the general public exposure to electric and magnetic fields being produced by Eskom's new 765 kV transmission lines. The study is based on a typical scenario of the general public exposure beneath the Mercury – Zeus 765 kV transmission Line.

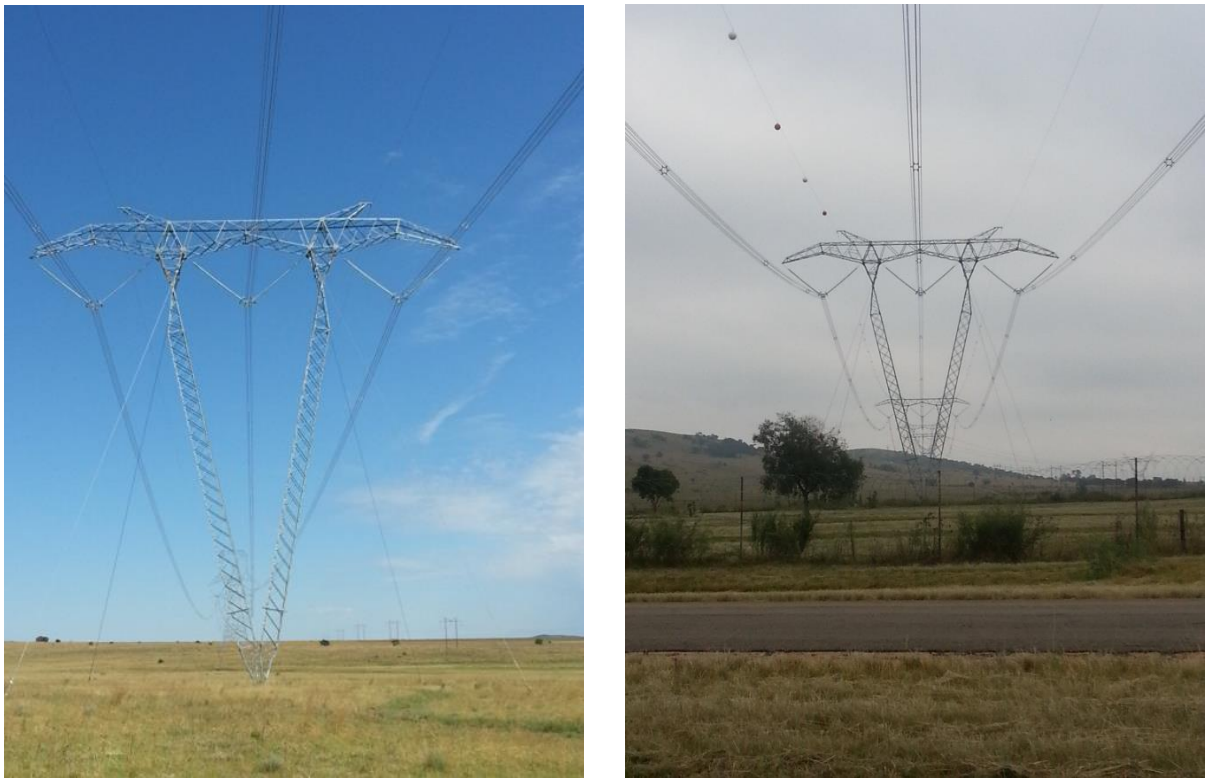


Figure 6.1: Typical tower geometry for the Mercury – Zeus 765 kV transmission line

6.2 Electric Field Discussion and Measurement Procedure

The electric field strength is defined as the electric force per unit charge. It causes displacement of electric charges in conductive objects (including living bodies). Since these fields are alternating, the electric charges move back and forth. This movement results in an 'induced' alternating current, and induced electric field, inside the conductive object or body.

If an object of uniform conductivity is exposed to an electric field, the induced current inside the object will determine how well it will conduct electricity. In contrast, the associated induced electric field strongly depends on the electrical conductivity of the body or object.

An object exposed to an electric field produces an induced current which depends on the following:

a) frequency of the field;
b) shape and size of the conducting object;
c) characteristics (magnitude, polarisation, degree of non-uniformity, etc.) of the unperturbed field; and
d) whether the body is in electrical contact with the ground and near other conducting bodies.

Electric fields are easily disturbed by the presence of objects, even if these objects are poor electrical conductors (trees, fences, vegetation, buildings, etc.). These objects will have a direct influence on the electric field that is being measured. The screening effect affects the magnitude of the field and must be taken into account when an accurate exposure assessment is to be conducted.

The term "unperturbed field", is used to imply one of the following alternate meanings:

- When the environment includes objects, such as trees, furniture and buildings. These objects are normally fixed objects and will affect the electric field. The electric field measurements will incorporate these effects. In these conditions, "unperturbed field" should be understood as a 'field in the absence of movable objects or persons',
- Characterising the EMF from a transmission line implies estimating the electric field distribution in the absence of any local object perturbations. In this case, the

"unperturbed field" is understood to be "an electric field in the absence of any object (movable or not) or persons".

Electric field measurements should normally be performed under unperturbed electric field conditions. This means that all movable objects and living bodies/matter should be at sufficient distance from the electric field probe, unless there is a specific requirement for them to be there, such as occupational exposure in high exposure areas. This was followed in this research by ensuring that all movable objects, as well as the person/s doing the measurements, were kept clear of the electric field probe.

Measurement of the electric fields produced by power systems can be conducted according to the following standards:

- **IEC 62110:** Electric and Magnetic Field Levels Generated by AC Power Systems – Measurement Procedures with regard to Public Exposure;
- **IEEE 644:** Standard Procedures for Measurement of Power Frequency Electric and Magnetic Fields from AC Power Lines.

The standardised procedures have been used in the measurements of the unperturbed electric field beneath a 765 kV transmission line (Mercury - Zeus).

When conducting human exposure to electric field measurements, it is useful to provide a visual representation of the field distribution in the vicinity of the overhead or underground power lines. This is accomplished by taking spot measurements at individual points of interest. However, when measuring electric fields beneath power lines, it is useful to produce a profile of fields' perpendicular to the line.

An aerial view of the measurement area should be given, indicating the line, towers and all the noticeable elements, such as trees, fences, roads, etc. The environment and height of the vegetation should also be recorded, as it can be of importance when measuring and analysing the electric fields. The overhead conductor's height from ground level is important with regard to electric field characterisation and should be measured.

6.2.1 Recording the measurement time

The date and time of the measurement should be recorded. The electric field does not vary much around HV equipment, as it depends on the height of the conductors and the system voltage, which will have small variations present. Therefore, the recording of the precise time of each individual E-field measurement is not needed.

6.2.2 Recording of the environmental factors

Air temperature, wind and the conductor current determine the conductor temperature, which affects the sag and the ground-conductor clearance of the line. As a result, the measured electric field at a particular point may change. As a consequence, it is important to record the weather parameters (temperature, humidity and pressure) and conductor voltage and current, particularly when a comparison to computation or modelling results is to be performed.

6.2.3 Electric field measurement protocol

Limits on human exposure to ELF electric fields are generally quoted in terms of the RMS value of the unperturbed field (i.e., the E-field which would exist at a given location in the absence of living bodies and of movable objects).

When conducting electric field assessments of overhead lines, the measurement location should be flat and free of objects (trees, tall grass, fences, buildings and other irregularities). Lateral profiles, should start from the centre of the power line to a distance as far as possible or as required (normally beyond the servitude boundary). The layout of the area being measured will determine this.

A constant height of the electric field meter probe above ground (1 m) should be used throughout the electric field measurement routine. The field meter probe should be placed on an insulating support. This support should not affect the electric field measurement. The time of the electric field measurements should be recorded so that they can be correlated with the values of the line parameters recorded by the grid operator. Since the electric field generated by the power line voltage fluctuates slowly, an average value of the voltage on the line (averaged over the measurement period) is generally sufficient to be used in the

predictions and can be extrapolated to other higher voltage values and consequently lower phase heights of conductors.

6.3 765 kV Electric and Magnetic Field Site Measurements

Taking note of the Section 6.2 on the procedure for electric field measurements, the following four criteria have been recorded beneath a 765 kV transmission line: site selection, time of measurements, equipment used for measurements, and electric field measurements.

6.3.1 Measurement Site selection

The site selection criterion used to conduct the electric field measurements was through a customer complaint. The customer requested that electric and magnetic fields be measured from the Mercury – Zeus 765 kV transmission line adjacent to the property occupied by his family. It must be noted that the phase conductor heights could vary along the line. But at the point of measurement, the phase heights were measured, so that predictions could be used to confirm the measurements with system data. Measurements were conducted beneath the existing 765 kV transmission line (Mercury – Zeus) (see *Figure 6.2* for the area of measurement (Indicated by the red arrow)).

Figure 6.2 indicates the following: the purple line is the Mercury – Zeus 765 kV transmission line, the blue lines are the 88 kV distribution lines and the green lines the 11 kV distribution network respectively. The dotted green lines are access roads. The purple dot represents tower 201. The measurements were conducted at mid-span between towers 201 and 202.

6.3.2 Time of measurement and environmental parameters

EMF measurements were conducted on the 20 February 2013 between 08h30 and 10h30 and again on the 25 February 2013 between 08h47 and 09h30 as electric field measurements were problematic on the 20 February 2013. The weather conditions were fair and warm on both days. The temperature was 15°C and the relative humidity was 60%.

6.3.3 Equipment used for measurements

A NARDA ELF exposure system (Serial No: K-0044) was used to measure both the electric and magnetic fields, with the relevant measuring probes (see Appendix A for the full set of

measurements and Appendix B for specifications of the measurement equipment). The measurement probes were positioned 1 m above ground for both the electric and magnetic field measurements conducted.

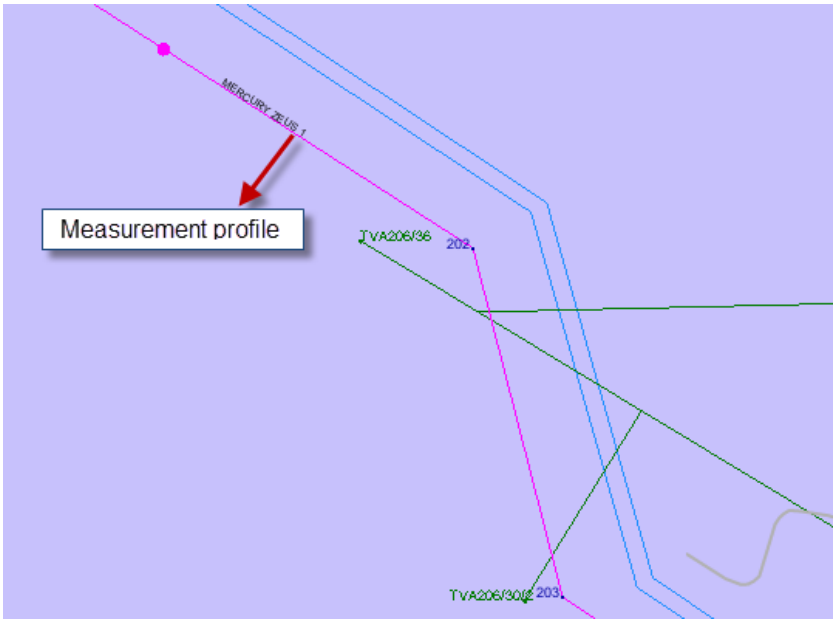


Figure 6.2: Lateral half profile (red arrow) indicating area of measurement beneath the Mercury – Zeus 765 kV transmission line (TXSIS)

6.3.4 Electric field measurements

The maximum recorded electric and magnetic fields were measured beneath the 765 kV transmission line (see Appendix A for complete set of measurements). *Table 6.1* presents the maximum electric and magnetic fields measured beneath the Mercury-Zeus 765 kV transmission line at the area of measurement.

Table 6.1: Maximum electric and magnetic fields measured: Mercury – Zeus Line

	MERCURY – ZEUS 765 kV LINE	
	20/2/2013	25/2/2013
ELECTRIC FIELD (kV/m)	-	5.53
MAGNETIC FIELD (μT)	4.48	6.50

The system parameters (load, currents and voltage) during the time of measurement are shown in *Figure 6.3* (20/2/2013) and *Figure 6.4* (25/2/2013), obtained from the Eskom Transmission Energy Management System (TEMSE). These recordings are a five minute average for the time of measurement.

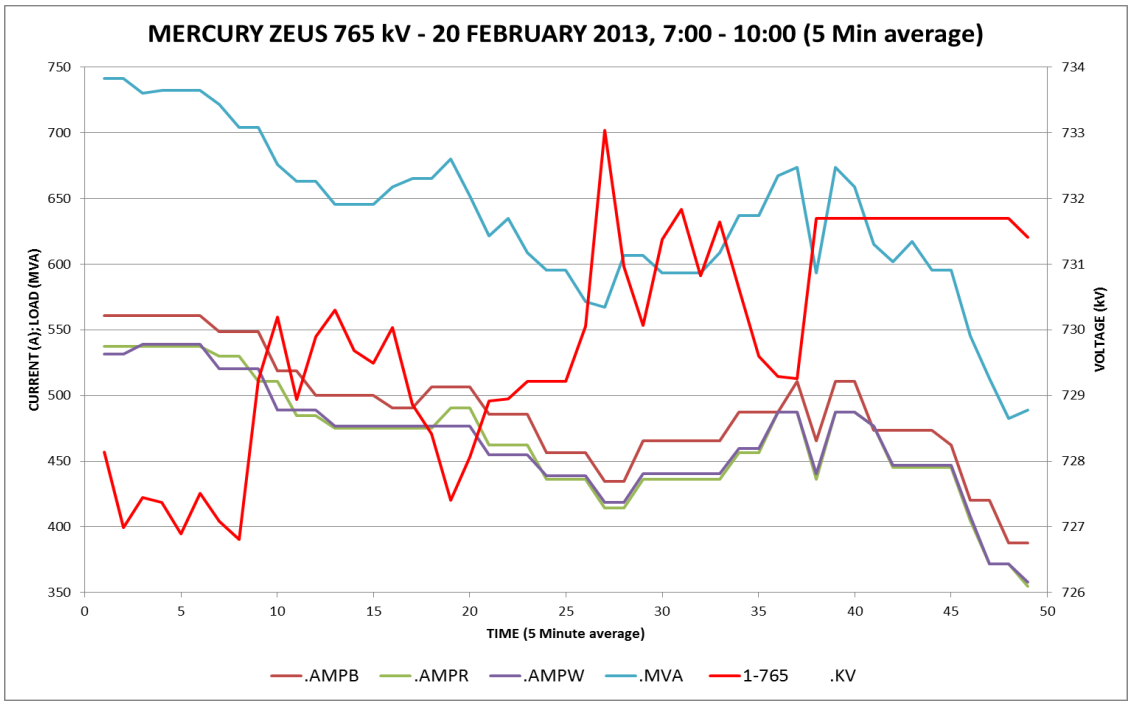


Figure 6.3: Mercury – Zeus 765 kV transmission line system parameters – 20/2/2013

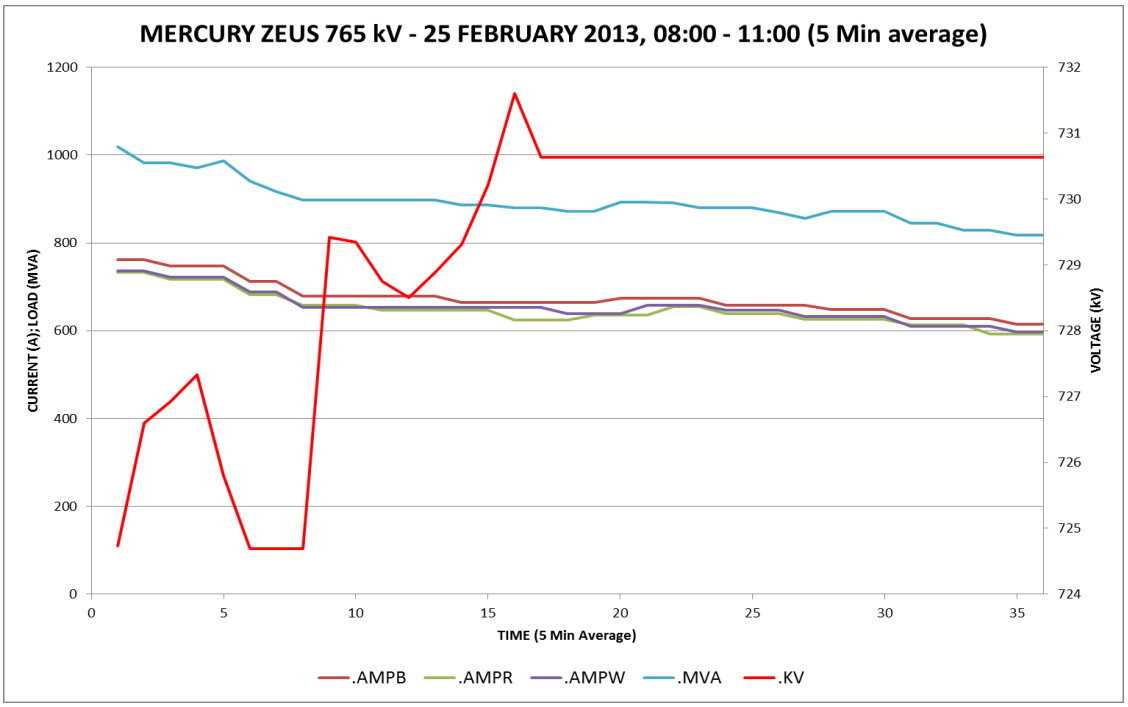


Figure 6.4: Mercury – Zeus 765 kV transmission line system parameters – 25/2/2013

6.4 Comparison of the Measurements to the Predictions

From *Figures 6.3 and 6.4* it can be noted that the load was largest on the 25 February 2013. The predictions of the electric fields beneath the Mercury – Zeus 765 kV transmission line used heights of the three phase conductors of 20.19 m, 20.45 m and 20.37 m respectively from left to right. The height variation is due to the slope of the ground beneath the existing Mercury – Zeus 765 kV transmission line, where the measurements were taken. *Table 6.2* below shows the line design parameter used in the predictions.

