

University of Southern Queensland
Faculty of Engineering & Surveying

Evaluation of Commercial EMF Software

A dissertation submitted by

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Abstract

Electricity has become an integral part of life during the nineteenth and twentieth century. As a society we have become more reliant on electric energy and it is considered an essential service by the majority of customers.

As such electric utilities are under increasing pressure to provide a reliable source of electric energy, with built in redundancy to guarantee continuity of supply. The additional redundancy coupled with the high growth in electric energy usage has resulted in electric utilities placing both High and Low Voltage infrastructures closer to homes, schools and places of work.

The general public are concerned with adverse health effects associated with exposure to electric and magnetic fields (EMFs) radiated from this electricity infrastructure.

The scientific community despite years of research and large amounts of research funding, has found no direct link between EMFs and adverse effects on human health. Despite this electric utilities are adopting a policy of 'prudent avoidance' which defines limits on EMF exposure levels.

In order to comply with this policy there is a requirement to purchase software to accurately estimate and model the EMF radiated from High and Low Voltage infrastructure. This project will develop a systematic procedure for evaluation and selection of EMF software by developing theoretical models and carrying out laboratory tests to verify the results obtained.

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Contents

Abstract	i
Acknowledgments	iv
List of Figures	ix
List of Tables	xi
Chapter 1 Introduction	1
1.1 Justification for the Project	1
1.2 Objective of the Project	2
1.3 Overview of the Dissertation	3
Chapter 2 Literature Review	4
2.1 EMF Background Information	5
2.2 EMF Standards	12
2.3 EMF Modeling Theory	16
2.3.1 Electric Fields Theory	18

CONTENTS	vi
2.3.2 Magnetic Fields Theory	20
2.4 Chapter Summary	23
Chapter 3 Theoretical Models	25
3.1 Physical Structures	27
3.2 Model Theory	30
3.3 Model Algorithms	33
3.4 Chapter Summary	37
Chapter 4 Experimental Verification	41
4.1 Experiments	43
4.1.1 Experiment Method	43
4.1.2 Experiments Equipment & Procedures	45
4.1.3 Experiments Construction Details	47
4.1.4 Measured Magnetic Fields Results	49
4.2 Commercial EMF Software results	50
4.2.1 Narda Model Results	51
4.2.2 EPRI Model Results	53
4.2.3 CDEGS Model Results	54
4.3 MATLAB Results	55
4.4 Discussion of Results	56

4.4.1	Experiments 1 and 2	56
4.4.2	Experiments 3 and 4	59
4.4.3	Experiment 5	62
4.5	Chapter Summary	63
Chapter 5 Commercial EMF Software Evaluation and Selection		65
5.1	EMF Software Solutions	67
5.1.1	Narda EFC 400	67
5.1.2	EPRI EMF Workstation SUBCALC	68
5.1.3	SES CDEGS - HiFREQ	69
5.2	Selection Criteria	70
5.3	Response to Selection Criteria	73
5.4	Recommendation	82
5.5	Chapter Summary	83
Chapter 6 Conclusions and Further Work		85
6.1	Achievement of Project Objectives	86
6.2	Further Work for CDEGS EMF Software	87
References		89
Appendix A Project Specification		93

Appendix B	MATLAB code for symmetrical Magnetic Field	95
Appendix C	MATLAB code for non symmetrical Magnetic Field	98
Appendix D	Photographs of Experiments Structure A	102
Appendix E	Photographs of Experiments Structure B	105
Appendix F	Experiment and Model Results	108

List of Figures

2.1	Electric fields diverging from conductor	7
2.2	Magnetic fields curling around conductor	8
2.3	Typical values of magnetic field exposure	9
2.4	Example of unequal polarized magnetic field	15
2.5	Example of equal polarized magnetic field	16
3.1	Vector r in single conductor, symmetrical magnetic fields	34
3.2	Vector r in three conductor, symmetrical magnetic fields	38
3.3	Vector r in non symmetrical magnetic fields	38
4.1	Structure A symmetrical magnetic fields	48
4.2	Structure B isometric view for non symmetrical magnetic fields	49
4.3	Structure B side elevation view non symmetrical magnetic fields	50
4.4	Comparison of Experiment 1 magnetic fields results	57
4.5	Comparison of Experiment 2 magnetic fields results	58
4.6	Comparison of Experiment 3 magnetic fields results	60

4.7	Comparison of Experiment 4 magnetic fields results	61
4.8	Comparison of Experiment 5 magnetic fields results	63

List of Tables

2.1	EMF Short Term Exposure Levels ($50Hz$)	14
3.1	Programming steps for symmetrical magnetic fields calculation	39
3.2	Programming steps for non symmetrical magnetic fields calculation	40
4.1	Experiment details	45
4.2	Experiment equipment	46
4.3	Experiment procedures	47
4.4	Experiment 1 to 5 Measured Magnetic Fields at -750mm	51
4.5	Experiment 1 to 5 Narda Modeled Magnetic Fields at -750mm	52
4.6	Experiment 1 to 5 EPRI Modeled Magnetic Fields at -750mm	53
4.7	Experiment 1 to 5 CDEGS Modeled Magnetic Fields at -750mm	54
4.8	Experiment 1 to 5 MATLAB Modeled Magnetic Fields at -750mm	55
5.1	EPRI Sub-Packages and modules	69
5.2	CDEGS sub-packages	70

5.3 Commercial available EMF software costing 79

Chapter 1

Introduction

1.1 Justification for the Project.

The general public and electric industry employees are concerned with exposure to electric and magnetic fields (EMFs) radiating from electrical infrastructure. They are particularly concerned that electric and magnetic fields may be associated with an increased risk of illness, ranging from various forms of cancer to birth defects.

Electric and magnetic fields are a natural consequence as a result of the use and transfer of electric energy. Electric fields are generated by the voltage applied to a conductor while magnetic fields are generated by the electric current with-in a conductor. The scientific community despite years of research and large amounts of research funding, has found no direct link between EMFs and adverse effects on human health although some epidemiology studies have found a weak association between long term EMF exposure and an increased risk of childhood leukemia. Expert panels agree that we are still lacking answers to certain scientific questions. These questions require further research which is ongoing.

As a result of this uncertainty electric utilities including Ergon Energy, are adopting a form of 'prudent avoidance' or 'path of least regret' by limiting new EMF exposures to the levels society at large has found acceptable. The principal of prudent avoidance

invests modest expenditure to relocate infrastructure away from sensitive areas.

Ergon Energy has issued guidelines for new electrical infrastructure to provide practical guidance in the application of EMF management techniques and to undertake cost monitoring of this procedure. As part of these guidelines Ergon Energy nominates the “Ergon Energy Interim Reference Levels for New Electrical Infrastructure”. These levels are largely based on levels specified by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) with some modifications.

In order to comply with these guidelines there is a requirement within Ergon Energy to accurately estimate and model the EMF generated from electrical infrastructure including underground cable routes, overhead power lines and high voltage sub stations.