Table 6.2: System parameters of the 765 kV transmission line used for predictions

PARAMETER	**UNIT**
Phase Conductor	Tern
Number of Conductors per Phase	6
Earth Resistivity	100 Ω-m
Electric Field Computed and Measurement Height	1 m
Phase rotation (left to right)	0°, 120°, 240°

Figure 6.5 below shows the measured (brown) electric fields for half lateral profile of the Mercury - Zeus 765 kV transmission line. The measured positive (red) and negative (green) instrument error are also shown. The predicted (blue) electric fields used in this dissertation were conducted using the SES-EnvioPlus module of the CDEGS software package and are also presented in *Figure 6.5* for comparison. The electric fields were predicted, using a system voltage of 730 kV (average from TEMSE system shown in *Figures 6.3 and 6.4*) phase-to-phase voltages.

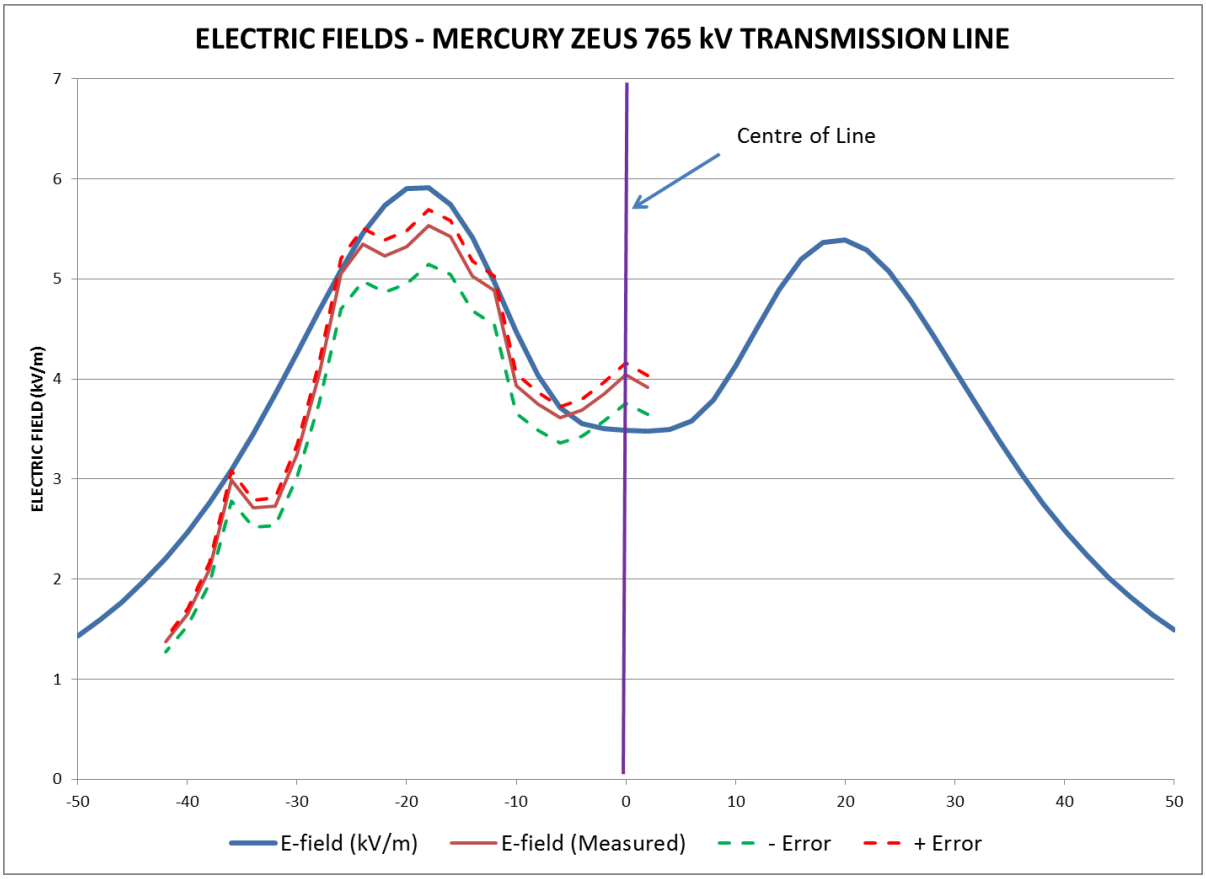


Figure 6.5: Electric fields: Mercury – Zeus 765 kV transmission line (25/2/2013) (computed vs measured)

From *Figure 6.5* above, the measured and predicted electric fields were seen to be similar in value. This gives confidence in what was measured at the site in relation to the predictions performed. The measured electric fields are only done for a half profile, as this is what is called for in the measurements standards. If need be, the profile can be duplicated on the other side, as this is a flat horizontal structure.

The difference in alignment is due to the uneven terrain (farm area) beneath the transmission line where the measurements were conducted.

6.5 Conclusion

The measured electric fields at the measurements site have been presented and compared to predictions using CDEGS. The Mercury – Zeus 765 kV line design parameters were used to compare the measured to predicted electric fields. A good agreement is shown. The electric fields have been used in Chapter 7, to conduct the human model dosimetry of the virtual family models [Christ et al., 2007].

CHAPTER 7: HUMAN EXPOSURE TO A 765 kV POWER LINE: EVALUATED THROUGH 3D ANATOMICAL DOSIMETRY

The 3D anatomical models used in the dissertation are presented and discussed. Simple models have also been presented, as these are used for clarification of reduction in internal field within the human body. The results obtained from the use of SEMCAD X software based on FDTD and the 3D anatomical models are also presented and compared to the international guidelines and standards where the comparisons are discussed.

7.1 Introduction

The case studies used in this dissertation make use of four anatomical models (Duke, Ella, Billie and Thelonious) from the virtual family model [Christ et al., 2007] supplied by the IT'IS foundation. The Electro-Quasi-Static (EQS) approximations were performed in this study using a voxel size of 4 x 4 x 4 mm. This is due to the memory constraints of the computer, as well as for each model used.

This dissertation presents the data obtained from the four human models, with verification of the fields (see Chapters 3, 5 and 6) and anatomical model verification, based on Duke (see Chapter 5).

The virtual family models from IT'IS are shown in *Figure 7.1* and the specifications of each are shown in *Table 7.1*.

Virtual Family models. From left to right: Duke, Ella, Billie, Thelonious, Louis, Eartha, Dizzy and Roberta.



Figure 7.1: IT'IS 3D-Anatomical models available [Christ et al., 2007]

Table 7.1: Virtual model specifications [Christ et al., 2007]

Name	Gender	Age (years)	Height (m)	Mass (kg)	BMI (kg/m^2)
Duke	Male	34	1.77	72	23.1
Ella	Female	26	1.63	59	22.0
Billie	Female	11	1.47	35	16.5
Thelonious	Male	6	1.17	19	14.0
Louis	Male	14	1.69	50	17.7
Eartha	Female	8	1.36	31	16.7
Dizzy	Male	8	1.39	26	13.4
Roberta	Female	5	1.09	18	14.9

Computations of the EQS approximations were performed on each human model of the virtual family (see *Figure 7.2*). The in-situ electric field and the current densities for each model were calculated and are presented in this chapter.

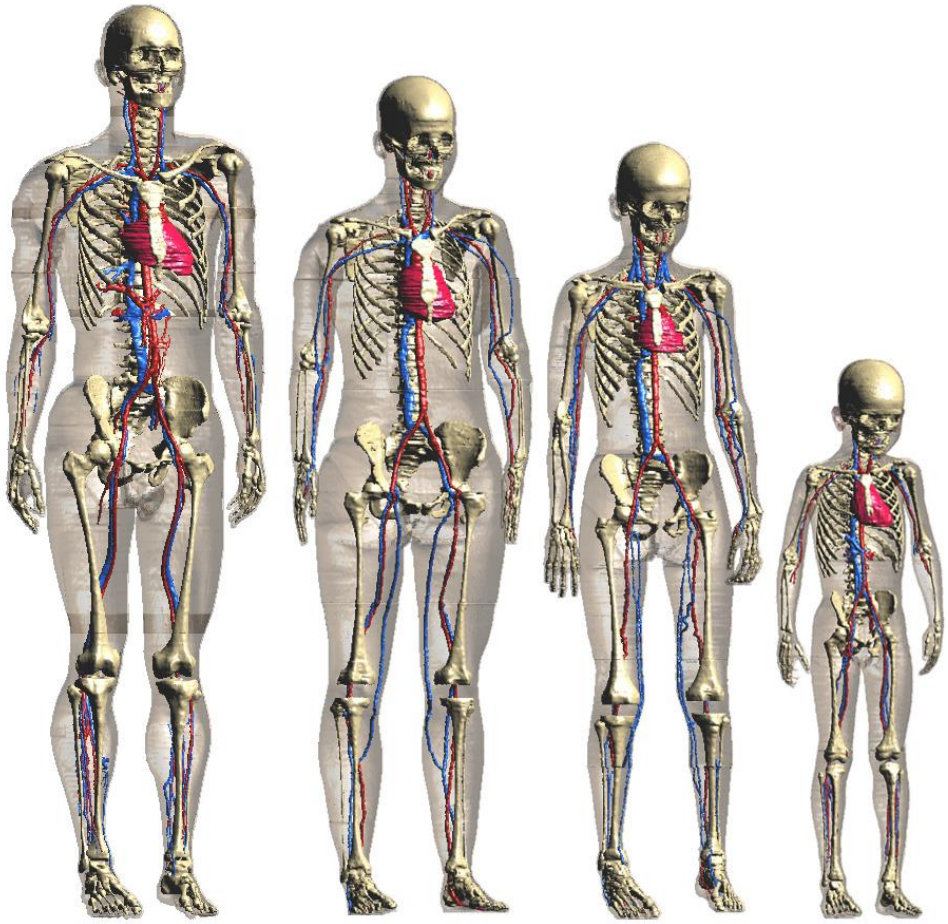


Figure 7.2: Anatomical models used: Duke, Ella, Billie and Thelonious [Christ et al., 2007]

Figure 7.3 shows Thelonious with the various internal organs that are included in the 3D anatomical model used in the modelling of the in-situ electric fields and current densities within the human body. The other models, Duke, Ella and Billie have the same internal organs, but have different shapes and sizes.

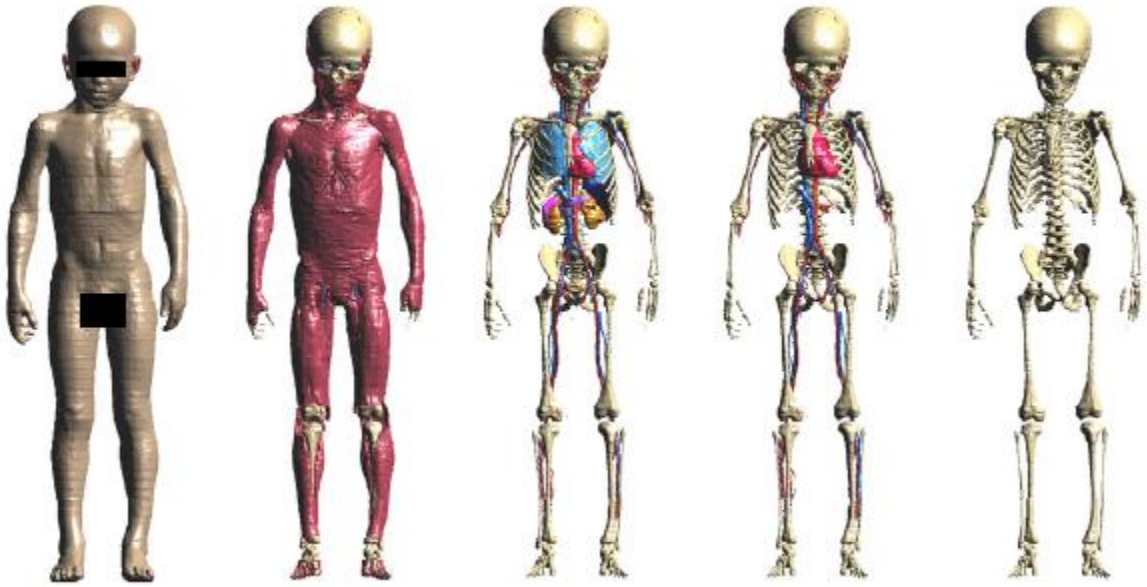


Figure 7.3: Thelonious: skin, muscle, inner organs, blood vessels, skeleton [Christ et al., 2007]

7.2 Analysis of Geometry Shapes

The most evident physical difference that arises in the human body anatomy definition is the difference of the geometry of one subject to another. The comparison of the results found in the literature [Gabriel et al., 1996; ICNIRP, 2001; Polk & Postow, 1996] provides a partial validation of the modelling. In particular, the obtained values are reasonably close to existing data (differences rarely exceed 50%) and the largest differences can be at least partly explained by known features of the models, like size and position effects. However, this analysis highlights the difficulties in comparing different models and methods. Discretization and post processing are likely to play a negligible role.

7.3 Dosimetry Model Set-up and Explanation

The dosimetry prediction model used in this dissertation makes use of the transmission line parameters from Chapter 6. The human model is placed in the electric field below the outer conductor of the 765 kV transmission line facing the conductors, energised at 730 kV, in an electric field of approximately 6 kV/m at 1 m from ground level (see *Figure 7.4* for the model layout). The expanded view of the human body is shown as an insert on *Figure 7.4* as the human body position. A ground plane has been modelled in all predictions for the electric field dosimetry. It was removed for the anatomical dosimetry of the electric field model cases

for computing the floating position of the human body. The electric field modelling results presented consist of a floating body and a grounded body beneath the 765 kV transmission line.