The main aim of this project is to develop a systematic procedure for the evaluation and selection of commercially EMF software, which will lead to a recommendation for the purchasing of EMF modeling software in order to estimate the EMF generated by High Voltage Sub Stations and Distribution, Sub-Transmission and Transmission Networks.

This systematic procedure will then be applied to commercial EMF software programs from the following manufacturers:

- Narda Safety and Test Solutions German based
- Electric Power Research Institute (EPRI) US based, and
- Engineering Services and Technology (SES) Canada based.

By carrying out this project an understanding of EMF research, standards, theory modeling procedures and evaluation skills will also be developed.

1.2 Objective of the Project

The aim of this project is to develop a systematic procedure for the evaluation and selection of EMF software.

Specific Objectives are:

1. To carry out a literature review on the requirement for EMF monitoring, electromagnetic modeling on which EMF software is based and EMF standards;
2. To develop a number of theoretical models based on principals such as Maxwell Laws and Biot-Savart Law to verify numerical results from commercially available EMF software simulating simple conductor configuration;
3. To carry out laboratory tests on simple conductor configuration and compare test results with theoretical models and commercial software prediction;
4. To develop a list of criteria against which commercially EMF software could be evaluated;
5. To carry out an evaluation of a small number of software packages according to the criteria developed above.

1.3 Overview of the Dissertation

This dissertation is organized as follows:

Chapter 2 describes the background theory and literature review for the project.

Chapter 3 discusses the theoretical models developed to compare the results of magnetic fields measurement against results from software models.

Chapter 4 provides experimental verification.

Chapter 5 introduces three commercially available software programs, develops a set of a selection criteria for the evaluation of EMF software and recommends the software to be purchased.

Chapter 6 concludes the dissertation and suggests further work in the area of ‘software integration’.

Chapter 2

Literature Review

This chapter will provide the results of a Literature Review on electric and magnetic fields applicable to extra low frequency of $50Hz$. The Literature Review is designed to identify applicable background information, exposure standards and computation theory in order to develop a systematic procedure for the evaluation and selection of EMF software.

The chapter aims to,

- Provide background information on EMF's and results of health studies applicable to the power industry,
- Identify applicable standards which limit EMF exposure to the general public and electric industry employees,
- Identify the computation theory used in EMF models, and
- Provide of the key points.

The Literature Review details identified in this chapter are used in chapter 3 to further develop EMF computer models and algorithms in order to verify the numerical results obtained from commercially available EMF software.

2.1 EMF Background Information

Generally there are two kinds of electric and magnetic fields. The first type is static electric and magnetic fields (EMFs) which occur naturally in the atmosphere. Static electric fields are naturally generated under thunder clouds, but are also associated with direct current (DC) distribution in items such as electric trains. Static magnetic fields naturally occur within the earth surface and we associate these fields with the north and south pole. The second type of EMF's are man made and are usually associated with alternating current (AC) equipment and infrastructure used in electric energy transmission and communication systems. (WHO 2006*b*) This report is specifically aimed at electric and magnetic fields from man made sources and as such all references and theory identified is applicable to alternating current at extra low frequency of $50Hz$ (or $60Hz$ when references are made to American sources).

Electric and magnetic fields are intrinsically related to electric charge. Electric charge is carried by fundamental particles called atoms, which consist of Electrons and Protons. These Electrons contain a negative charge, while Protons contain a positive charge. (Dobney 1996)

Two groups of charges exert a force on each other if charged by different energy levels. The energy levels can be a different amount or opposite polarity. This force represents the electric field. As electric fields are caused by force which is measured in Volts, we describe the electric field in units of Newton per Coulomb (N/C) or more commonly in Volts per meter (V/m).

If a conducive material, such as Copper or Aluminum, is placed between two groups of charges, which has a voltage difference or an electric potential between them, the charges will attempt to equalise and electric current will flow. When this current flows, the motion of charges produces an additional force on each other which is represented as the magnetic field. As magnetic fields are caused by movement of charges or electric current, which has units of Ampere (A), we measure magnetic field in units of Ampere per meter (A/m). Usually when we mention magnetic fields we are concerned with the magnetic flux density, which depends on the medium in which the magnetic field exist. These terms are often interchangeable, however magnetic flux density will be used for

this project. The unit of magnetic flux density is the Telsa. This is a relatively large unit and is more commonly expressed as micro Telsa (μT). Another unit associated with magnetic flux density is the milliGauss (mG). Although the Gauss units are used frequently in EMF Literature and specifications, the International System of Units (SI) uses Telsa to quantify magnetic flux density and therefore will be used for this project. Gauss and Telsa are directly proportional to each other with ten mG equal to one μT . (Morgan 1988)

As electric and magnetic fields are intrinsically related to voltage and current, they are produced by all electric items such as Power Lines, Transformers, Electric Wiring and Appliances.

Some attributes of electric fields include;

- They are produced by different energy or voltage levels and therefore can exist in wiring even if the appliance that is connected to the wiring is turned off,
- They are proportional to the voltage levels that created them, ie the greater the voltage, the greater the electric field,
- Electric fields tend to spread out or diverge from a source,
- Because of this divergence, they are relatively easily shielded or weakened by items such as walls, building, human skin and trees,
- Electric fields reduce in strength with increasing distance from the voltage source that created them.

Some attributes of magnetic fields include;

- They are produced by movement of charges or current and therefore only exist in wiring when the appliance is turned on,
- They are proportional to the current that created them, ie the greater the current, the greater the magnetic field,
- Imaginary lines of magnetic fields encircle or curl around the current source that created them,

- Because magnetic fields curl around that current source, they are not easily shielded or weakened by most items,
- They reduce in strength with increasing distance from the current source that created them.

(adapted from (EMF-RAPID 1995))

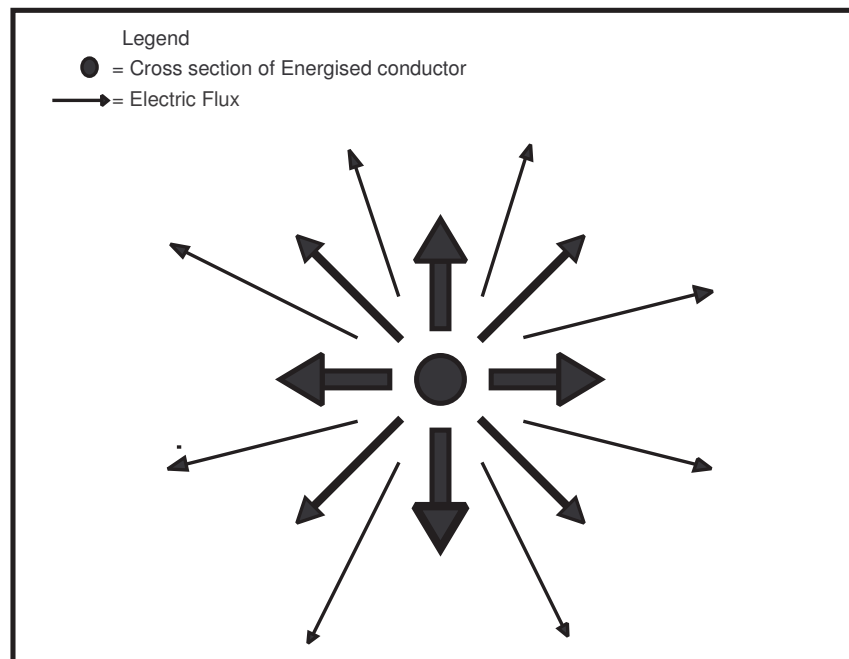


Figure 2.1: Electric fields diverging from conductor (adapted from (Kraus 1999))