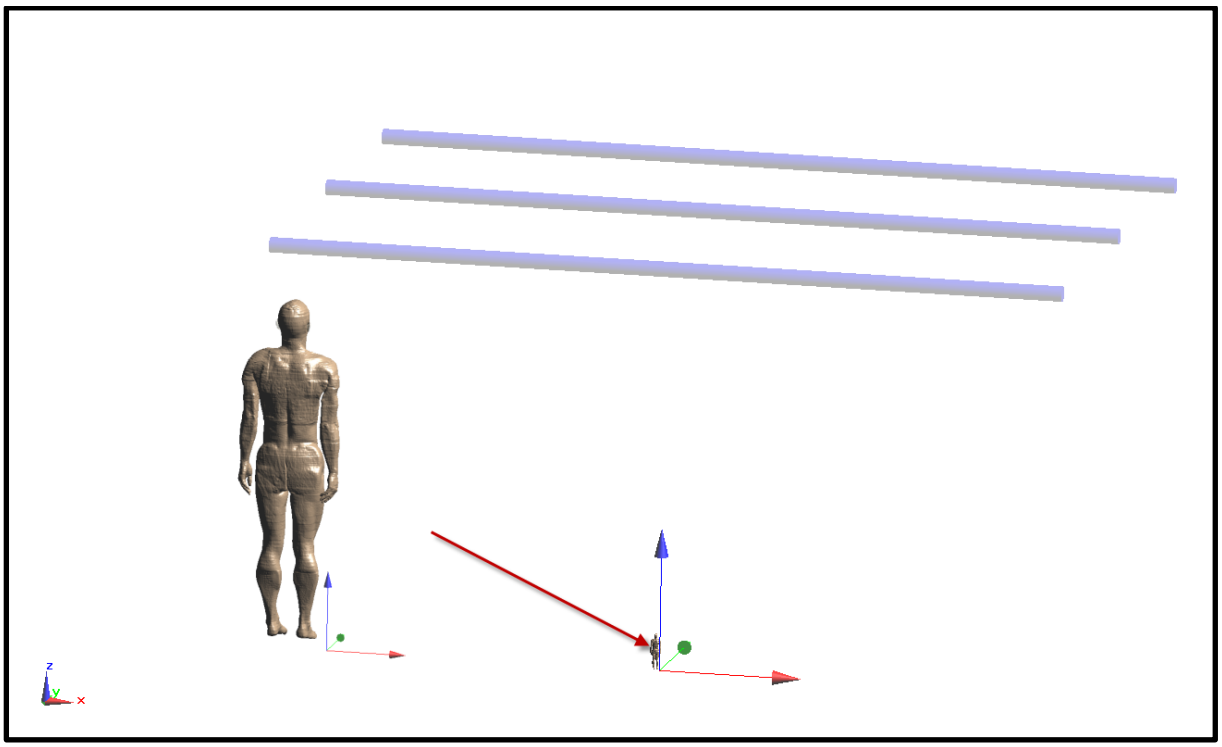


Figure 7.4: Model set-up used for the anatomical modelling of human exposed to 765 kV transmission line

The EQS dosimetry was performed on each model of the virtual family (Duke, Ella, Billie and Thelonious). The in-situ electric field (V/m) and the current densities (A/m^2) for each model were calculated.

Figure 7.5 shows the internal organs of the human body used in the dosimetry, to conduct the comparison of the in-situ electric field and current densities to the ICNIRP guidelines [ICNIRP, 1998, ICNIRP, 2010] and IEEE [IEEE, 2002] basic restrictions. This is done, as the Reference Level (5 kV/m) has been exceeded and through dosimetry it needs to be evaluated whether the Basic Restrictions are not exceeded.

From the four human models used from the virtual family (Duke, Ella, Billie and Thelonious), the RMS moduli of the individual body parts are presented and discussed.

Three scenarios were modelled using a system voltage of 765 kV (phase to phase):

- Human body floating, that is, body placed above ground with no contact with the ground plane,

- Human body on a perfect ground plane, that is, perfect ground plane is a zero resistivity plane,
- Human body on a ground plane with an earth resistivity of 100 ohm-meters.

The 100 ohm-meters ground resistivity was chosen, as this is close to a perfect ground plane (zero resistivity). The importance of the above scenarios is to show that the placement of the human body in relation to the ground plays an important part in showing compliance with the Basic Restriction for both the ICNIRP guidelines [ICNIRP, 1998, ICNIRP, 2010] and the IEEE standard [IEEE, 2002].

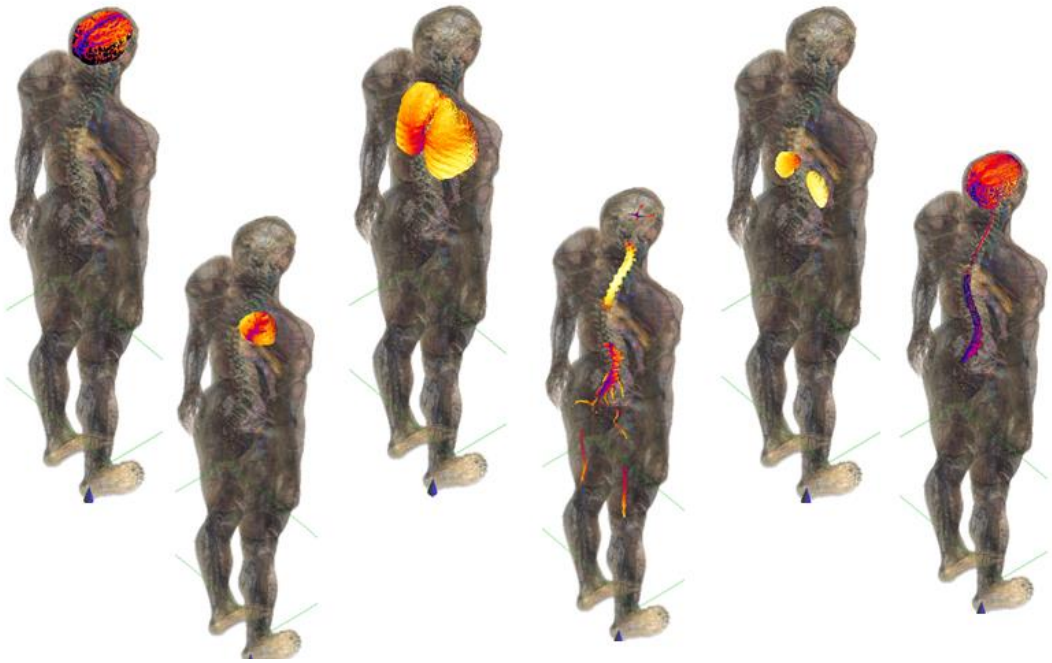


Figure 7.5: Internal organs (Duke) of the 3D-anatomical body used for comparison with the basic restrictions of ICNIRP from left to right (brain, heart, lungs, nerves, kidneys and cerebrospinal fluid)

7.4 Dosimetry Results and Discussions

In this section the dosimetry performed through computations on the human models beneath the Mercury Zeus 765 kV line are presented. Comparisons with the Basic Restrictions of the ICNIRP 1998 and ICNIRP 2010 guidelines as well as the IEEE C95.6 standard are presented.

The current density [ICNIRP, 1998] and in-situ electric field [ICNIRP, 2010] for the general public exposures are 2 mA/m^2 and 20 mV/m, respectively. The IEEE C95.6 [IEEE, 2002]

Basic Restriction is 14.73 mV/m for the brain, 943 mV/m for the heart, and 2.1 V/m for the hands, wrist, feet and ankles.

The dosimetry results for each of the human models (Duke, Ella, Billie and Thelonious) are presented below. Each sub-section will present the following:

a) compliance with the ICNIRP 1998 guideline (current density);
b) compliance with the ICNIRP 2010 guideline (in-situ electric field); and
c) compliance with the IEEE C95.6 standard (in-situ electric field).

The error of margin from the dosimetry when compared with existing data found in the literature provided a partial validation of the modelling. In particular, the obtained values are reasonably close to existing data (differences rarely exceed 50%) [WHO, 2007]. Differences can be partly explained by known features of the models, like size effects and placement of the internal organs. However, this analysis highlights the difficulties in comparing different models and methods. The development of an adapted method to handle this complexity is a major challenge in numerical dosimetry.

7.4.1 Duke

A. ICNIRP 1998 – Duke.

The ICNIRP 1998 [ICNIRP, 1998] guideline defines a Basic Restriction of 2 mA/m^2 for the general public' which needs to be complied with through dosimetry. *Table 7.2* shows the compliance for the body floating, *Table 7.3* shows for the body perfectly grounded and *Table 7.4* shows for the body grounded on a 100 ohm-meter ground resistivity.

Table 7.2: Duke - Basic Restriction compliance to the ICNIRP 1998 guideline – Human body floating

BODY ORGAN	J (x,y,z,f0) Surface Average [ICNIRP 1998] (A/m^2)	COMPLIANCE TO ICNIRP 1998 GUIDELINE (2 mA/m^2)
Cornea	1.45E-07	Comply
Nerves	5.91E-08	Comply
Cerebrospinal fluid	1.46E-06	Comply
Heart (lumen + muscle)	2.98E-07	Comply
Kidney (cortex + medulla)	7.76E-08	Comply
Lungs	7.92E-08	Comply
Brain (grey + white matter)	1.33E-07	Comply

Table 7.3: Duke - Basic Restriction compliance to the ICNIRP 1998 guideline – Human body perfectly grounded

BODY ORGAN	J (x,y,z,f0) Surface Average [ICNIRP 1998] (A/m^2)	COMPLIANCE TO ICNIRP 1998 GUIDELINE ($2\ mA/m^2$)
Cornea	1.41E-03	Comply
Nerves	1.93E-03	Comply
Cerebrospinal fluid	2.49E-02	**Exceed**
Heart (lumen + muscle)	6.84E-03	**Exceed**
Kidney (cortex + medulla)	2.10E-03	**Exceed**
Lungs	2.09E-03	**Exceed**
Brain (grey + white matter)	1.62E-03	Comply

Table 7.4: Duke - Basic Restriction compliance to the ICNIRP 1998 guideline – Human Body on Ground of 100 ohm-meter

BODY ORGAN	J (x,y,z,f0) Surface Average [ICNIRP 1998] (A/m^2)	COMPLIANCE TO ICNIRP 1998 GUIDELINE ($2\ mA/m^2$)
Cornea	6.94E-08	Comply
Nerves	3.20E-07	Comply
Cerebrospinal fluid	4.12E-06	Comply
Heart (lumen + muscle)	8.34E-07	Comply
Kidney (cortex + medulla)	2.77E-07	Comply
Lungs	2.55E-07	Comply
Brain (grey + white matter)	6.60E-08	Comply

From the dosimetry, it can be noted that the exceeding the Basic Restriction is only present in the comparison of the ICNIRP 1998 guideline ($2\ mA/m^2$) where Duke is placed on a perfect ground plane (0 ohm-meter). When the ground is modelled with a more realistic value (100 ohm-metre), compliance with the Basic Restriction is shown.

B. ICNIRP 2010 – Duke.

The ICNIRP 2010 [ICNIRP 2010] guideline defines a Basic Restriction of 20 mV/m for the general public, which needs to be complied with through dosimetry. *Table 7.5* shows for the compliance for the body floating, *Table 7.6* shows for the body perfectly grounded and *Table 7.7* shows the body grounded on a 100 ohm-meter ground resistivity.

Table 7.5: Duke - Basic Restriction compliance to the ICNIRP 2010 guideline – Human body floating

BODY ORGAN	E(x,y,z,f0) Volume-Average [ICNIRP 2010] (V/m)	COMPLIANCE TO ICNIRP 2010 GUIDELINE (20 mV/m)
Cornea	5.31E-07	Comply
Nerves	3.14E-06	Comply
Cerebrospinal fluid	8.82E-07	Comply
Heart (lumen + muscle)	1.86E-06	Comply
Kidney (cortex + medulla)	1.00E-06	Comply
Lungs	1.36E-06	Comply
Brain (grey + white matter)	2.61E-06	Comply

Table 7.6: Duke - Basic Restriction compliance to the ICNIRP 2010 guideline – Human body perfectly grounded

BODY ORGAN	E(x,y,z,f0) Volume-Average [ICNIRP 2010] (V/m)	COMPLIANCE TO ICNIRP 2010 GUIDELINE (20 mV/m)
Cornea	3.73E-03	Comply
Nerves	8.17E-02	**Exceed**
Cerebrospinal fluid	1.38E-02	Comply
Heart (lumen + muscle)	5.03E-02	**Exceed**
Kidney (cortex + medulla)	2.80E-02	**Exceed**
Lungs	3.41E-02	**Exceed**
Brain (grey + white matter)	2.72E-02	**Exceed**

Table 7.7: Duke - Basic Restriction compliance to the ICNIRP 2010 guideline – Human body on ground of 100 ohm-meter

BODY ORGAN	E(x,y,z,f0) Volume-Average [ICNIRP 2010] (V/m)	COMPLIANCE TO ICNIRP 2010 GUIDELINE (20 mV/m)
Cornea	2.22E-07	Comply
Nerves	1.37E-05	Comply
Cerebrospinal fluid	2.06E-06	Comply
Heart (lumen + muscle)	5.93E-06	Comply
Kidney (cortex + medulla)	3.52E-06	Comply
Lungs	4.25E-06	Comply
Brain (grey + white matter)	1.33E-06	Comply

From the dosimetry, it can be noted that exceeding of the Basic Restriction is only present in the comparison of the ICNIRP 2010 guideline (20 mV/m) where Duke is placed on a

perfect ground plane (0 ohm-meter). When the ground is modelled with a more realistic value (100 ohm-meter), compliance with the Basic Restriction is shown.

C. IEEE C95.6 - Duke.

The IEEE C95.6 [IEEE 2002] standard defines a Basic Restriction of 14.73 mV/m for the brain, 943 mV/m for the heart and 2.1 V/m for the hands, wrists, feet and ankles. The standard needs to be complied with through dosimetry. *Table 7.8* shows the compliance for the body floating, *Table 7.9* shows for the body perfectly grounded, and *Table 7.10* shows the body grounded on a 100 ohm-meter ground resistivity.

Table 7.8: Duke - Basic Restriction compliance to the IEEE C95.6 standard – Human body floating

BODY ORGAN	E(x,y,z,f0) Line-Average [IEEE C95.6-2002] (V/m)	COMPLIANCE TO IEEE C95.6 STANDARD
Cornea	3.75E-07	Comply
Nerves	2.87E-06	Comply
Cerebrospinal fluid	8.78E-07	Comply
Heart (lumen + muscle)	1.70E-06	Comply
Kidney (cortex + medulla)	9.58E-07	Comply
Lungs	1.36E-06	Comply
Brain (grey + white matter)	2.34E-06	Comply

Table 7.9: Duke - Basic Restriction compliance to the IEEE C95.6 standard – Human body perfectly grounded

BODY ORGAN	E(x,y,z,f0) Line-Average [IEEE C95.6-2002] (V/m)	COMPLIANCE TO IEEE C95.6 STANDARD
Cornea	3.73E-03	Comply (943 mV/m)
Nerves	8.12E-02	Comply (943 mV/m)
Cerebrospinal fluid	1.19E-02	Comply (14.73 mV/m)
Heart (lumen + muscle)	4.65E-02	Comply (943 mV/m)
Kidney (cortex + medulla)	2.40E-02	Comply (943 mV/m)
Lungs	3.41E-02	Comply (943 mV/m)
Brain (grey + white matter)	2.55E-02	**Exceed (14.73 mV/m)**

Table 7.10: Duke - Basic Restriction compliance to the IEEE C95.6 standard – Human body on ground of 100 ohm-meter

BODY ORGAN	E(x,y,z,f0) Line-Average [IEEE C95.6-2002] (V/m)	COMPLIANCE TO IEEE C95.6 STANDARD
Cornea	2.21E-07	Comply (943 mV/m)
Nerves	1.26E-05	Comply (943 mV/m)
Cerebrospinal fluid	2.06E-06	Comply (14.73 mV/m)
Heart (lumen + muscle)	5.60E-06	Comply (943 mV/m)
Kidney (cortex + medulla)	3.21E-06	Comply (943 mV/m)
Lungs	4.25E-06	Comply (943 mV/m)
Brain (grey + white matter)	1.21E-06	Comply (14.73 mV/m)

From the dosimetry it can be noted that excess of the Basic Restriction is only present in the comparison of the IEEE C95.6 standard, where the brain is shown to exceed the Basic Restriction (14.73 mV/m) when Duke is placed on a perfect ground plane (0 ohm-meter). When the ground is modelled with a more realistic value (100 ohm-meter), the compliance with the Basic Restriction is shown.

7.4.2 Ella

A. *ICNIRP 1998 – Ella.*

The ICNIRP 1998 [ICNIRP, 1998] guideline defines a Basic Restriction of 2 mA/m^2 for the general public, which needs to be complied with through dosimetry. *Table 7.11* shows the compliance for the body floating, *Table 7.12* shows for the body perfectly grounded and *Table 7.13* shows the body grounded on a 100 ohm-meter ground resistivity.