The cross section of the energised conductor in figure 2.1 shows how the electric field diverges from its source. Generally electric fields which are produced by voltage sources are associated with High Voltage infrastructure, while magnetic fields which are produced by current sources are associated with both High and Low Voltage Infrastructure. The voltage of the Electric Power System is fairly constant and therefore the associated electric fields are generally stable and are easily shielded by items such as structures, vegetation or human skin. Safety requirements stipulate that High Voltage conductors be constructed at certain distances from the ground, which increases the distance between electric field sources and the general public. Therefore electric fields do not present a significant health risk and are generally excluded from most research.

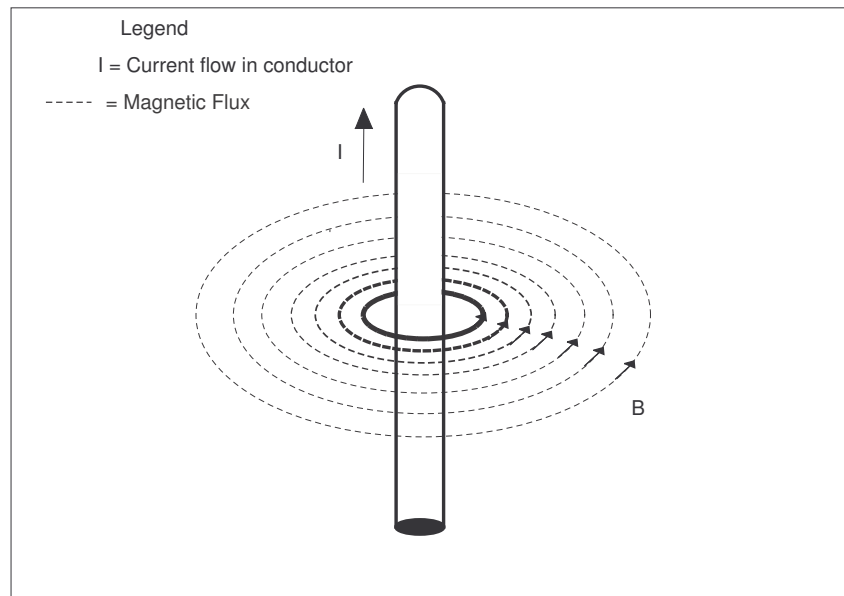


Figure 2.2: Magnetic fields curling around conductor (adapted from (Kraus 1999))

The cross section of the current carrying conductor in figure 2.2 shows the magnetic field encircling or curling around the conductor. This curling ensures that magnetic fields are not easily shielded or weakened by items such as structures vegetation or human skin.

Electric and magnetic fields reduce in strength with increasing distance from the source of the field. The magnetic field impact on a person from a High Voltage power line may be less than that of a household electrical appliance such as a stove or hair dryer. This is because the magnetic field from the power line is initially at a higher value, it will be significantly weakened by the time it reaches the home. In contrast the appliance has a weaker magnetic field but a person can place themselves directly in that weaker field while using the appliance. (Garrido 2003). This is demonstrated in figure 2.3 which shows typical values of magnetic fields radiated from electric appliances measured at normal user distance. For comparison figure 2.3 also includes typical magnetic field values from Low Voltage(LV) power line, Electrical Substation and a High Voltage(HV) power line. Inspection of figure 2.3 shows that in this typical case, the hairdryer has a greater exposure level than the high voltage power line. As the chart also demonstrates the electric stove, personal computer (PC), television (TV) and electrical blanket all have a greater exposure value that the low voltage power line.

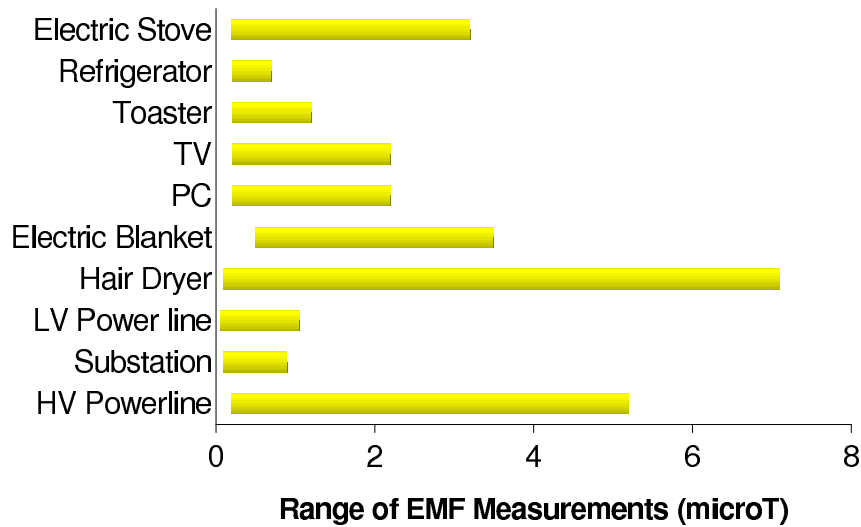


Figure 2.3: Typical values of magnetic field exposure in domestic homes and neighbourhoods. For domestic appliances, values are measured at normal user distance. Substation values are measured at the fence, LV power line values are measured 10 meters from centre line and HV power line measured at edge of easement. (adapted from (ARPANSA 2004))

The existence of EMFs from electrical infrastructure coupled with the increasing demand for electric energy, results in a greater EMF exposure for the general public. Despite decades of EMF Research Projects into EMF exposure and health concerns, no major public health risks have emerged, but uncertainties still remain. (WHO 2006*a*). There are three main areas of research undertaken or currently underway,

- Laboratory studies on single cells or organs to see how they behave when exposed to different levels of EMFs,
- Laboratory studies on animals or humans to check for effect of EMF exposure, and
- Epidemiological studies that examine if people exposed to various levels of EMFs have a above normal chance of contracting a disease such as cancer or other general health issues such as increased risk of miscarriage during pregnancy.

The results of these studies are generally not conclusive and do not provide straight forward answers. Scientists appear to agree that there is a legitimate basis for concern,

but can't provide a direct cause and effect relationship between EMF and adverse health problems. In fact quite often one research findings will contradict another research group results, which ultimately reduces our confidence in the research. The language used in some EMF reviews is also not conclusive, quite often they include the terms such as,

- Suggestive of an association,
- Has not been scientifically established,
- No firm evidence,
- We suspect but cannot be certain.