Table 7.11: Ella - Basic Restriction compliance to the ICNIRP 1998 guideline – Human body floating

BODY ORGAN	J (x,y,z,f0) Surface Average [ICNIRP 1998] (A/m^2)	COMPLIANCE TO ICNIRP 1998 GUIDELINE (2 mA/m^2)
Cornea	6.36E-06	Comply
Nerves	5.02E-06	Comply
Cerebrospinal fluid	2.53E-04	Comply
Heart (lumen + muscle)	2.95E-05	Comply
Kidney (cortex + medulla)	5.99E-06	Comply
Lungs	1.13E-05	Comply
Brain (grey + white matter)	9.53E-06	Comply

Table 7.12: Ella - Basic Restriction compliance to the ICNIRP 1998 guideline – Human body perfectly grounded

TISSUE	J (x,y,z,f0) Surface Average [ICNIRP 1998] (A/m^2)	COMPLIANCE TO ICNIRP 1998 GUIDELINE ($2\ mA/m^2$)
Cornea	6.77E-05	Comply
Nerves	7.32E-05	Comply
Cerebrospinal fluid	3.16E-03	**Exceed**
Heart (lumen + muscle)	3.89E-04	Comply
Kidney (cortex + medulla)	8.33E-05	Comply
Lungs	1.56E-04	Comply
Brain (grey + white matter)	1.08E-04	Comply

Table 7.13: Ella - Basic Restriction compliance to the ICNIRP 1998 guideline – Human body on ground of 100 ohm-meter

BODY ORGAN	J (x,y,z,f0) Surface Average [ICNIRP 1998] (A/m)	COMPLIANCE TO ICNIRP 1998 GUIDELINE ($2\ mA/m^2$)
Cornea	5.19E-05	Comply
Nerves	5.42E-05	Comply
Cerebrospinal fluid	1.72E-03	Comply
Heart (lumen + muscle)	2.99E-04	Comply
Kidney (cortex + Medulla)	6.54E-05	Comply
Lungs	1.20E-04	Comply
Brain (Grey + white matter)	7.45E-05	Comply

From the dosimetry it can be noted that the excess of the Basic Restriction is only present in the comparison of the ICNIRP 1998 guideline, where the cerebrospinal fluid has shown excess of the Basic Restriction ($2\ mA/m^2$) where Ella is placed on a perfect ground plane (0 ohm-metre). When the ground is modelled with a more realistic value (100 ohm-metre), compliance with the Basic Restriction is shown.

B. *ICNIRP 2010 - Ella*

The ICNIRP 2010 [ICNIRP, 2010] guideline defines a Basic Restriction of 20 mV/m for the general public which needs to be complied with through dosimetry. *Table 7.14* shows for the compliance for the body floating, *Table 7.15* shows for the body perfectly grounded and *Table 7.16* shows for the body grounded on a 100 ohm-meter ground resistivity.

Table 7.14: Ella - Basic Restriction compliance to the ICNIRP 2010 guideline – Human body floating

BODY ORGAN	E(x,y,z,f0) Volume-Average [ICNIRP 2010] (V/m)	COMPLIANCE TO ICNIRP 2010 GUIDELINE (20 mV/m)
Cornea	1.51E-05	Comply
Nerves	1.94E-04	Comply
Cerebrospinal fluid	1.47E-04	Comply
Heart (lumen + muscle)	1.67E-04	Comply
Kidney (cortex + medulla)	7.24E-05	Comply
Lungs	1.75E-04	Comply
Brain (grey + white matter)	1.43E-04	Comply

Table 7.15: Ella - Basic Restriction compliance to the ICNIRP 2010 guideline – Human body perfectly grounded

BODY ORGAN	E(x,y,z,f0) Volume-Average [ICNIRP 2010] (V/m)	COMPLIANCE TO ICNIRP 2010 GUIDELINE (20 mV/m)
Cornea	1.61E-04	Comply
Nerves	2.90E-03	Comply
Cerebrospinal fluid	1.58E-03	Comply
Heart (lumen + muscle)	2.24E-03	Comply
Kidney (cortex + medulla)	9.58E-04	Comply
Lungs	2.38E-03	Comply
Brain (grey + white matter)	1.77E-03	Comply

Table 7.16: Ella - Basic Restriction compliance to the ICNIRP 2010 guideline – Human body on ground of 100 ohm-meter

BODY ORGAN	E(x,y,z,f0) Volume-Average [ICNIRP 2010] (V/m)	COMPLIANCE TO ICNIRP 2010 GUIDELINE (20 mV/m)
Cornea	1.23E-04	Comply
Nerves	2.29E-03	Comply
Cerebrospinal fluid	9.00E-04	Comply
Heart (lumen + muscle)	1.87E-03	Comply
Kidney (cortex + medulla)	7.86E-04	Comply
Lungs	1.86E-03	Comply
Brain (grey + white matter)	1.12E-03	Comply

From the dosimetry, it can be noted, that Ella complies with the Basic Restriction as defined in the ICNIRP 2010 guideline (20 mV/m).

C. *IEEE C95.6 - Ella*

The IEEE C95.6 [IEEE, 2002] standard defines a Basic Restriction of 14.73 mV/m for the brain, 943 mV/m for the heart and 2.1 V/m for the hands, wrists, feet and ankles. The standard needs to be complied with through dosimetry. *Table 7.17* shows for the compliance for the body floating, *Table 7.18* shows for the body perfectly grounded and *Table 7.19* shows for the body grounded on a 100 ohm-meter ground resistivity.

Table 7.17: Ella - Basic Restriction compliance to the IEEE C95.6 standard – Human body floating

BODY ORGAN	E(x,y,z,f0) Line-Average [IEEE C95.6-2002] (V/m)	COMPLIANCE TO IEEE C95.6 STANDARD
Cornea	1.51E-05	Comply (943 mV/m)
Nerves	1.92E-04	Comply (943 mV/m)
Cerebrospinal fluid	1.30E-04	Comply (14.73 mV/m)
Heart (lumen + muscle)	1.43E-04	Comply (943 mV/m)
Kidney (cortex + medulla)	6.96E-05	Comply (943 mV/m)
Lungs	1.70E-04	Comply (943 mV/m)
Brain (grey + white matter)	1.42E-04	Comply (14.73 mV/m)

Table 7.18: Ella - Basic Restriction compliance to the IEEE C95.6 standard – Human body perfectly grounded

BODY ORGAN	E(x,y,z,f0) Line-Average [IEEE C95.6-2002] (V/m)	COMPLIANCE TO IEEE C95.6 STANDARD
Cornea	1.61E-04	Comply (943 mV/m)
Nerves	2.90E-03	Comply (943 mV/m)
Cerebrospinal fluid	1.35E-03	Comply (14.73 mV/m)
Heart (lumen + muscle)	1.93E-03	Comply (943 mV/m)
Kidney (cortex + medulla)	9.54E-04	Comply (943 mV/m)
Lungs	2.35E-03	Comply (943 mV/m)
Brain (grey + white matter)	1.77E-03	Comply (14.73 mV/m)

Table 7.19: Ella - Basic Restriction compliance to the IEEE C95.6 standard – Human body on ground of 100 ohm-meter

BODY ORGAN	E(x,y,z,f0) Line-Average [IEEE C95.6-2002] (V/m)	COMPLIANCE TO IEEE C95.6 STANDARD
Cornea	1.23E-04	Comply (943 mV/m)
Nerves	2.29E-03	Comply (943 mV/m)
Cerebrospinal fluid	9.00E-03	Comply (14.73 mV/m)
Heart (lumen + muscle)	1.65E-03	Comply (943 mV/m)
Kidney (cortex + medulla)	7.55E-04	Comply (943 mV/m)
Lungs	1.82E-03	Comply (943 mV/m)
Brain (grey + white matter)	1.11E-03	Comply (14.73 mV/m)

From the dosimetry it can be noted that Ella complies with the Basic Restriction as defined in the IEEE C95.6 standard (2 mA/m^2).

7.4.3. Billie

A. ICNIRP 1998 - Billie.

The ICNIRP 1998 [ICNIRP, 1998] guideline defines a Basic Restriction of 2 mA/m^2 for the gen^{e}ral public, which needs to be complied with through dosimetry. *Table 7.20* shows for the compliance for the body floating, *Table 7.21* shows for the body perfectly grounded and *Table 7.22* shows for the body grounded on a 100 ohm-meter ground resistivity.

Table 7.20: Billie - Basic Restriction compliance to the ICNIRP 1998 guideline – Human body floating

BODY ORGAN	J (x,y,z,f0) Surface Average [ICNIRP 1998] (A/m^2)	COMPLIANCE TO ICNIRP 1998 GUIDELINE (2 mA/m^2)
Cornea	4.71E-06	Comply
Nerves	9.29E-06	Comply
Cerebrospinal fluid	1.96E-04	Comply
Heart (lumen + muscle)	3.09E-05	Comply
Kidney (cortex + medulla)	7.56E-06	Comply
Lungs	1.09E-05	Comply
Brain (grey + white matter)	7.84E-06	Comply

Table 7.21: Billie - Basic Restriction compliance to the ICNIRP 1998 guideline – Human body perfectly grounded

BODY ORGAN	J (x,y,z,f0) Surface Average [ICNIRP 1998] (A/m^2)	COMPLIANCE TO ICNIRP 1998 GUIDELINE ($2\ mA/m^2$)
Cornea	5.12E-05	Comply
Nerves	3.31E-04	Comply
Cerebrospinal fluid	2.77E-03	**Exceed**
Heart (lumen + muscle)	4.18E-04	Comply
Kidney (cortex + medulla)	1.11E-04	Comply
Lungs	1.58E-04	Comply
Brain (Grey + white matter)	8.28E-05	Comply

Table 7.22: Billie - Basic Restriction compliance to the ICNIRP 1998 guideline – Human body on ground of 100 ohm-meter

BODY ORGAN	J (x,y,z,f0) Surface Average [ICNIRP 1998] (A/m^2)	COMPLIANCE TO ICNIRP 1998 GUIDELINE ($2\ mA/m^2$)
Cornea	3.82E-05	Comply
Nerves	3.10E-04	Comply
Cerebrospinal fluid	1.92E-03	Comply
Heart (lumen + muscle)	3.21E-04	Comply
Kidney (cortex + medulla)	9.02E-05	Comply
Lungs	1.24E-04	Comply
Brain (grey + white matter)	6.33E-05	Comply

From the dosimetry it can be noted that the excess of the Basic Restriction is only present in the comparison of the ICNIRP 1998 guideline, where the cerebrospinal fluid has shown excess of the Basic Restriction ($2\ mA/m^2$) when Billie is placed on a perfect ground plane (0 ohm-meter). When the ground is modelled with a more realistic value (100 ohm-meter), compliance with the basic restriction is shown.

B. *ICNIRP 2010 - Billie*

The ICNIRP 2010 [ICNIRP, 2010] guideline defines a Basic Restriction of 20 mV/m for the general public, which needs to be complied with through dosimetry. *Table 7.23* shows for the compliance for the body floating, *Table 7.24* shows for the body perfectly grounded and *Table 7.25* shows for the body grounded on a 100 ohm-meter ground resistivity.

Table 7.23: Billie - Basic Restriction compliance to the ICNIRP 2010 guideline – Human body floating

BODY ORGAN	E(x,y,z,f0) Volume-Average [ICNIRP 2010] (V/m)	COMPLIANCE TO ICNIRP 2010 GUIDELINE (20 mV/m)
Cornea	1.12E-05	Comply
Nerves	3.78E-04	Comply
Cerebrospinal fluid	1.08E-04	Comply
Heart (Lumen + Muscle)	2.28E-04	Comply
Kidney (cortex + Medulla)	9.92E-05	Comply
Lungs	1.65E-04	Comply
Brain (Grey + white matter)	1.29E-04	Comply

Table 7.24: Billie - Basic Restriction compliance to the ICNIRP 2010 guideline – Human body perfectly grounded

BODY ORGAN	E(x,y,z,f0) Volume-Average [ICNIRP 2010] (V/m)	COMPLIANCE TO ICNIRP 2010 GUIDELINE (20 mV/m)
Cornea	1.22E-04	Comply
Nerves	1.46E-02	Comply
Cerebrospinal fluid	1.38E-03	Comply
Heart (lumen + muscle)	3.30E-03	Comply
Kidney (cortex + medulla)	1.46E-03	Comply
Lungs	2.39E-03	Comply
Brain (grey + white matter)	1.36E-03	Comply

Table 7.25: Billie - Basic Restriction compliance to the ICNIRP 2010 guideline – Human body on ground of 100 ohm-meter

BODY ORGAN	E(x,y,z,f0) Volume-Average [ICNIRP 2010] (V/m)	COMPLIANCE TO ICNIRP 2010 GUIDELINE (20 mV/m)
Cornea	9.06E-05	Comply
Nerves	1.28E-02	Comply
Cerebrospinal fluid	1.01E-03	Comply
Heart (lumen + muscle)	2.50E-03	Comply
Kidney (cortex + medulla)	1.18E-03	Comply
Lungs	1.88E-03	Comply
Brain (grey + white matter)	1.04E-03	Comply

From the dosimetry it can be noted that Billie complies with the Basic Restriction as defined in the ICNIRP 2010 guideline (20 mV/m).

C. IEEE C95.6 - Billie

The IEEE C95.6 [IEEE, 2002] standard defines a Basic Restriction of 14.73 mV/m for the brain, 943 mV/m for the heart and 2.1 V/m for the hands, wrists, feet and ankles. This standard needs to be complied with through dosimetry. *Table 7.26* shows for the compliance for the body floating, *Table 7.27* shows for the body perfectly grounded and *Table 7.28* shows for the body grounded on a 100 ohm-meter ground resistivity.

Table 7.26: Billie - Basic Rstriction compliance to the IEEE C95.6 standard – Human body floating

BODY ORGAN	E(x,y,z,f0) Line-Average [IEEE C95.6-2002] (V/m)	COMPLIANCE TO IEEE C95.6 STANDARD
Cornea	1.12E-05	Comply (943 mV/m)
Nerves	3.46E-04	Comply (943 mV/m)
Cerebrospinal fluid	1.00E-04	Comply (14.73 mV/m)
Heart (lumen + muscle)	2.05E-04	Comply (943 mV/m)
Kidney (cortex + medulla)	9.00E-05	Comply (943 mV/m)
Lungs	1.65E-04	Comply (943 mV/m)
Brain (grey + white matter)	1.29E-04	Comply (14.73 mV/m)

Table 7.27: Billie - Basic Restriction compliance to the IEEE C95.6 standard – Human body perfectly grounded

BODY ORGAN	E(x,y,z,f0) Line-Average [IEEE C95.6-2002] (V/m)	COMPLIANCE TO IEEE C95.6 STANDARD
Cornea	1.22E-04	Comply (943 mV/m)
Nerves	1.46E-02	Comply (943 mV/m)
Cerebrospinal fluid	1.28E-03	Comply (14.73 mV/m)
Heart (lumen + muscle)	2.97E-03	Comply (943 mV/m)
Kidney (cortex + medulla)	1.32E-03	Comply (943 mV/m)
Lungs	2.39E-03	Comply (943 mV/m)
Brain (grey + white matter)	1.36E-03	Comply (14.73 mV/m)

Table 7.28: Billie - Basic Restriction compliance to the IEEE C95.6 standard – Human body on ground of 100 ohm-meter

BODY ORGAN	E(x,y,z,f0) Line-Average [IEEE C95.6-2002] (V/m)	COMPLIANCE TO IEEE C95.6 STANDARD
Cornea	9.06E-05	Comply (943 mV/m)
Nerves	1.28E-02	Comply (943 mV/m)
Cerebrospinal fluid	9.13E-04	Comply (14.73 mV/m)
Heart (lumen + muscle)	2.28E-03	Comply (943 mV/m)
Kidney (cortex + medulla)	1.07E-03	Comply (943 mV/m)
Lungs	1.88E-03	Comply (943 mV/m)
Brain (grey + white matter)	1.04E-03	Comply (14.73 mV/m)

From the dosimetry it can be noted that Billie complies with the Basic Restriction as defined in the IEEE C95.6 standard.

7.4.4 Thelonious

A. ICNIRP 1998 -Thelonious

The ICNIRP 1998 [ICNIRP, 1998] guideline defines a Basic Restriction of 2 mA/m^2 for the general public, which needs to be complied with through dosimetry. *Table 7.29* shows for the compliance for the body floating, *Table 7.30* shows the body perfectly grounded and *Table 7.31* shows for the body grounded on a 100 ohm-meter ground resistivity.

Table 7.29: Thelonious - Basic Restriction compliance to the ICNIRP 1998 guideline – Human body floating

BODY ORGAN	J (x,y,z,f0) Surface Average [ICNIRP 1998] (A/m^2)	COMPLIANCE TO ICNIRP 1998 GUIDELINE (2 mA/m^2)
Cornea	4.11E-06	Comply
Nerves	5.42E-06	Comply
Cerebrospinal fluid	1.68E-04	Comply
Heart (lumen + muscle)	1.95E-05	Comply
Kidney (cortex + medulla)	6.79E-06	Comply
Lungs	8.15E-06	Comply
Brain (grey + white matter)	6.02E-06	Comply

Table 7.30: Thelonious - Basic Restriction compliance to the ICNIRP 1998 guideline – Human body perfectly grounded

BODY ORGAN	J (x,y,z,f0) Surface Average [ICNIRP 1998] (A/m^2)	COMPLIANCE TO ICNIRP 1998 GUIDELINE ($2\ mA/m^2$)
Cornea	5.72E-05	Comply
Nerves	7.51E-05	Comply
Cerebrospinal fluid	7.51E-05	Comply
Heart (lumen + muscle)	2.81E-04	Comply
Kidney (cortex + medulla)	1.17E-04	Comply
Lungs	1.24E-04	Comply
Brain (grey + white matter)	7.06E-05	Comply

Table 7.31: Thelonious - Basic Restriction compliance to the ICNIRP 1998 guideline – Human body on ground of 100 ohm-meter

BODY ORGAN	J (x,y,z,f0) Surface Average [ICNIRP 1998] (A/m^2)	COMPLIANCE TO ICNIRP 1998 GUIDELINE ($2\ mA/m^2$)
Cornea	4.66E-05	Comply
Nerves	5.81E-05	Comply
Cerebrospinal fluid	1.72E-03	Comply
Heart (lumen + muscle)	2.17E-04	Comply
Kidney (cortex + medulla)	9.21E-05	Comply
Lungs	9.54E-05	Comply
Brain (grey + white matter)	5.47E-05	Comply

From the dosimetry it can be noted that Thelonious complies with the Basic Restriction as defined in the ICNIRP 1998 standard ($2\ mA/m^2$).

B. ICNIRP 2010 - Thelonious

The ICNIRP 2010 [ICNIRP, 2010] guideline defines a Basic Restriction of 20 mV/m for the general public, which needs to be complied with through dosimetry. *Table 7.32* shows for the compliance for the body floating, *Table 7.33* shows for the body perfectly grounded and *Table 7.34* shows for the body grounded on a 100 ohm-meter ground resistivity.

Table 7.32: Thelonious - Basic Restriction compliance to the ICNIRP 2010 guideline – Human body floating

BODY ORGAN	E(x,y,z,f0) Volume-Average [ICNIRP 2010] (V/m)	COMPLIANCE TO ICNIRP 2010 GUIDELINE (20 mV/m)
Cornea	9.93E-06	Comply
Nerves	2.43E-04	Comply
Cerebrospinal fluid	9.69E-05	Comply
Heart (lumen + muscle)	1.17E-04	Comply
Kidney (cortex + medulla)	8.68E-05	Comply
Lungs	1.47E-04	Comply
Brain (grey + white matter)	1.10E-04	Comply

Table 7.33: Thelonious - Basic Restriction compliance to the ICNIRP 2010 guideline – Human body perfectly grounded

BODY ORGAN	E(x,y,z,f0) Volume-Average [ICNIRP 2010] (V/m)	COMPLIANCE TO ICNIRP 2010 GUIDELINE (20 mV/m)
Cornea	1.46E-04	Comply
Nerves	3.41E-03	Comply
Cerebrospinal fluid	1.16E-03	Comply
Heart (lumen + muscle)	1.54E-03	Comply
Kidney (cortex + medulla)	1.56E-03	Comply
Lungs	1.93E-03	Comply
Brain (grey + white matter)	1.24E-03	Comply

Table 7.34: Thelonious - Basic Restriction compliance to the ICNIRP 2010 guideline – Human body on ground of 100 ohm-meter

BODY ORGAN	E(x,y,z,f0) Volume-Average [ICNIRP 2010] (V/m)	COMPLIANCE TO ICNIRP 2010 GUIDELINE (20 mV/m)
Cornea	1.20E-04	Comply
Nerves	2.62E-03	Comply
Cerebrospinal fluid	9.00E-04	Comply
Heart (lumen + muscle)	1.21E-03	Comply
Kidney (cortex + medulla)	1.22E-03	Comply
Lungs	1.50E-03	Comply
Brain (grey + white matter)	9.61E-04	Comply

From the dosimetry it can be noted that Thelonious complies with the Basic Restriction as defined in the ICNIRP 2010 standard (20 mV/m).

C. IEEE C95.6 - Thelonious

The IEEE C95.6 [IEEE, 2002] standard defines a Basic Restriction of 14.73 mV/m for the brain, 943 mV/m for the heart, and 2.1 V/m for the hands, wrists, feet and ankles. This standard needs to be complied with through dosimetry. *Table 7.35* shows for the compliance for the body floating, *Table 7.36* shows for the body perfectly grounded and Table 7.37 shows for the body grounded on a 100 ohm-meter ground resistivity.

Table 7.35: Thelonious - Basic Restriction compliance to the IEEE C95.6 standard – Human body floating

BODY ORGAN	E(x,y,z,f0) Line-Average [IEEE C95.6-2002] (V/m)	COMPLIANCE TO IEEE C95.6 STANDARD
Cornea	9.92E-06	Comply (943 mV/m)
Nerves	2.41E-04	Comply (943 mV/m)
Cerebrospinal fluid	9.69E-05	Comply (14.73 mV/m)
Heart (lumen + muscle)	1.17E-04	Comply (943 mV/m)
Kidney (cortex + medulla)	8.44E-05	Comply (943 mV/m)
Lungs	1.37E-04	Comply (943 mV/m)
Brain (Grey + white matter)	1.03E-04	Comply (14.73 mV/m)

Table 7.36: Thelonious - Basic Restriction compliance to the IEEE C95.6 standard – Human body perfectly grounded

BODY ORGAN	E(x,y,z,f0) Line-Average [IEEE C95.6-2002] (V/m)	COMPLIANCE TO IEEE C95.6 STANDARD
Cornea	1.46E-04	Comply (943 mV/m)
Nerves	3.27E-03	Comply (943 mV/m)
Cerebrospinal fluid	1.16E-03	Comply (14.73 mV/m)
Heart (lumen + muscle)	1.54E-03	Comply (943 mV/m)
Kidney (cortex + medulla)	1.56E-03	Comply (943 mV/m)
Lungs	1.93E-03	Comply (943 mV/m)
Brain (grey + white matter)	1.22E-03	Comply (14.73 mV/m)

Table 7.37: Thelonious - Basic Restriction compliance to the IEEE C95.6 standard – Human body on ground of 100 ohm-meter

BODY ORGAN	E(x,y,z,f0) Line-Average [IEEE C95.6-2002] (V/m)	COMPLIANCE TO IEEE C95.6 STANDARD
Cornea	1.19E-04	Comply (943 mV/m)
Nerves	2.54E-03	Comply (943 mV/m)
Cerebrospinal fluid	9.00E-04	Comply (14.73 mV/m)
Heart (lumen + muscle)	1.21E-03	Comply (943 mV/m)
Kidney (cortex + medulla)	1.22E-03	Comply (943 mV/m)
Lungs	1.49E-03	Comply (943 mV/m)
Brain (grey + white matter)	9.13E-04	Comply (14.73 mV/m)

From the dosimetry it can be noted that Thelonious complies with the Basic Restriction (as defined in the IEEE C95.6 standard).

7.5 Results Discussion

Table 7.2 through to *Table 7.37* present the dosimetry calculations conducted using SEMCAD X for each of the human models (Duke, Ella, Billie and Thelonious) and compares them with the ICNIRP 1998 guideline (current density), ICNIRP 2010 guideline (in-situ electric field) and the IEEE C95.6 Standard (in-situ electric field). The computed current densities and in-situ electric fields that exceed the Basic Restriction have been indicated in red in the tables, where the Basic Restrictions [ICNIRP 1998, ICNIRP 2010 and the IEEE C95.6] have been exceeded.

From the dosimetry shown in *Table 7.2* through *Table 7.37* it can be noted that the in-situ electric fields and current densities of the various body parts vary. This is dependent on the human model being used. The differences noted, are due to the size, shape and BMI composition of the human model.

Comparing all the models to the current density of 2 mA/m^2 for the general public, the dosimetry shows that the levels computed comply with the ICNIRP 1998 [ICNIRP, 1998] Basic Restriction.

From an in-situ electric field point of view it can be noted that when the body is floating (not in contact with the ground) the exposure computed complies with the Basic Restrictions [ICNIRP 2010 and IEEE C96.6]. In the case of the body being in contact with the ground, some of the models show non-compliance with the Basic Restrictions, but when the ground

is modelled as a representative object (100 ohm-meter), the models show compliance with the Basic Restrictions.

It must also be noted, that the human models used in this dissertation do not have any clothes on. This is the worst case scenario for exposure. If a layer of clothes is modelled, a reduction of approximately 3.5% can be achieved with the head exposed, and 7% if the body is fully clothed (see *Figure 7.6* for the two models used).

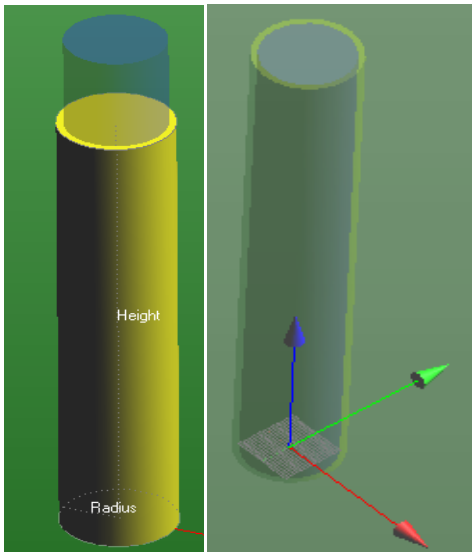


Figure 7.6: Simple model with head exposed (left) and fully clothed (right)

Eskom designs 765 kV lines to comply with 10 kV/m within the servitude. This translates to an approximate minimum height from ground level of 15.1 m. *Figure 7.7* highlights the effect of height on the electric field beneath a 765 kV transmission line. It plots electric field strength levels at heights of 15.1 m, 17 m, 19 m and the actual measurement height of the Mercury – Zeus 765 kV transmission line. It can be noted, that the electric field could increase from 6 kV/m (measured) to approximately 9 kV/m at a phase height of 15.1 m. Even at the increased electric field level of 9 kV/m, compliance with the Basic Restrictions to the ICNIRP guidelines and IEEE C95.6 standard is met. This has been shown in Appendix C, where the electric field of 5 kV/m and 10 kV/m is shown using the Duke human model. *Figure 7.7* highlights how the electric field at ground level will be affected with the difference in height of the phase conductors from ground level.

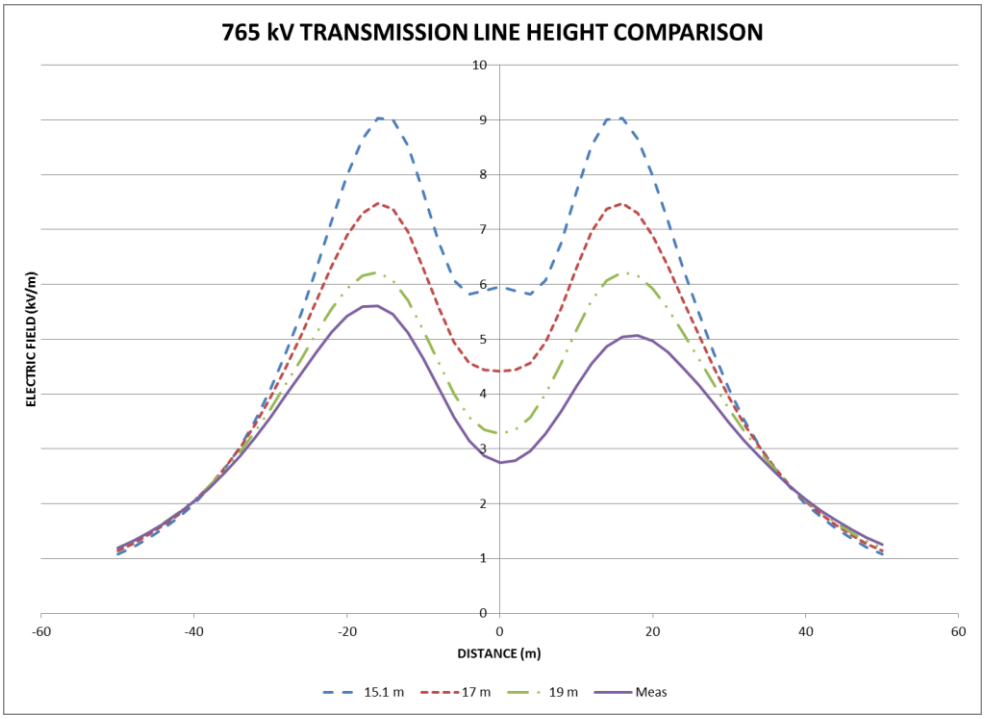


Figure 7.7: Electric field comparison with varied height comparisons

In conclusion, a case study of in-situ electric field (E) and current densities (J) induced by a three-phase power line in a human body have been computed. The obtained result showed an asymmetrical pattern in the field distributions inside the body, which is due to the different phase and orientation between electrically and magnetically induced fields. Most importantly, the localisation of maximum fields is not the same for E and J; therefore, E and J are not equivalent from the point of view of the constraints imposed for limiting exposure to EMF.

7.6 Conclusion

The results of the dosimetry have been analysed and discussed in this chapter. It has been shown, that the human body exposed to the electric field from a 765 kV transmission line can comply with the Basic Restrictions of the ICNIRP [ICNIRP, 1998, ICNIRP, 2010] guideline and the IEEE standard [IEEE, 2002].

CHAPTER 8: CONCLUSION

8.1 SUMMARY

In this dissertation, the interaction of low-frequency electric fields with the human body is analysed using field measurements, predictions and simulations. It further addresses the research questions proposed in Section 2.3.

In all calculations of the human body, a high-resolution, three dimensional anatomical model of the human body obtained from modern medical imaging techniques is used. With these detailed anatomical models, the fields are computed with greater resolution within a human body. Numerical calculations are often substituted for internal field measurements because they are less invasive and more efficient. Various articles have been published in the field of numerical computation of induced fields in a human body. In this dissertation, a numerical technique based on the Finite-Difference Time-Domain (FDTD), electromagnetic quasi-static (EQS) approximations is applied in the analysis of low frequency electric field exposure of the human body, with its main focus on Eskom's 765 kV transmission line expansion projects.

A short history of bio-electromagnetism is presented followed by the characterisation of the frequency dependent interaction of electromagnetic fields and biological tissue with emphasis on the low-frequency regime. A discussion on human exposure limits and International standards and guidelines is included.

The dielectric properties of biological tissue and the geometrical modelling of the human body are discussed. After introducing the FDTD, which establishes the basis of all field calculations in this dissertation, some general remarks on the computation of electromagnetic fields in tissue, along with commonly used numerical techniques, are discussed and presented.

In the low-frequency regime two different types of imposed current flow inside biological tissue can be identified: direct contact of tissue with an electric potential difference (electric excitation) and induction of currents inside the tissue by an external time-varying magnetic field (magnetic excitation).

The simulation software used in the dissertation, are the SEMCAD X [SPEAG] and CDEGS [CDEGS] software packages. These are validated using simple models for comparison purposes.

The model of the 765 kV transmission line is used to verify the electric fields obtained using the SEMCAD X and CDEGS software. The human model validation is via comparison with simple models in published references and standards.

Measurement procedures used to conduct the electric field measurements are discussed. It covers the data measured from an existing 765 kV transmission line (half profile), and compares the measured values with the predicted values using CDEGS and draws conclusions.

The 765 kV transmission line measurements discussed above, are used in the dosimetry and are based on a 3D anatomical human body to compare compliance with the ICNIRP Basic Restrictions as the reference level of ICNIRP (5 kV/m) was exceeded. It compared the current densities and in-situ electric fields obtained from both the ICNIRP (1998 and 2010) guidelines [ICNIRP, 1998 and ICNIRP, 2010] Basic Restrictions, and draws conclusions.