(adapted from (EMF-RAPID 1995, Morgan 1988))

If exposure to EMFs does increase the risk of disease, then it is expected the individual risk is likely to be small (Sahl 1995). Some research reviews indicate that epidemiological studies support an association between long term exposure to EMFs and an increased risk of developing leukemia in children. (EMF-RAPID 2002, Gibbs 1991) This has prompted the International Agency for Research on Cancer (IARC) to classify,

- Extremely low frequency magnetic fields as possibly carcinogenic to humans,
- Extremely low frequency electric fields as not carcinogenic to humans.

The IARC has observed that as a result of pooled analysis of nine well conducted studies, no excess risk was seen for exposure to ELF magnetic fields below $0.4\mu T$ while above this exposure value, there was a twofold excess risk. (IARC 2002) Some reports indicate that this is applicable to 3% of American homes.(Syfers 2006) However a leading United Kingdom epidemiologist, Sir Richard Doll, when concluding a study between EMFs and the risk of cancer, considered that "...the evidence is currently not strong enough to justify a firm conclusion that such fields (EMFs) cause leukemia in children" (NRPB 2001).

While the results of the research are generally not conclusive there is however a possibility that EMF has an association with adverse health effects. To combat this possible

association, electric utilities have adopted a policy of prudent avoidance as the most appropriate response while planning new or augmenting existing Electrical Infrastructure. Initially Prudent Avoidance involved limiting EMF exposures to values that researchers had found acceptable, however section 2.2 does detail a more precise definition involving limits for induced current in the body as a result of short term EMF exposure. It is not based on firm scientific basis or engineering theory and is considered by many to be of little benefit. Despite this prudent avoidance was defined by Sir Harry Gibbs in a inquiry into High Voltage Transmission Line Development for the NSW Government, as “...prudent to do whatever can be done without undue inconvenience and at modest expense to avert possible risk”. (Gibbs 1991) Even though it is considered that adopting a policy of prudent avoidance provides no proven benefit, most electrical utilities in Australia, including Ergon Energy, have adopted this policy. (Gibbs 1991, McManus 1992) The policy of prudent avoidance will be further discussed in section 2.2, where EMF short term exposure reference limits are identified.

2.2 EMF Standards

The Australian Radiation Protection and Nuclear Safety Agency (ARPANSA), is a Australian Federal Government agency that has the responsibility for protecting the people and the environment from the potential harmful effects of radiation such as exposure to $50Hz$ EMFs. They advise that there is currently no Australian Standards which regulates the exposure to $50Hz$ magnetic fields. (ARPANSA 2006). However there are guidelines available, both Australian and International, which recommend limits on exposure to EMFs with the intention that they will provide some protection against adverse health effects.

In Australia the National Health and Medical Research Council (NHMRC) published the ‘Interim guidelines on limits of exposure to 50/60Hz electric and magnetic fields’ in 1989. These guidelines have since been rescinded by the NHMRC and responsibility has been transferred to ARPANSA. These 1989 guidelines are currently under review and ARPANSA are planning to replace them with an Extra Low Frequency (ELF) Radiation Standard, which will provide exposure limits from $0Hz$ to $3kHz$, as well as precaution advice on how to manage EMFs exposure. The new ARPANSA ELF standard is expected to be issued for public comment shortly.

The now rescinded interim guidelines produced by NHMRC were based on guidelines developed in 1989 by the International Non-ionizing Radiation Committee of the International Radiation Protection Association (IRPA/INIRC). The IRPA/INIRC guidelines have been superseded in 1998 by the ‘Guidelines for Limiting Exposure to Time-Varying Electric, Magnetic and Electromagnetic Fields (Up to 300GHz)’ produced by the International Commission on Non-Ionizing Radiation Protection (ICNIRP). (NHMRC 1989, ICNIRP 1998). The new ARPANSA ELF standard is expected to follow international trends and reference the ICNIRP guidelines but be slightly different in content. Even though ARPANSA are describing the new document as a standard, compliance will only become a mandatory requirement if referenced by a regulating body such as State or Federal Government.

The ICNIRP Guidelines are designed to only prevent short term EMF induced current, causing adverse health effects. ICNIRP describes adverse health effects as “detectable

impairment of the health of the exposed individual or their offspring". The exposure limits in the ICNIRP guidelines do not provide protection against increased health risks associated with long term EMF exposure. This is because ICNIRP, along with other national agencies, has recognised that epidemiological research has provided suggestive but unconvincing links between EMF and carcinogenic effects, such as cancer, and the existing studies are an insufficient basis for settings more restrictive long term exposure limits. (ICNIRP 1998, TRPC 2006)

The EMF exposure limits in the ICNIRP guidelines comprise of,

- Basic Restrictions which provide limits on the induced current allowed in the body as a result of short term EMF exposure. This EMF induced current in a body is very difficult to measure or predict.
- EMF Reference Levels which are provided for practical exposure assessment purposes, to determine if the EMF Basic Restriction induced current limit will be exceeded. If an EMF value is measured or modeled below the Reference Level then compliance with the Basic Restriction induced current limit is assured. If the exposure level is measured or modeled above the Reference Level then further investigation is required to determine if the Basic Restriction induced current limit is exceeded.

The ICNIRP guidelines provide both Basic Restriction induced current limits and Reference Levels which are different for the general public and occupational population. The general public population exposure values contain a safety factor to further reduce the values recommended for the occupational population exposure. The justification for the varying exposure values is that the general public can comprise of both young children and the elderly all with varying health status. In contrast the occupation population generally consists of fit adults who are more aware of the potential health risks and are trained to carry out appropriate safety precautions and health checks. Table 2.1 lists the ICNIRP Guidelines Basic Restriction induced current limits and Reference Levels for both the general public and occupational population to short term EMF exposure.

Ergon Energy currently has a procedure in place which provides practical guidance to the application of EMF management techniques in regards to the siting and location of new electrical infrastructure. These guidelines support the policy of prudent avoidance and provide interim reference EMF limits which are largely based on the ICNIRP guidelines. The Ergon Energy procedure undertakes cost monitoring and analysis to ensure that level of cost incurred complies with the prudent avoidance philosophy of modest expenditure. (ERGON 2005)

The ICNIRP short term exposure levels that are applicable to 50Hz electric and magnetic fields are shown in table 2.1.

Table 2.1: ICNIRP EMF Short Term Exposure Levels (50Hz)(Adapted from rounded off values of table 4, 6 & 7 and figure 1 & 2 of the Guidelines for Limiting Exposure to Time-Varying Electric, Magnetic and Electromagnetic Fields. (Up to 300GHz). (ICNIRP 1998))

Item	Description	Occupational Population	General Public Population
Basic Restriction	Induced Current Limit	$10mA/m^2$	$2mA/m^2$
Reference Level	Magnetic Field	$500 \mu T$	$100 \mu T$
	Electric Field	$10 kV/m$	$5 kV/m$

Magnetic fields from alternating current sources are also alternating in proportion to the frequency of the supply system. With these magnetic fields expanding and collapsing 50 times a second, it is common for the magnetic field axes to have varying rates of expansion and collapse. This can lead to magnetic fields which are polarized with an elliptical characteristic which presents difficulty in defining the level of magnetic field. There are generally two methods of estimating and measuring EMF in order to compare with the values listed in table 2.1. The first method is to specify the maximum field vector which exists at a point. This is the value which would be read by a single axis meter if the sensing coil or antenna was rotated and oriented in a direction to read the maximum value which exists. Inspection of figure 2.4 shows in this particular case the maximum value is $9\mu T$.

The second method is to specify the Resultant or RMS value of magnetic field vector

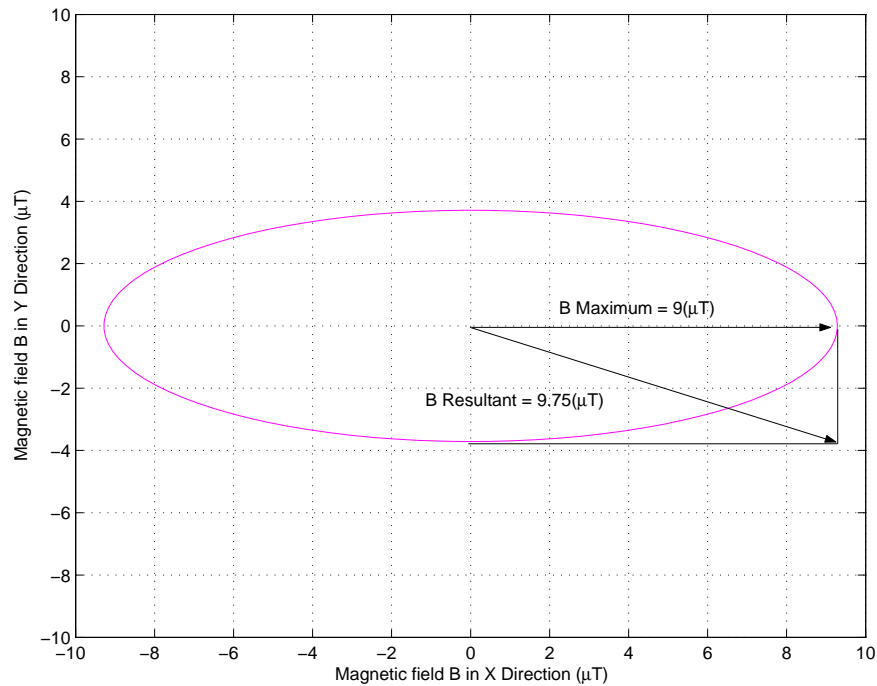


Figure 2.4: Example of polarized magnetic field with unequal resultant and maximum values

which exists at a point. This is the value which would be read by a triaxial axis meter if it had three sensing coils, one each for the X, Y and Z axis. Inspection of figure 2.4 shows in this particular case the Resultant value is $9.75\mu T$, which is a difference of 8%. Inspection of figure 2.5 shows a particular case when the Resultant and Maximum are both equal to $5\mu T$. The difference between the Resultant and the Maximum value can be up to $\sqrt{2}$ or 141.4% which occurs when the minor and major axis are equal which is known as circularly polarized. (Southern California Edison 1995, Enertech 2001) The EMF resultant values are more commonly encountered and will be utilised in this report.

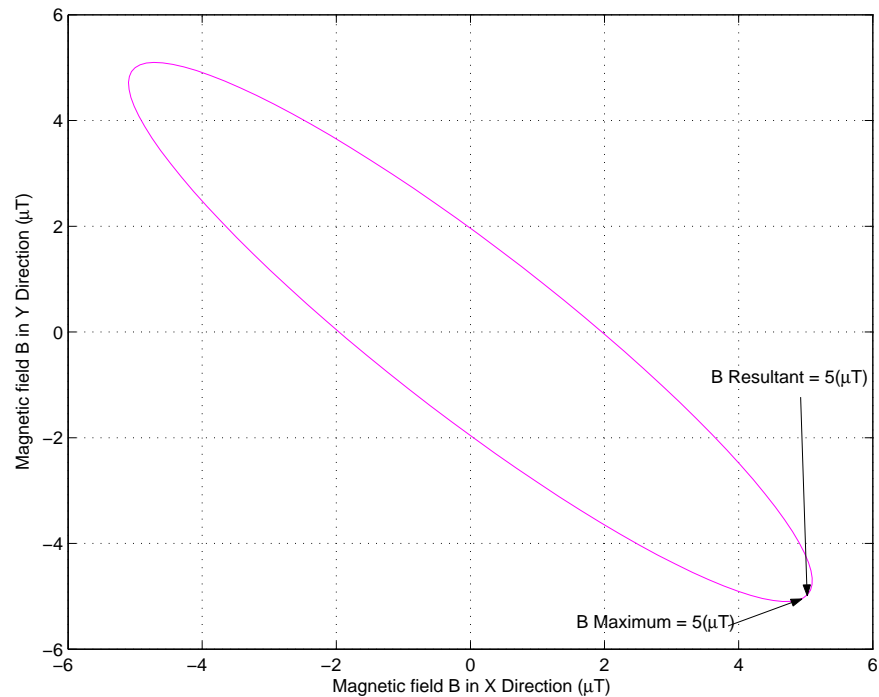


Figure 2.5: Example of polarized magnetic field with equal resultant and maximum values

2.3 EMF Modeling Theory

Generally when we discuss electric energy theory, we assume that electric energy is transmitted from a source to a load through conductive medium such as copper or aluminum wires. This is generally referred to as circuit theory and is considered to be a generalized view of the electric energy transfer process. An alternative view is called field theory which proposes that the energy is actually transmitted from the source to the load by electric and magnetic fields. Field theory proposes that the conductive medium is merely a wave guide to define the energy transfer path. As mentioned in section 2.1, electric fields are caused by different electric charge energy levels and magnetic fields are caused by the movement of electric charges. Modeling the electric and magnetic fields is generally explained using charges and field theory.