8.2 Conclusions

From the information presented in this dissertation and referring to the research questions (Section 2.3) the following can be noted:

- The measured electric field from the Mercury – Zeus 765 kV transmission line exceeds the Reference Level (5 kV/m) for both the ICNIRP 1998 [ICNIRP, 1998] and ICNIRP 2010 [ICNIRP, 2010] guidelines. The exceeding of the Reference Level means that the Basic Restriction of the ICNIRP guidelines needs to be complied with. This has been addressed in this dissertation through the use of 3D anatomical human body dosimetry. The CDEGS [CDEGS] and SEMCAD X [SPEAG] software packages with the virtual family human body models [Christ et al., 2007] applying the FDTD method on four human models (Duke Ella, Billie, and Thelonious) [Christ et al., 2007] was conducted and has been presented and discussed to show compliance to both the ICNIRP 1998 (current densities) and ICNIRP 2010 (in-situ electric field).
- From the 3D anatomical modelling conducted, the compliance to the ICNIRP 1998 (2 mA/m^2) and ICNIRP 2010 (20 mV/m) guidelines' Basic Restrictions to 5 kV/m has shown compliance, while at 10 kV/m has shown some excesses in certain body

organs of Duke on an ideal ground plane, but complies with the basic restriction with a ground plane of 100 ohm-meter.

- The accuracy through the use of dosimetry to show compliance to the Basic Restrictions of the ICNIRP guidelines, from the modelling and reported in the literature is shown to be less than 50%. This is reasonable as the models used are not the same and the placement of the internal organs, size and shape are different for each model used. It has been shown in Appendix C that even if the external unperturbed electric field is doubled from 5 kV/m to 10 kV/m (100%), the internal current density or in-situ electric field inside the human body is still complied with through the use of dosimetry.
- Benchmarking of the models used in this dissertation were analysed and compared to similar models used in the literature [Dawson et al, 1998; Dimbylow, 1998; WHO, 2007]. The results showed good agreement with each other and thus confidence is achieved through the dosimetry conducted in this dissertation.
- This dissertation has also highlighted that the human body posture plays a role in the effect of the external electric field being produced on the human body surface. This could have an effect on the internal body organ, but will still be within the 50% margin as reported in the literature [Dawson et al., 1998; Dimbylow, 1998; WHO, 2007], as the organ placement, size and shape will be in the same position. The only difference will be the extremities (arms), which will have a wide-spread surface electric field and in some instances screen the head from the electric field exposure. This was not conducted it this dissertation, as the posable human models were not available to the author, but will be conducted later, once the posable models have been procured.

The overall conclusion of this dissertation has shown that through the use of measurement, predictions using CDEGS [CDEGS] and 3D anatomical dosimetry using the SEMCAD X [SPEAG] software and the 3D anatomical models [Christ et al., 2007], can be used to show compliance with the Reference Levels and Basic Restrictions of the ICNIRP guidelines [ICNIRP, 1998 and ICNIRP, 2010] using human body dosimetry. This holds true for all distribution and transmission lines designed and operated in Eskom Holdings SOC Limited, where they are designed to meet 10 kV/m at ground level.

8.3 Future Work

Future work, which will be a continuation of this work, will focus on utility workers and exposure inside a 765 kV substation. This work will entail measurements, predictions and computer modelling of the human within this environment.

Measurements will be performed on human specimens within this environment. The currents induced in the human specimens will be captured and compared to the models. Both the electric and magnetic fields will be measured in conjunction with the current induced on the human specimen.

It is known that an ungrounded human, such as a substation worker, receives contact currents when touching a grounded object in electric fields. Contact currents and internal electric fields induced in the human when exposed to non-uniform electric fields at 50 Hz will be numerically calculated. This will be done using a realistic human model standing at a distance of 0.1–0.5 m from the grounded conductive object. Both the amplitude and frequency will be captured and analysed.

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APPENDIX A – MEASURED ELECTRIC AND MAGNETIC FIELDS BENEATH THE EXISTING MERCURY – ZEUS 765 kV TRANSMISSION LINE

Measurements were conducted beneath the Mercury – Zeus 765 kV transmission line. The measured values are shown in *Table A1*.

TABLE A1: Electric and Magnetic Fields Beneath the existing Mercury – Zeus 765 kV Transmission Line

LOCATION DISTANCE (m)	**ELECTRIC FIELD (kV/m)**		**MAGNETIC FIELD (μT)**	
	20/2/2013	**25/2/2013**	**20/2/2013 (550 A)**	**25/2/2013 (650 A)**
Centre of line (0)	-	3.92	4.60	6.36
2	-	4.04	4.61	6.47
4	-	3.85	4.48	6.5
6	-	3.69	4.46	6.48
8	-	3.61	4.36	6.41
10	-	3.75	4.31	6.27
12	-	3.93	4.07	6.13
14	-	4.88	3.95	5.94
16	-	5.03	3.65	5.71
18	-	5.42	3.51	5.53
20	-	5.53	3.21	5.12
22	-	5.32	2.85	4.72
24	-	5.23	2.59	4.48
26	-	5.35	2.28	4.09
28	-	5.05	2.11	3.67
30	-	4.04	1.84	3.35
32	-	3.25	1.69	3.08
34	-	2.73	1.50	2.73
36	-	2.71	1.31	2.54
38	-	2.99	1.20	2.32
40	-	2.1	1.08	2.06
42	-	1.65		1.85
44	-	1.37		1.73

APPENDIX B - MEASUREMENT EQUIPMENT SPECIFICATIONS

An EFA-300 Field Analyser manufactured by NARDA is used to conduct the electric and magnetic field measurements. It was last calibrated on the 11th December 2012. The calibration certificate numbers are:

TABLE B1: EFA-300 Calibration Certificates

Equipment	**Serial Number**	**Calibration Certificate Number**
B-Field meter EFA-300	K-0044	22453000k004420121211
E-Field unit	H-0028	22459031-H0028-121211
B-Field probe 100 cm^2	AA-0013	22459010AA001320121211

The EFA-300 field analyser for measuring magnetic and electric fields in the workplace and in public spaces are designed for professional users in the power industry, at municipal utilities, by insurers, and for health and safety professionals in industry. In the low frequency range, they handle virtually any required measurement, simply and precisely. The instrument provides field analysis using an Fast Fourier Transform (FFT) computation in addition to measuring magnetic and electric fields.

The accuracy of the EFA-300 field analyser is given in *Table B2*.

TABLE B2: EFA-300 Specifications

Mode	**Range**	**Magnetic Field**	**Electric field**
Sensor system		Coil sensor	Plate electrode
Frequency range	Broadband (+0/-3dB) selectable	5 Hz to 2 kHz, 30 Hz to 2 kHz, 5 Hz to 32 kHz or 30 Hz to 32 kHz	
	Band pass/ band stop filter	15 Hz to 2 kHz (resolution 0.1 Hz)	
Noise level (RMS) [b]	Broadband, 30 Hz to 2 kHz	4 nT	0.7 V/m
	Broadband, 5 Hz to 32 kHz	10 nT	4.5 V/m
Uncertainty (typical) [a]	Broadband, 30 Hz to 2 kHz	±3% @ ≥ 40 nT	±3% @ ≥ 5 V/m
	Broadband, 5 Hz to 32 kHz	±3% @ ≥ 80 nT	±3% @ ≥ 40 V/m

a. Uncertainty includes all partial uncertainties (absolute, linearity, frequency response, and isotropy) as well as temperature and humidity related deviations.
Signal sinusoidal, level >10% of selected measurement range; additional uncertainties apply with the steep frequency band limits.

b. RMS = Root Mean Squared

APPENDIX C - DUKE MODEL COMPARISON BETWEEN PARALLEL PLATES

A model (*Figure C1*) was used, to compute the in-situ electric fields and current densities inside the human body (Duke), to check compliance to the ICNIRP guideline [ICNIRP 1998, ICNIRP 2010] and IEEE standard [IEEE 2010].

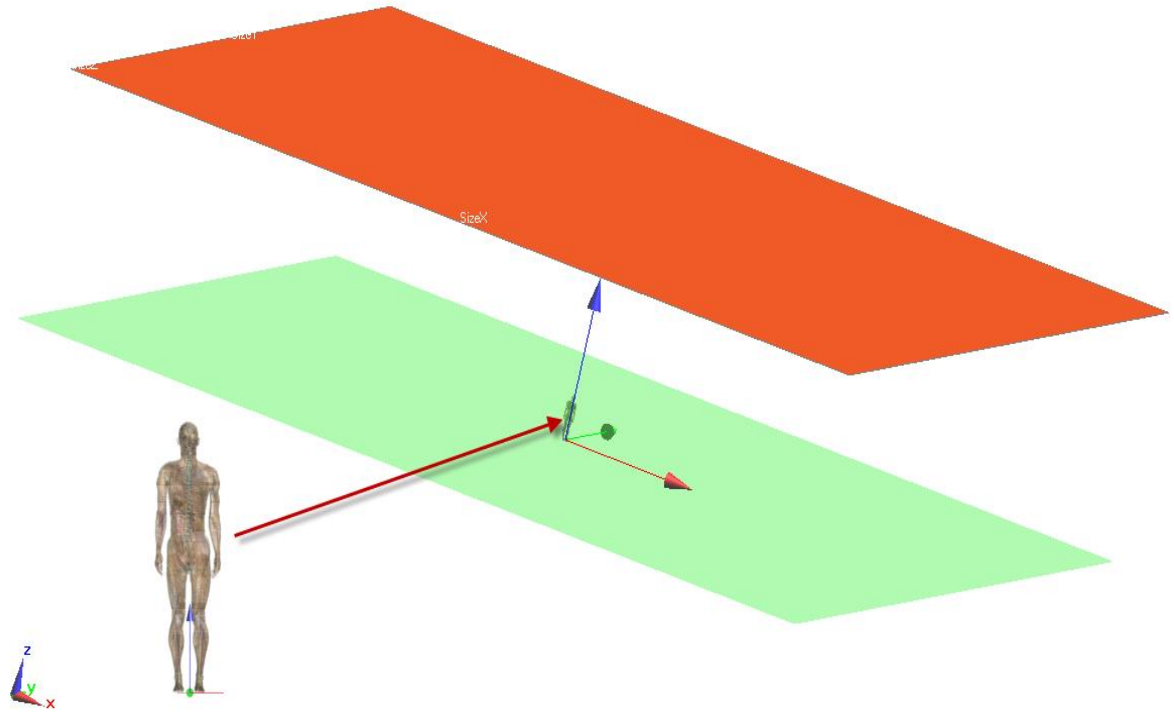


FIGURE C1: Human Exposure Model Used to Calculate the In-situ Electric Field and Current Densities

C.1. EXPOSURE SYSTEM

The exposure system consisted of two parallel plates separated by 10 m from each other. One plate was grounded, with a zero potential, while the other plate was energized with a potential of 50 kV and 100 kV, to give a homogenous field of 5 kV/m and 10 kV/m respectively.

The human model (Duke) was positioned between the plates with his feet on the grounded plate. See *Figure C1*.

The electric field distribution between the parallel plates is shown in *Figure C2.*

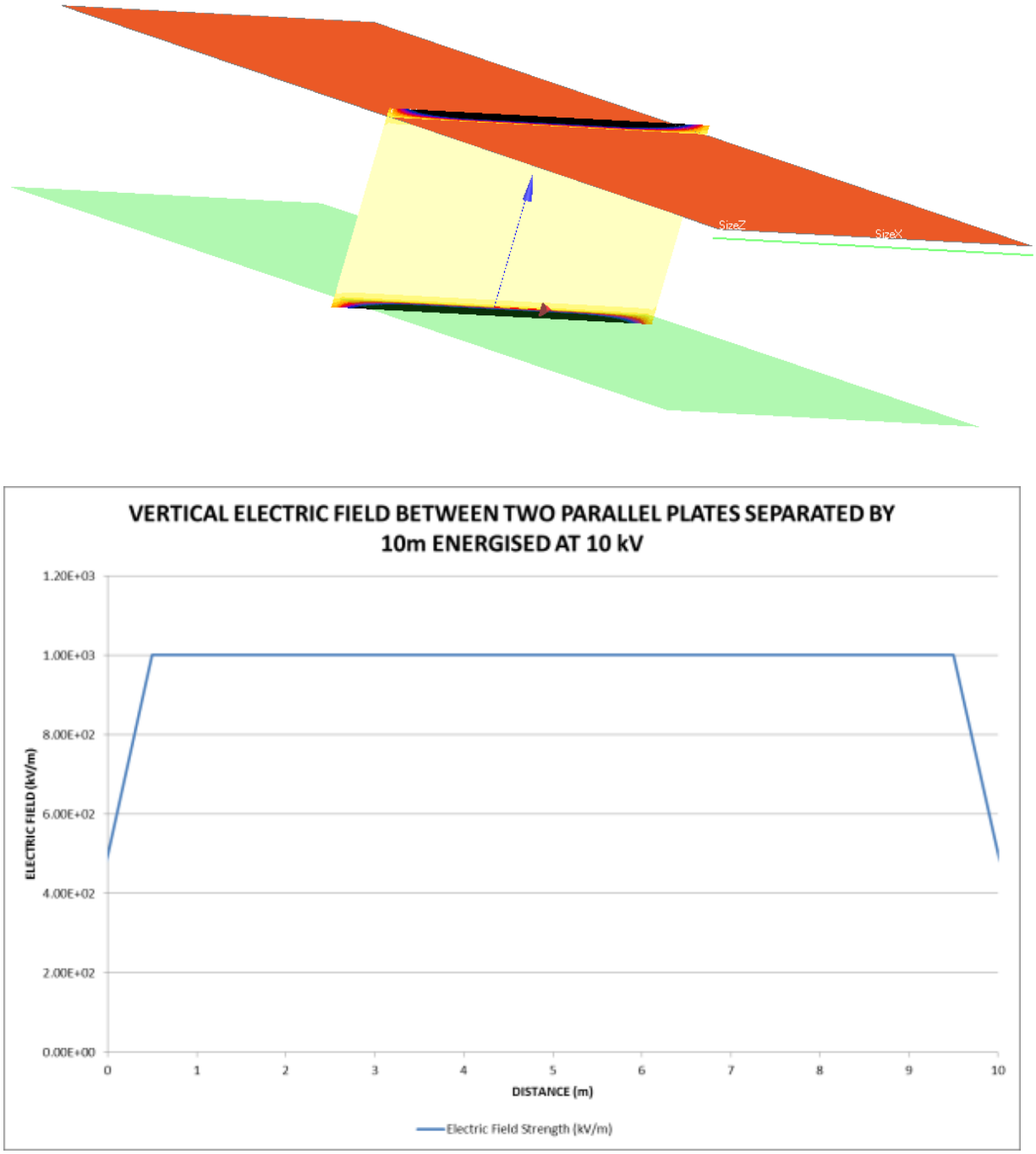


FIGURE C2: Distribution of the Electric Field between the Parallel Plates, Without the Human Body Present. Top: Three Dimensional Model, Bottom:Vertical Electric Field Strength between the Plates

C.2. DEFINITION OF QUANTITIES

Various quantities have been simulated and presented in this Appendix. They are defined below, and are computed using the SEMCAD X software.

C.2.1. E(x,y,z,f0) Volume-Average [ICNIRP 2010]

ICNIRP guidelines recommend determining the induced electric field at any location r_0 as a vector average of the electric field within a small contiguous tissue cubic volume of 2x 2x2 mm^3.

$$< E(r_0) >_v = \frac{1}{V}\int_v E(r)dv \qquad \text{(C.1)}$$

where $0 < V \leq 8\ mm^3$ is the volume of lossy tissue within the cube. The average is performed on a cube centred at each tissue voxel.

C.2.2. E(x,y,z,f0) Line-Average [IEEE]

The spatial averaging of the E-Field along a straight line is recommended in IEEE C95.1 2005 standard under Section 4.1.1.

$$< E(r_0) >_L = \frac{1}{L}\int_L E(r) \cdot \hat{l_0} dl = \frac{V}{L}\hat{l_0} \qquad \text{(C.2)}$$

C.2.3. J(x,y,z,f0) Surface-Average [ICNIRP 1998]

In the ICNIRP guidelines, current density J [A/m^2] is averaged by computing the current flow I_s [A] through a circular surface S perpendicular to the current direction $\hat{n_0}$ at the centre point r_0 and dividing by its area. The averaged current density at each location is formulated as follows:

$$< J(r_0) >_s = \frac{1}{A}\int_S J(r) \cdot \hat{n_0}\, dS = \frac{I_S}{\pi R^2}\hat{n_0} \qquad \text{(C.3)}$$

where $A = \pi R^2$ denotes the area of the circular surface.