Initially it was considered that electric and magnetic fields were separate identities but in 1873 a Scottish physicist, James Clerk Maxwell proposed that electric and magnetic fields were coupled and essentially part of the same phenomenon. To support this proposition, Maxwell using field theory proposed four equations which are now known

as Maxwell's Equations. Generally it is necessary to solve Maxwell's Equations for a particular installation to find the electric and magnetic fields. However this leads to complex maths which does create greater precision, but has the disadvantage of inaccuracies associated with unknown circulating currents. Electric and magnetic fields are coupled as proposed by Maxwell, but at extra low frequency, they are also relatively slow moving and therefore can be investigated using separate electric and magnetic field equations with an acceptable level of accuracy. These equations will be developed in the next sections. (Suplee 2000, Kraus 1999, Garrido 2003)

2.3.1 Electric Fields Theory

As indicated in section 2.1, a force that exists between two charges or charge groups is defined as the electric field. A french military engineer, Charles Augustin Coulomb, using a very sensitive torsion balance, discovered in 1785, that two balls were attracted or repulsed based on a force which was proportional to the charge between them and inversely proportional to the distance squared between them. (Suplee 2000) This is described mathematically as,

$$F = F\hat{r} = \frac{Q_1Q_2}{4\pi\epsilon r^2}\hat{r} \quad (N) \quad (2.1)$$

If we divide equation 2.1 by Q_2 we get the equation for an electric field from a single point charge,

$$E = \frac{F}{Q_2} = \frac{Q_1}{4\pi\epsilon r^2}\hat{r} \quad (N/C) \text{ or } (V/m) \quad (2.2)$$

where,

Q_1 = charge 1, (C)

Q_2 = charge 2, (C)

r^2 = radial distance from charge 1 to charge 2, (m)

\hat{r} = dimensionless unit vector in radial direction

ϵ = permittivity or dielectric constant, (F/m)

This discovery and subsequent equation is commonly known as Coulomb's Law and is one of the fundamental laws for solving electric fields problems. (Bennett 2001, Kraus 1999)

In general when we wish to model the electric fields from electric infrastructure such as overhead power lines, we are concerned with measuring the total field from a transmission line rather than a single point charge on the line. We use line charges to describe the transmission line net charges on an observation point. The term Q_1 in equation 2.2 is replaced with charge density ρ_L which has units of C/m. If the line is sufficiently

long, which is correct for most cases, then the equation for electric field due to a line charges is,

$$E = \frac{\rho_L}{2\pi\epsilon r} \hat{r} \quad (N/C) \text{ or } (V/m) \quad (2.3)$$

For a three phase overhead transmission line we can sum the electric fields contribution of each conductor using the equation 2.3 to get the total electric field at an observation point.

As was indicated in section 2.1, due to shielding effects, electric fields are generally excluded from most EMF research. This is also due to the requirement to suspend high voltage transmission lines to satisfy safety clearance between the transmission lines and ground or nearby structures. Compliance with these safety clearances ensure that the electric fields calculated by equation 2.3 does not exceed the electric field Reference Levels for general population in table 2.1. Special safety control measures are in place to manage the Reference Levels for the occupational population while working on or near High Voltage Infrastructure.

2.3.2 Magnetic Fields Theory

As indicated in section 2.1, the force caused by the movement of charges is defined as the magnetic field. Two french scientists, Jean-Baptiste Biot and Felix Savart, discovered in 1820 that the relationship between the magnetic field H at an observation point and the current which caused it. This relationship is known as the Biot-Savart law and is expressed as

$$dH = \frac{Idl \sin \theta}{4\pi r^2} \quad (A/m) \quad (2.4)$$

We can modify equation 2.4 to calculate the magnetic flux density,

$$dB = \frac{\mu Idl \sin \theta}{4\pi r^2} \quad (T) \quad (2.5)$$

where,

- μ = permeability of the medium, (H/m)
- I = current, (A)
- $d\ell$ = short section of current carrying conductor, (m)
- dH = increment magnetic field at an observation point, (A/m)
- dB = increment magnetic flux density at an observation point, (T)
- θ = angle between an observation point and short section of conductor $d\ell$,
- r = distance vector between section of conductor $d\ell$ and an observation point, (m)

For small sections of current carrying conductor $d\ell$, the incremental magnetic flux density dB , calculated by equation 2.5 is a tangent to an imaginary line of magnetic field which encircle the current carrying conductor. The direction of the tangent is given by the Right Hand Rule. The Right Hand Rule specifies when a conductor is gripped by the right hand, with the thumb pointing in the direction of current flow, the fingers point in the direction of magnetic field lines which encircle the conductor. (Lonngren 2005)

If the magnetic field calculated by equation 2.4 is integrated, then the total magnetic field can be calculated. This was discovered in the early eighteenth century by experiments carried out by a french physicist Andre-Marie Ampere. The relationship between current and magnetic fields is stated as,

$$I = \oint H \bullet d\ell = \int \int J \bullet dS \quad (A) \quad (2.6)$$

Maxwell added another term to Ampere's law stated in equation 2.6, to include a time changing displacement current density. This modified equation is,

$$I = \int_s \left(J + \frac{\partial D}{\partial t} \right) \bullet dS \quad (A) \quad (2.7)$$

where,

dS = surface element, (m^2)

I = current, (A)

$d\ell$ = short section of current carrying conductor, (m)

H = Magnetic field, (A/m)

\oint = line integral around closed path

\int_s = integral over surface enclosed by path

J = current density, (A/m^2)

$\frac{\partial D}{\partial t}$ = time changing displacement current density, (A/m^2)

This relationship described in equation 2.5, 2.6 and it's modified version in equation 2.7 is commonly known as Ampere's Law or the integral of the Biot-Savart Law, and it relates a magnetic field distribution and the electric current which caused it. This is one of the fundamental laws for solving magnetic fields problems. (Suh 2000) The Biot-Savart Law (equation 2.5) is frequently used to calculate the magnetic fields from electrical infrastructure such as transmission lines. The Biot-Savart Law when used to calculate the magnetic fields from electrical infrastructure assumes that the free space, in which the waves travel, is homogeneous, which means that it consists of one permeability μ . (Suplee 2000, Kraus 1999, Berlec 1998)

The models developed using equation 2.5 and 2.6 are reliable and can accurately predict the magnetic fields emitted by electric devices such appliances and coils. (Ohnishi 2002, Garrido 2003) One study to compare the magnetic fields predicted by three computer models against actual measurements of a 400kV dual circuit transmission line, found that the maximum difference between predicted and measured results was $\pm 7\%$. This

difference was largely attributed to measurement errors. (Swanson 1995)

2.4 Chapter Summary

This chapter provides background information on EMF's and comments on health studies completed or underway on EMF's and associated health effects. Applicable EMF standards and guidelines to the power industry are identified. This chapter also identifies equations used in EMF computation methods. Key points discussed in this chapter include.

- Electric and magnetic fields are intrinsically related. Electric fields have units of volts per meter (V/m) while magnetic fields have units of Telsa (T) which more commonly expressed as micro Telsa (μT), and
- Electric fields are proportional to the voltage source that caused them while magnetic fields are proportional to the current source which caused them. Both electric and magnetic fields are reduced as the distance from the source is increased.
- Electric fields are not included in the majority of research as they are easily shielded and, due to safety reasons associated with insulation levels, their source are sufficiently removed from the general public and do not result in dangerous exposure levels. As a result of this, only magnetic fields will be considered in this project.
- Currently no Australian Standards exist to regulate EMF exposure although a Federal Government agency ARPANSA, is currently developing EMF exposure standard. Currently the short term exposure limits specified in guidelines produced by the international organization ICNIRP are generally adopted and implemented by most electric utilities, and
- The IARC has classified long term magnetic fields exposure as possibly carcinogenic to humans, the association between long term EMF exposure and health risks is weak and not proven. Most electric utilities including Ergon Energy use a policy of prudent avoidance to manage EMF exposure. This policy aims to reduce only short term EMF exposure below values specified in ICNIRP guidelines. There are no long term EMF exposure values specified by ICNIRP.

- Electric fields are calculated by using Coulomb Law, while magnetic fields are generally calculated using Ampere Law or Biot-Savart Law. One of Maxwell's equations is a modified version of Ampere Law.

Chapter 3

Theoretical Models

As part of the requirement to develop a systematic procedure for the evaluation and selection of EMF software, it is required to compare the outputs of such software with measurements that are applicable to real life situations. Due to safety reasons and fluctuation of loads, it is difficult to accurately measure magnetic fields emitted from high voltage power lines. Hence models of power lines are constructed in a laboratory and connected to a fixed load. This produces stable magnetic fields which can be accurately measured. This chapter will identify physical structures which are constructed in order to carry out these experiments and also provide details on the theoretical models and algorithms developed in order to verify the numerical results obtained from commercially available EMF software. The chapter is organized in the following areas,

- Identify physical structures which will be used to compare EMF values from theoretical models developed, physical models built and commercially available EMF software outputs,
- Identify theory required to model EMF emitted by the physical structure,
- Develop computer algorithms to implement the theory identified,
- Summary of key points.

The results of this chapter will be utilised in chapter 4 to carry out experiments which will be used to verify the results of commercially available EMF software.

3.1 Physical Structures

This section provides details on physical structures identified for the comparison of magnetic field values. The physical structures will be used in the following areas,

- Constructed in the laboratory in order to measure actual magnetic field emitted by the structures, which is used to verify the accuracy of commercially available EMF software. This is developed further in section 4.
- As a basis for identified theory and software algorithms to predict magnetic fields outputs in order to verify the accuracy of commercially available EMF software. This is developed further in section 3.2 & 3.3, and
- As a basis for commercially available EMF software in order to compare the magnetic fields outputs with predicted and measured results. This is developed further in section 4.

The majority of Electric Transmission and Distribution Networks consist of three conductors with a conductor allocated to one phase of a three phase power supply system. This is commonly known as a three phase system and has three sinusoidal voltages, which are ideally of the same magnitude, but are electrically separated from each other by 120° . (Ramakrishnan 1996)

These electric networks are usually classed as,

- Transmission Networks. These networks are energised in voltages ranging from $110kV$ to $230kV$ and above. They generally transmit electric energy from a generation plant to a city, large town or large industrial customer. Transmission Networks are mainly installed on overhead, suspended conductors and are generally separated from residential areas.
- Sub-Transmission Networks. These networks are energised in voltages ranging from $33kV$ to $66kV$ and transmit electric energy to smaller towns, within cities or to a large industrial customer. Sub-Transmission Networks can be under-

ground especially in built up areas but are more commonly installed on overhead, suspended conductors.

- **Distribution Networks.** These networks are energised in voltages ranging from $11kV$ to $22kV$, however in rural areas single wire earth return systems (SWER) are common, particularly in low demand areas and are energised at 12.7 or $19.1kV$. Distribution Networks are generally underground in built-up residential areas and overhead in less populated and rural areas. Distribution Networks generally supply electric energy to small pole top transformers or packaged substations ranging in size from $50kVA$ to $1500kVA$. From these sub-stations electric energy is distributed to each customer by single or three phase conductors energised at $415V$ or $240V$.

Distribution Networks are usually interconnected in residential locations, work places and public areas. As such, infrastructure within the Distribution Network class provide the dominate source of magnetic fields exposure to the general public. Distribution Networks are usually located in dedicated service corridors or along road ways. The Physical Structure used in this project is designed to simulate a typical overhead Distribution Network.

The physical layout of overhead Distribution Networks depends on the voltage level, local environment or terrain and stringing tension. Typical $22/11kV$ Distribution Networks have horizontal suspended conductors placed $500mm$ apart. The layout of these conductors will vary to include both horizontal and vertical conductors.

Taking this into consideration, the following two types of Physical Structures are used in order to compare results,

- **Structure A:** This structure consists of three horizontal suspended conductors $500mm$ apart. This structure models horizontal conductors that are assumed to be infinitely long and contain no sag. The current distribution from these conductors is assumed to be symmetrical. Magnetic field values are calculated or measured on a cross section grid at regular distances from the conductors.
- **Structure B:** This structure consists of three conductors spaced $500mm$ apart

containing vertical and horizontal conductors. These conductors have a finite length and the current distribution from these conductors is assumed to be non symmetrical. These magnetic fields values are calculated or measured on a cross section grid at regular distances from the conductors.

The physical structures offer the dual advantage of being to construct in the laboratory in order to measure magnetic fields while also similar to structures encountered in Distribution Networks. Although a Distribution Network is typically energised at $22/11kV$, due to safety concerns, the Physical Structures constructed in the Laboratory are energised at $415V$. As we are concerned with measuring magnetic fields associated with current flow only, and not electric fields, the energisation of these physical structures at $415V$, will not effect the experiment objectives.

3.2 Model Theory

This section will further develop the general magnetic field theory identified in section 2.3.2, in order to generate computer algorithms in section 3.3. The physical models, Structure A and Structure B, identified in section 3.1 require two different but related types of magnetic field calculation theory,

- Structure A has symmetrical current distribution and the conductors can be assumed to be infinitely long.
- Structure B has non symmetrical current distribution and the conductors are finite in length.

Section 2.3.2 identified that electric current can be calculated using Ampere Law or it's modified form in Maxwell equation. The Maxwell equation 2.7 is reproduced below,

$$I = \int_s \left(J + \frac{\partial D}{\partial t} \right) \bullet dS \quad (A) \quad (3.1)$$

For low frequency magnetic fields, such as our current system frequency of $50Hz$, the time changing displacement current density $\frac{\partial D}{\partial t}$ in equation 3.1 added by Maxwell is approximately zero. When calculating symmetrical magnetic fields and assuming that the conductors are infinitely long, equation 3.1 is manipulated to solve magnetic flux density (B) and is simplified as,

$$B = \frac{\mu I}{2\pi r} \quad (T) \quad (3.2)$$

adapted from (Fishbane 1996)

where,

B = Magnetic flux density an an observation point, (T)

μ = permeability of the medium, (H/m)

I = current, (A)

r = distance vector between the conductor L and an observation point, (m)

The equation 3.2 is only applicable for calculation of external magnetic fields in symmetrical, infinitely long conductors. If there is more than one conductor, then the magnetic field contribution from each conductor is calculated and summated to give the total magnetic field at an observation point. There are internal magnetic fields inside each conductor, however due to the relatively small diameter of the conductors compared to the distance between the conductors and the observation point, it is assumed that the contribution from the internal magnetic fields is negligible. The equation 3.2 is used for calculation of magnetic fields emitted from Structure A and is easily implemented in a computer algorithm once the dimensions of r and the current I are known. The Structure A computer algorithms will be developed in section 3.3.