C.3. SIMULATED RESULTS

The following simulated results are presented:

- E(x,y,z,f0) Volume-Average [ICNIRP 2010]
- E(x,y,z,f0) Line-Average [IEEE]
- J(x,y,z,f0) Surface-Average [ICNIRP 1998]

C.3.1. E(x,y,z,f0) Volume-Average [ICNIRP 2010]

TABLE C1: In-situ Electric Field of Various Body Organs (Duke) in V/m

E(x,y,z,f0) Volume-Average [ICNIRP-2010]				
Body organ	Field applied (kV/m)			
	5		10	
	Real Modulus (V/m)	RMS Modulus (V/m)	Real Modulus (V/m)	RMS Modulus (V/m)
Body	**3.40E+00**	**1.05E+02**	**6.80E+00**	**2.10E+02**
Brain (Grey and White)	5.85E-03	1.10E-02	1.17E-02	**2.20E-02**
Cerebrospinal fluid	1.41E-03	5.57E-03	2.81E-03	1.11E-02
Cornea	8.93E-05	9.84E-04	1.79E-04	1.97E-03
Heart (Lumen and Muscle)	9.15E-03	1.97E-02	1.83E-02	**3.94E-02**
Kidney (Cortex and Medulla)	3.75E-03	9.66E-03	7.50E-03	1.93E-02
Liver	5.61E-03	1.83E-02	1.12E-02	**3.66E-02**
Lung	4.51E-03	1.30E-02	9.03E-03	**2.61E-02**
Nerves	6.89E-03	**3.30E-02**	1.38E-02	**6.59E-02**

At 5 kV/m field strength, the simulations have shown that the exposure of the human body complies with the ICNIRP 2010 guidelines basic restriction of 20 mV/m for the general public. When the field is increased to 10 kV/m, the basic restriction of 20 mV/m is exceeded in some of the body organs (Shown in red in *Table C1*).

C.3.2. E(x,y,z,f0) Line-Average [IEEE]

The IEEE C95.6 standards basic restriction is 14.73 mV/m for the brain, 943 mV/m for the heart, and 2.1 V/m for the hands, wrist, feet and ankles at 50 Hz.

TABLE C2: In-situ Electric Field of Various Body Organs (Duke) in V/m

E(x,y,z,f0) Line-Average [IEEE C95.1-2005]				
Body organ	Field applied (kV/m)			
	5		10	
	Real Modulus (V/m)	RMS Modulus (V/m)	Real Modulus (V/m)	RMS Modulus (V/m)
Body	**2.84E+00**	**8.75E+01**	5.68E+00	1.75E+02
Brain (Grey and White)	5.45E-03	1.10E-02	1.09E-02	**2.20E-02**
Cerebrospinal fluid	1.33E-03	5.09E-03	2.65E-03	1.02E-02
Cornea	8.36E-05	9.84E-04	1.67E-04	1.97E-03
Heart (Lumen and Muscle)	8.29E-03	1.82E-02	1.66E-02	3.63E-02
Kidney (Cortex and Medulla)	3.53E-03	9.22E-03	7.06E-03	1.84E-02
Liver	5.55E-03	1.83E-02	1.11E-02	3.66E-02
Lung	4.41E-03	1.29E-02	8.83E-03	2.57E-02
Nerves	6.69E-03	3.26E-02	1.34E-02	6.53E-02

At 5 kV/m field strength, the simulations have shown that the exposure of the human body complies with the IEEE C95.1 standards basic restriction for the general public. When the field is increased to 10 kV/m, the basic restriction is exceeded in the brain only (Shown in red in *Table C2*).

C.3.3. J(x,y,z,f0) Surface-Average [ICNIRP 1998]

TABLE C3: Current Densities of Various Body Organs (Duke) in A/m^2

J(x,y,z,f0) Surfave-Average [ICNIRP 1998]				
Body organ	Field applied (kV/m)			
	5		10	
	Real Modulus (A/m^2)	RMS Modulus (A/m^2)	Real Modulus (A/m^2)	RMS Modulus (A/m^2)
Body	9.37E-03	**4.57E-02**	**1.87E-02**	**9.13E-02**
Brain (Grey and White)	3.33E-04	6.82E-04	6.65E-04	1.36E-03
Cerebrospinal fluid	2.81E-03	1.11E-02	**5.62E-03**	**2.23E-02**
Cornea	3.52E-05	4.14E-04	7.00E-05	8.29E-04
Heart (Lumen and Muscle)	6.27E-04	2.64E-03	1.25E-03	**5.27E-03**
Kidney (Cortex and Medulla)	2.80E-04	7.71E-04	5.60E-04	1.54E-03
Liver	1.44E-04	5.98E-04	2.89E-04	1.20E-03
Lung	2.71E-04	8.14E-04	5.41E-04	1.63E-03
Nerves	1.62E-04	7.76E-04	3.24E-04	1.55E-03

At 5 kV/m field strength, the simulations have shown that the exposure of the human body complies basically with the ICNIRP 1998 guidelines basic restriction of 2 mA/m^2 for the general public. When the field is increased to 10 kV/m, the basic restriction of 2 mA/m^2 is exceeded in some of the body organs (Shown in red in *Table C3*), but as the focus of the ICNIRP 1998 guideline is current density in the central nervous system, the exposed human complies to the guideline.

C.4. CONCLUSION

In this appendix, the finite difference time domain (FDTD) has been used to solve the electro-quasi-static (EQS) formulation aiming not only to characterize the in-situ electric field and current density induced in the human body due to electric field exposure at extremely low frequencies but also to clarify the influence of different electric fields.

The conclusions that could be drawn are, as follows:

- The human body exposed to the 5 kV/m and 10 kV/m has been simulated and compared.
- The results are referenced to the basic restrictions of the ICNIRP 1998 and ICNIRP 2010 guidelines as well as the IEEE C95.1 standard.
- From the simulations, it is shown, that some of the body organs exceed the basic restrictions of the in-situ electric field and current density. The in-situ electric field exceeds the basic restriction of 20 mV/m in some organs by double, while the current density of 2 mA/m^2 is exceeded three times when compared to the basic restriction of the ICNIRP 2010 and ICNIRP 1998 guidelines respectively.
- In general, the exposure to the ICNIRP 1998 guidelines basic restriction (current density) is less stringent when compared to the ICNIRP 2010 basic restriction (in-situ electric field).

APPENDIX D – ESKOM DRAFT REVISED POLICY

Eskom	Policy	

Title: POWER FREQUENCY ELECTRIC AND MAGNETIC FIELDS (EMF)	Unique Identifier:	32-180
	Area of Applicability:	E
	Documentation Type:	PL
	Revision:	0
	Total Pages:	10
	Next Review Date:	August 2012
	Disclosure Classification:	CONTROLLED DISCLOSURE

Compiled by	Functional Responsibility	Authorized by
.....	.....	.....
KR Hubbard	W Poulton General Manager (Sustainability and Innovation)	Dr SJ Lennon Managing Director (Corporate Services Division)
Date:	Date:	Date: .....

DRAFT

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1. INTRODUCTION

Through this policy, Eskom commits to excellence in safety, health, the environment and quality. It confirms to all our stakeholders that Eskom will conduct business in a caring and responsible manner. This policy has been reviewed and has been reinforced by taking note of recent reviews such as:

- International guidelines (ICNIRP 1998, ICNIRP 2010) and standards (IEEE 2002)
- NIEHS Reports of Working Group/Director (1998/9) which comprehensively reviewed the relevant literature up to those dates
- The classification of extremely low frequency magnetic fields as a 'possible carcinogen' (IARC 2002) and the publication of a UK report by the Advisory Group on Non-ionizing Radiation of the National Radiological Protection Board (NRPB 2001), which concluded there to be some evidence that prolonged exposure to higher levels of power frequency magnetic fields (>0.4 μT) is associated with a small risk of leukaemia in children
- ICNIRP review of the literature (2003), which comprised the most complete review and analysis to date
- Documents of the NRPB (2004) Vol 15, No's. 2 & 3, which further analysed scientific evidence and issued guidance on protection, essentially recommending the implementation of the ICNIRP guidelines, mentioned above, but with a recommendation that the UK government consider whether a precautionary approach was needed in respect to exposures of children
- The World Health Organisation (WHO) environmental health criteria on extremely low frequency fields (WHO 2007)
- Stakeholder Advisory Group on extremely low frequency (ELF) EMFs (SAGE) Precautionary approaches to ELF EMFs (April 2007)
- EU recommendations for general public and occupational exposure which is mandatory throughout the European Union countries

Worldwide research into the possible biological effects of exposure to power frequency electric and magnetic fields (EMF) has yielded inconclusive results. Some epidemiological studies have suggested a possible link between long-term exposure to EMF and certain types of cancers. Other research has been unable to confirm these findings or discover any mechanism of causation. Research continues in many countries, including South Africa, to reach firm conclusions as to whether any detrimental health effects exist.

There is uncertainty as to whether a specific standard or guideline is needed to address ELF EMF exposure. Research over the past 30 years has addressed the question of whether exposure to ELF EMF might adversely affect human health. For most health outcomes, there is no evidence that EMF exposures have adverse effects.

Extremely low frequency (ELF) electromagnetic fields generated by electrical power transmission have been associated with an increased risk of childhood leukaemia, but the findings are not conclusive. Even if this association is real, the number of cases is likely to be very small. With reference to ELF fields, available data allows one to exclude any excess risk of (childhood) leukaemia and other cancers at the levels of exposure likely to be encountered by most (>99%) of the population. To date there is no convincing biological or biophysical support for a possible association between exposure to ELF fields and the risk of leukaemia or any other cancer.

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2. POLICY STATEMENT

2.1 POLICY

- Eskom recognises that scientific understanding of the effects of EMFs is increasing and will continue to review all relevant scientific developments in EMF from across the world and assess any implications to Eskom's planning, design and operation.
- Eskom will participate in identified initiatives on the biological effects of EMF. Eskom holds the view that South Africa should support international studies on the biological effects of EMF, but confine local research to areas where local expertise and unique conditions can complement international efforts. Participation and interaction nationally and internationally by an Eskom representative should attend overseas conferences and working groups related to EMF. Eskom cannot expect to be an informed builder of power systems without doing this.
- Eskom will measure and calculate electric and magnetic field intensities, as well as contact currents and related exposure levels associated with the provision and use of electrical energy. This information will be made available upon request.
- Eskom will inform its relevant staff (i.e. those exposed to EMF) on EMF topics and health matters.
- Eskom will respond to stakeholder queries on EMF that relate to Eskom's infrastructure and operations.
- Eskom will take an approach to the management of EMFs based on international accepted practices.
- Eskom's existing power line networks were designed to meet 10 kV/m exposure limit within the servitude boundary. In areas where this level is exceeded, warning sighs will be erected, to inform the general public of high levels of exposure.
- In the absence of national EMF standards and/ or regulations in South Africa, Eskom will design overhead transmission lines to meet an electric field exposure design limit of 5 kV/m for power lines ≤ 400 kV, and 10 kV/m above 400 kV within the servitude boundary. Such an approach will be in line with international recommendations (IEEE 2002 and WHO 2007).
- Eskom will ensure that the design of power lines will meet a magnetic field exposure limit of ≤ 200 µT (micro-Tesla) within the servitude.
- Live line work will continue.

2.2 POLICY PRINCIPLES

The following are the guiding principles (KR Hubbard 2009: Framework Document) by which Eskom will operate and apply the decision-making that requires the consideration of ELF and EMF:

- Decisions taken are to ensure no impact on public health through installation and operation of its plant.
- In the absence of regulation and there being no impact of power line design, Eskom should not be placed in a situation where retrofit is preferred at some later stage.
- Eskom should ensure all reasonable precaution has been taken.
- Eskom be kept abreast of world trends in terms of standards setting and application. Based on these findings, Eskom will set applicable exposure limits.

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- In cases where EMF exposure limits are in the future regulated, a grand-father clause should be negotiated to cover existing infrastructure that may have been constructed prior to the regulations for the life span of the structures.
- Eskom will engage and where necessary collaborate with relevant stakeholders in EMF research and standard setting.
- In the long term, a precautionary approach is advisable.

3. SUPPORTING CLAUSES

Index of Supporting Clauses

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3.1 SCOPE

This policy details Eskom's precautionary approach to the electric and magnetic fields generated by Eskom's power lines and other electrical devices.

3.1.1 Purpose

The purpose of the policy is to set out Eskom's position and approach to the management of electric and magnetic fields generated by its operations.

3.1.2 Applicability

This policy shall apply throughout Eskom Holdings Limited divisions, subsidiaries, and entities wherein Eskom has a controlling interest.

3.2 NORMATIVE/INFORMATIVE REFERENCES

Parties using this policy shall apply the most recent edition of the documents listed below.

3.2.1 Normative

[1] ISO 9001 Quality Management Systems.

[2] ISO 14001 Environmental Management System

[3] International Commission on Non-Ionizing Radiation Protection (ICNIRP), Guidelines for Limiting Exposure to Time-Varying Electric, Magnetic, and Electromagnetic Fields (up to 300 GHz), Health Physics, April1998, Volume 74 No 4

[3] IEEE, Std C95.6, IEEE Standard for Safety Levels with Respect to Human Exposure to Electromagnetic Fields, 0-3 kHz, 2002

[4] KR Hubbard, Eskom's Framework Document on The Impact of Exposure to Power Frequency (50Hz) and Extremely Low Frequency (ELF) Electric and Magnetic Fields (EMF), 2009

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[5] WHO, Environmental Health Criteria Monograph No.238, http://www.who.int/peh-emf/publications/elf_ehc/en/index.html, June 2007. Last accessed 30 Aug 07

[6] International Commission on Non-Ionizing Radiation Protection (ICNIRP), Guidelines for Limiting Exposure to Time-Varying Electric, Magnetic Fields (1Hz to 100 kHz), Health Physics, Dec 2010

3.2.2 Informative

[7] NIEHS (1998). Assessment of Health Effects from Exposure to Power-Line Frequency Electric and Magnetic Fields, Research Triangle Park, NC.

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[12] World Health Organisation (WHO) www.who.int/emf , 15 Apr 2006.

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[16] International Commission for Non-Ionising Radiation Protection (ICNIRP) http://www.icnirp.de/pubEMF.htm , 15 Apr 2006.

[17] National Radiological Protection Board (NRPB) http://www.hpa.org.uk/radiation/ , 15 Apr 2006.

[18] Department of Health (South Africa) http://www.doh.gov.za/search/index.html , 15 Apr 2006.

3.3 DEFINITIONS

3.3.1 Power frequency – Number of sinusoidal cycles of current or voltage of the electric power system per second, measured in Hertz. In South Africa it is 50Hz.

3.3.2 Electric field – A vector field (E) generated by the applied voltage on the power line, measured in volts per meter (V/m).

3.3.3 Electric Field Strength (E) – Force exerted by an electric field on an electric point charge, divided by the electric charge. Electric field strength is expressed in Newton per coulomb or volts per meter (NC = V/m).

3.3.3 Magnetic field strength – A field vector (H) that is equal to the magnetic flux density divided by the permeability of the medium. Expressed in amperes per meter (A/m)

3.3.4 Magnetic flux density – The force on a moving unit positive charge at a point in a magnetic field per unit velocity. A vector field quantity (B) expressed in Tesla (T).

3.3.5 Magnetic field – A vector field generated by the applied current flowing in the power line.

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3.3.6 Precautionary approach – If an action or policy has a suspected risk of causing harm to the public or to the environment, in the absence of scientific consensus, that the action or policy is not harmful, the burden of proof that it is not harmful falls on those who advocate taking the action.

3.4 ABBREVIATIONS

Abbreviation	Description
CNS	Central Nervous System
ELF	Extremely Low Frequency
EMF	Electric and Magnetic Fields
GHz	Giga Hertz
Hz	Hertz
IARC	International Agency for the Research on Cancer
ICNIRP	International Commission on Non-Ionizing Radiation Protection
IEEE	Institute of Electrical and Electronics Engineers
ISO	International Standards Organisation
kHz	Kilo Hertz
kV/m	Kilo-volt per meter
MD	Managing Director
mV/m	Milli-volt per meter
NIEHS	National Institute of Environmental Health Sciences
NRPB	National Radiological Protection Board
PNS	Peripheral Nervous System
µT	Micro-Tesla
WHO	World Health Organisation

3.5 ROLES AND RESPONSIBILITIES

- The Functional Representative for Transmission's Asset Management shall be responsible for ensuring that the management of electric and magnetic fields in Eskom reflects current practices and is kept up to date with new changes.
- Corporate Services Division's, Sustainability and Innovation business unit shall be responsible for monitoring international developments in EMF, assisting the Eskom line divisions, liaison with the EMF Programme, provide measurements and consulting and updating this and related policies.
- The Group Communications Department is responsible for responding to queries on EMF.
- All Eskom design departments to ensure the set EMF limits and associated design principles are applied in their design processes.

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3.6 PROCESS FOR MONITORING

Eskom through the research function will review this policy on EMF as new information becomes available.

The Assurance and Forensics Department will conduct internal audits and monitor and report on performance with an agreed audit programme and established business performance reporting procedures.

Limitations of exposure that are based on the physical quantity or quantities directly related to the established health effects are termed basic restrictions. In the ICNIRP guideline, the physical quantity used to specify the basic restrictions on exposure to EMF is the internal electric field strength E_i, as it is the electric field that affects nerve cells and other electrically sensitive cells.

Biological effects of EMF are caused by the current induced in the body and the internal electric field strength by such fields. From a 'safe exposure' point of view, basic restrictions of internal electric field strength are set to prevent negative effects on normal nervous system functioning. The biological effect risks come from transient nervous system responses including peripheral (PNS) and central nerve stimulation (CNS), the induction of retinal phosphenes and possible effects on some aspects of brain function.

In view of the considerations above for frequencies in the range 10 Hz to 25 Hz, occupational exposure should be limited to fields that induce electric field strengths in CNS tissue of the head (i.e., the brain and retina) of less than 50 mV/m in order to avoid the induction of retinal phosphenes. These restrictions should also prevent any possible transient effects on brain function. These effects are not considered to be adverse health effects; however, ICNIRP recognizes that they may be disturbing in some occupational circumstances and should be avoided but no additional reduction factor is applied. Phosphene thresholds rise rapidly at higher and lower frequencies, intersecting with the thresholds for peripheral and central myelinated nerve stimulation at 400 Hz. At frequencies above 400 Hz, limits on peripheral nerve stimulation apply in all parts of the body.

Exposure in controlled environments, where workers are informed about the possible transient effects of such exposure, should be limited to fields that induce electric fields in the head and body of less than 800 mV/m in order to avoid peripheral and central myelinated nerve stimulation. A reduction factor of 5 has been applied to a stimulation threshold of 4 V/m in order to account for the uncertainties described above. Such restrictions rise above 3 kHz.

For the general public for CNS tissue of the head a reduction factor of 5 is applied, giving a basic restriction of 10 mV/m between 10 and 25 Hz. Above and below these values, the basic restrictions rise. At 1,000 Hz it intersects with basic restrictions that protect against peripheral and central myelinated nerve stimulation. Here, the reduction factor of 10 results in a basic restriction of 400 mV/m, which should be applied to the tissues of all parts of the body.

From the point of view of exposure evaluation it is also easier and more practical to measure electric and magnetic fields than to measure the internal electric field strength inside the human body. The designer must therefore rely on calculated electric and magnetic fields to assess whether or not a design complies with the ICNIRP guideline.

Based on the rationale mentioned above, the reference levels for electric and magnetic field exposure set by the ICNIRP guideline are presented in the following table:

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50 Hz Electric and magnetic field exposure guidelines set by ICNIRP

Exposure	Electric field (kV/m)	Magnetic field (μT)
Occupational	10	1000
Public	5	200

Should the reference level, spatially averaged over the whole body, be exceeded, the basic restriction must be met to comply with ICNIRP's basic restrictions of 100 mV/m (occupational) and 20 mV/m (public).

Typical electric fields that can be expected from transmission lines are shown in the following table:

Voltage (kV)	Max E-field (kV/m)	E field at servitude (kV/m)	Typical servitude width (m)*
765	10.0	2.5	40.0
400	4.7	1.5	23.5
275	3.0	0.5	23.5
132	1.3	0.5	15.5
88	0.8	0.3	15.5

* Reference from centre of line

Typical magnetic fields that can be expected from transmission lines are shown in the following table:

Voltage (kV)	Phase current (A)	Max M-field (μT)	Max M-field at servitude (μT)	Typical servitude width (m)*
765	560	6.0	1.5	40.0
400	650	10.5	2.5	23.5
275	350	6.0	1.0	23.5
132	150	4.0	1.0	15.5
88	60	1.3	0.2	15.5

* Reference from centre of line

EMFs emanating from power system substations and substation equipment must comply with the exposure limits using the boundary fence as reference.

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4. AUTHORIZATION

This document has been seen and accepted by:

Name	Designation
B Dames	Chief Executive
E Johnson	Chief Officer (Networks and Customer Service)
D L Marokane	Acting Chief Officer (Generation Business) and Managing Director (Primary Energy Division)
PS O'Flaherty	Finance Director
BE Bulunga	Managing Director (Human Resources Division)
MM Ntsokolo	Managing Director (Transmission Division)
Dr SJ Lennon	Managing Director (Corporate Services Division)
A Noah	Managing Director (Distribution Division) and Acting Managing Director (Special Project 2010)
K Steyn	Acting Managing Director (Enterprises Division)
K Lakmeeharan	Managing Director (System Operations and Planning Division)
T Govender	Managing Director (Generation Division)
CAK Choeu	Managing Director (Corporate Affairs)

5. REVISIONS

Date	Rev.	Remarks
August 2006	0	

6. DEVELOPMENT TEAM

This policy has been developed by KR Hubbard, S Naidoo and R Arscott with inputs from Environmental Liaison Committee and Occupational Health and Safety Liaison Committee.

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APPENDIX E – FINITE DIFFERENCE TIME DOMAIN (FDTD) NUMERICAL METHODS

This Appendix explains the FDTD numerical method being used in the SEMCAD X software package [SPEAG].

Maxwell's equations can be expressed in complex phasor form $X(r,t) = R\{e^{j\omega t}X_{(r)}\}$ with angular frequency ω:

$$\nabla \times E = -j\omega B \quad \text{(E.1)}$$

$$\nabla \times H = j\omega D + J \quad \text{(E.2)}$$

$$\nabla \cdot D = \rho \quad \text{(E.3)}$$

$$\nabla \cdot B = 0 \quad \text{(E.4)}$$

where *E, D, B, H, J* and ρ are the electric field, electrical displacement field, magnetic flux, magnetic field, current density and volume charge density, respectively. Three constitutive laws govern the electromagnetic theory together with Maxwell's equations:

$$D = \varepsilon E \quad \text{(E.5)}$$

$$B = \mu H \quad \text{(E.6)}$$

$$J = \sigma E + J_0 \quad \text{(E.7)}$$

whereσ is the effective conductivity, μ is the permeability,J_0 is the source current and ε is the permittivity given by $\varepsilon = \varepsilon_r\varepsilon_0$ where ε_r is the relative permittivity and ε_0 is the free space permittivity. A complex permittivity term is defined as $\tilde{\epsilon} = \varepsilon + \frac{\sigma}{j\omega}$.

The quasi-static laws are derived from Maxwell's equations by neglecting either the magnetic induction or the electric displacement current.

In the low frequency approximation Amperes law is reduced to$\nabla \times H = J$, insidea conductive homogeneous region, and to$\nabla \times H = j\omega D$ in a non-conductivehomogeneous region. The contribution from the displacement current in the outerregion is assumed to be negligible,

which leads to$\nabla \times H = 0$. Since all regions aresource-free the electric field in each region fulfils$\nabla \cdot E = 0$. The remaining two equations are unchanged. They read

$$\nabla \times E = -j\omega\mu_0 H, \qquad \nabla \cdot H = 0. \tag{E.8}$$

This is equivalent to replacing equation (E.1) with $\nabla \times E \cong 0$ or replacing equation (E.2) with$\nabla \times H \cong J$.

A decision as to whether a quasi-static field ought to be classified as electro-quasi-static (EQS) or Magneto-quasi-static (MQS) can be deduced by a simple rule of thumb: lower the frequency of the driving source to zero so that the fields become static, if the magnetic field dies out in this limit then the field is EQS; if the electric field dies out then the field is MQS. To justify the quasi-static approximations, one has to ensure that neglecting the magnetic induction in EQS or the displacement current in MQS does not produce significant error. By defining a typical length scale *d* and a characteristic time τ, the spatial derivatives that make upthe curl and divergence operators can be approximated as $\frac{1}{d}$and the temporal derivative as $\frac{1}{\tau}$. For the EQS approximation, based on equations (E.1) and (E.2), a term E_{error} as shown in equation (E.15) is defined as the electric field term neglected due to the approximation. The quasi-static field and the ratio of the error field to the quasi-static field are given in equations (E.9) and(E.10), respectively. In a similar manner, the ratio for the MQS approximation can be deduced and proven to be the same as that of the EQS case. Both the EQS and MQS approximations are valid by assuming a sufficiently low frequency and small dimensions i.e. $\omega^2\mu\tilde{\varepsilon}d^2 \ll 1$. This is equivalent to thestatement that either of the quasi-static approximations is valid if an electromagnetic wave can propagate through a length*d* in a time that is short compared to the τ of interest. Fora sinusoidal excitation,τ is the reciprocal of the angularfrequency ω. The condition $\omega^2\mu\tilde{\varepsilon}d^2 \ll 1$ must be satisfiedby all materials within the computation domain.

$$E_{error} = \frac{\mu\rho d^3\tilde{\varepsilon}}{\tau^2\varepsilon} \tag{E.9}$$

$$E_{EQS} = \frac{\rho d}{\varepsilon} \tag{E.10}$$

$$\frac{E_{error}}{E_{EQS}} = \frac{H_{error}}{H_{MQS}} = \frac{\mu\tilde{\varepsilon}d^2}{\tau^2} = \omega^2\mu\tilde{\varepsilon}d^2 \tag{E.11}$$

Assuming a vector potential A where $\nabla \times A = B$and a scalarelectric potential$\emptyset_e$, equation (E.1) can be written as

$$\nabla \times (E + j\omega A) = 0 \quad \text{(E.12)}$$

with vector identity $\nabla \times (\nabla \emptyset_e) = \vec{0}$, and E can be expressed as

$$E = \nabla \emptyset_e - j\omega A \quad \text{(E.13)}$$

$$\varepsilon_{rel}(\omega) = \varepsilon_\infty + \sum_{n=1}^{4} \frac{\Delta\varepsilon_n}{1+(i\omega\tau_n)^{1-\alpha_n}} + \frac{\sigma_{ion}}{i\omega\varepsilon_0} \quad \text{(E.14)}$$

From equations (2.2) (from Section 2), E.14 andE.6

$$\nabla \times \frac{1}{\mu} \nabla \times A = j\omega\tilde{\varepsilon}(\nabla \emptyset_e - j\omega A) + J \quad \text{(E.15)}$$

Taking $\nabla \cdot$ on both sides and assuming that no charge isgenerated ($\nabla \cdot J = 0$), equation (E.18) gives

$$\nabla \cdot \tilde{\varepsilon} \nabla \emptyset_e = j\omega \nabla \cdot \tilde{\varepsilon} A \quad \text{(E.16)}$$

Applying the EQS approximation and assuming no source current (J = 0), equation (E.15) is reduced to

$$\nabla \times \frac{1}{\mu} \nabla \times A = 0 \quad \text{(E.17)}$$

and equations (E.13) and (E.15) can be written as

$$E = \nabla \emptyset_e \quad \text{(E.18)}$$

And

$$\nabla \cdot \tilde{\varepsilon} \nabla \emptyset_e = 0 \quad \text{(E.19)}$$

Applying the MQS approximation, equation (E.14) becomes

$$\nabla \times \frac{1}{\mu}\nabla \times A = J_0 \quad \text{(E.20)}$$

The vector potential A is now equivalent to the magneto-static vector potential A_0 which is completely decoupled from the electric field. If the permeability μ is constant over the entire computation domain Ω, A_0 can be calculated by the Biot-Savart law:

$$A_0(r) = \frac{\mu}{4\pi}\int_\Omega \frac{J_0(r)}{|r-r'|}\, dr' \quad \text{(E.21)}$$

The electric and magnetic fields can be computed by solving equation (E.18) for the EQS case, and solving equations (E.16)and (E.21) for the MQS case, respectively. The computation can be further simplified if all the materials exhibit dielectric properties that obey either $\sigma \gg \omega\varepsilon$ (ohmic current dominant)or $\sigma \ll \omega\varepsilon$ (displacement current dominant). In either case,equation (E.16) can be simplified to:

$$\nabla \cdot \varepsilon\nabla\emptyset_e = j\omega\nabla \cdot \varepsilon A \quad \text{(E.22)}$$

or

$$\nabla \cdot \sigma\nabla\emptyset_e = j\omega\nabla \cdot \sigma A \quad \text{(E.23)}$$

and equation (E.19) can be simplified to:

$$\nabla \cdot \varepsilon\nabla\emptyset_e = 0 \quad \text{(E.24)}$$

or

$$\nabla \cdot \sigma\nabla\emptyset_e = 0 \quad \text{(E.25)}$$

Appendix F - Harmonization of Standards and Guidelines

There has been a growing interest over the years in determining the safe exposure levels of people, mainly workers, and the general public, to power frequency electric fields. Several organizations have developed standards and guidelines for permissible exposure levels to such fields. The most important organizations that have contributed to the establishment of these standards and guidelines are the Institute of Electrical and Electronics Engineers (IEEE) [IEEE, 2002], and the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [ICNIRP 1998 and ICNIRP, 2010]. There are other smaller organizations such as the American Conference of Governmental Industrial Hygienists (ACGIH) and The National Radiological Protection Board (NRPB) in the UK [NRPB, 2004]. The allowable reference levels quoted in many countries refer to the reference levels as set by the IEEE standard or the ICNIRP guideline. There are many benefits to having harmonised standards for EMF exposures. These are:

- Increased public confidence that governments and scientists agree on health risks;
- Reduced debate and fears about EMF;
- Health protection for everyone at the same high level;
- Avoid confusion in the public mind and stress about health effects from EMF exposure when there are different EMF limits required by different authorities

ELF guidelines are based on established effects in volunteers exposed to magnetic fields. These effects are drawn from muscle and nerve stimulation, as well as perceived flickering of light due to the induction of phosphenes in the retina. Table F.1, columns 3 and 4; show the list of external exposure limits for 50 Hz for the IEEE [IEEE, 2002], ICNIRP [ICNIRP, 2010] and NRPB [NRPB, 2004], while Table F.2 lists a summary of internal exposure limits (basic restrictions) for the same frequency.

Table F.1: Summary of External Exposure Limits of Electric and Magnetic Fields from Different Regulating Organizations at 50 Hz Frequency

Organization		**Occupational**	**General Public**
IEEE	Electric Field	20 kV/m	5 kV/m
	Magnetic Field	2.71 mT (Head & Torso)	0.904 mT (Head & Torso)
ICNIRP (2010)	Electric Field	10 kV/m	5 kV/m
	Magnetic Field	1 mT	0.2 mT
NRPB	Electric Field	12 kV/m	12 kV/m
	Magnetic Field	1.6 mT	1.6 mT
ACGIH	Electric Field	25 kV/m	-
	Magnetic Field	1 mT	-

In recent years, a number of laboratories have developed heterogeneous models of the human body with an anatomical shape including numerous organ tissues, to study the electric field exposure. Most of these models have been developed by computer segmentation of data from magnetic resonance imaging (MRI) [F1 –F4].

Table F.2: Summary of Internal Exposure Limits from Different Regulating Organisations at 50 Hz Frequency

Organisation	Organ	Occupational	General public
IEEE	Brain	53.1 mV/m	17.7 mV/m
	Heart	943 mV/m	943 mV/m
	Hands, wrists, feet and ankles	2100 mV/m	2100 mV/m
	Other tissue	2100 mV/m	701 mV/m
ICNIRP (2010)	Central nervous system (CNS) tissues of head	120 mV/m	24 mV/m
	All other tissues	800 mV/m	400 mV/m
NRPB	Central nervous system (CNS)	10 mA/m^2	10 mA/m^2

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