The equation 3.2 is not applicable to the calculation of magnetic fields emitted from Structure B as the structure is non symmetrical and contains both vertical and horizontal conductors of finite length. For this calculation we use the Biot Savart Law identified in Section 2.3.2. The Biot Savart Law from equation 2.5 is reproduced below,

$$dB = \frac{\mu I d\ell \sin\theta}{4\pi r^2} \quad (T) \quad (3.3)$$

The total magnetic field at an observation point P , is calculated by summing each dB , ie

$$B = \int dB = \int \frac{\mu I d\ell \sin\theta}{4\pi r^2} \quad (T) \quad (3.4)$$

and finally we can rearrange equation 3.4, and multiply by r to allow the use of cross products. ie

$$B = \int dB = \frac{\mu}{4\pi} \int \frac{I d\ell \times r}{r^3} \quad (T) \quad (3.5)$$

adapted from (Fishbane 1996)

Equation 3.5, can be implemented in a computer algorithm by choosing $d\ell$ sufficiently small. This is achieved by using n segments. As n segments approaches ∞ , $d\ell$ or $\Delta\ell$ approaches zero, the flux density B can be calculated as,

$$B = \frac{\mu}{4\pi} \lim_{n \rightarrow \infty} \sum_{i=1}^n \frac{I \Delta \ell \times r}{r^3} \quad (T) \quad (3.6)$$

adapted from (Garcia 1996) where,

- μ = permeability of the medium, (H/m)
- I = current, (A)
- $d\ell$ = short section of current carrying conductor, (m)
- dB = Increment Magnetic flux density at an observation point, (T)
- B = Total magnetic flux density at an observation point, (T)
- r = distance vector between section of conductor $d\ell$ and an observation point, (m)
- n = segment number

The equation 3.6 is applicable for calculation of external magnetic fields in both symmetrical and non symmetrical conductors. Similarly to the symmetrical case, there are internal magnetic fields inside each conductor, however due to the relatively small diameter of the conductors compared to the distance between the conductors and the observation point, it is assumed that the contribution from the internal magnetic fields is negligible. The equation 3.6 is used for calculation of magnetic fields emitted from Structure B and is implemented in a computer algorithm once the dimensions of r , the current I and the total conductor length is divided into small segments $\Delta\ell$. When this is known, equation 3.6 is implemented in a continuous loop over the entire structure to calculate the magnetic field contribution from each segment $\Delta\ell$. If there is more than one conductor, then the magnetic field contribution from each conductor is summated to give the total magnetic field at an observation point P . The computer algorithms will be developed in section 3.3.

3.3 Model Algorithms

This section will identify computer algorithms required to implement equations developed in section 3.2. The aim of the equations developed and associated computer algorithms is to model magnetic fields emitted from two Structures. The two equations developed are,

- Equation 3.2 for calculation of magnetic fields in symmetrical current distribution where the current carrying conductors are assumed to be infinitely long. This equation will be applied to magnetic field calculations for Structure A.
- Equation 3.6 for calculation of magnetic fields in non symmetrical current distribution where the current carrying conductors are finite in length. This equation will be applied to magnetic field calculations for Structure B.

For the implementation of equation 3.2 to calculate magnetic flux density in symmetrical fields in Structure A, there are two unknowns which need to be defined or calculated. The conductor in Structure A is assumed to be infinitely long and therefore the calculation is reduced to a two dimensional problem as we are assuming that the associated magnetic fields is homogenous for the entire length of the conductor.

The first unknown is the current in the conductor I . This is usually available by direct measurement or can be a derived value based on the applied voltage and connected load. The second unknown is the distance vector r . This distance vector r in equation 3.2 is the distance between the observation point P and the current carrying conductor a . By assuming symmetrical current distribution and infinitely long conductors, the distance vector r can be calculated by applying Pythagorean theorem to the vertical and horizontal distances between observation point P and the conductor a . This demonstrated in figure 3.1.

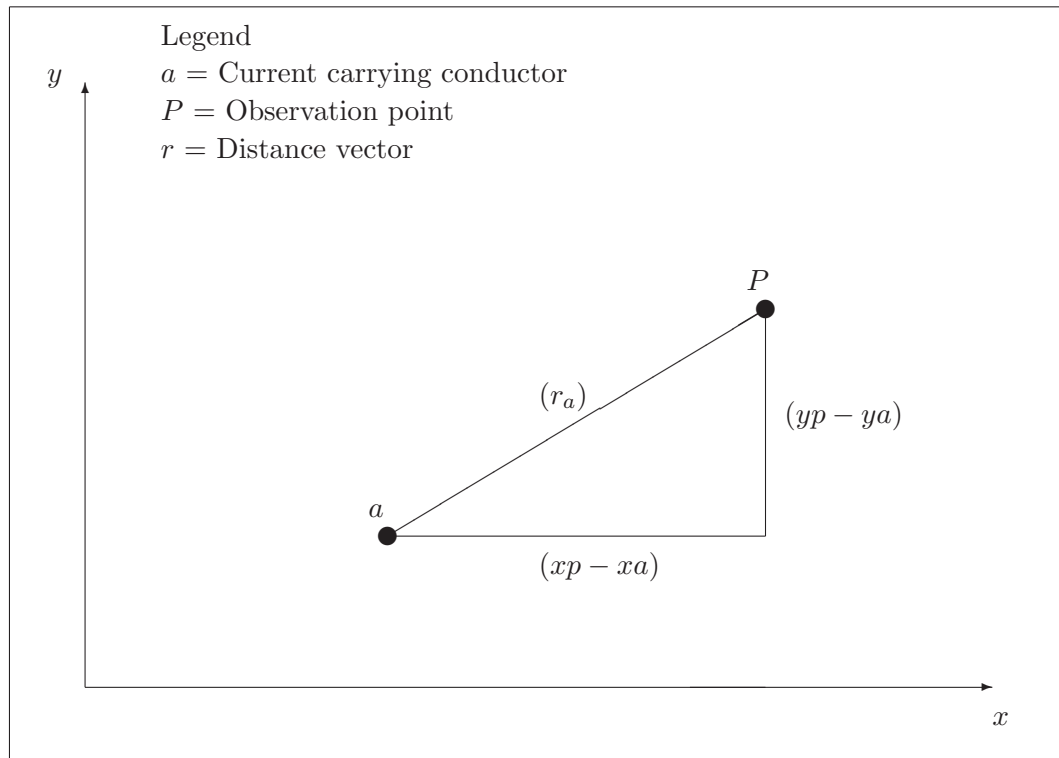


Figure 3.1: Structure A. Calculation of vector r in single conductor, symmetrical magnetic fields

The distance vector r_a is calculated as,

$$r_a = \sqrt{(xp - xa)^2 + (yp - ya)^2} \quad (m) \quad (3.7)$$

In Structure A there are three conductors, one for each phase. The magnetic field contribution from each conductor is determining separately, using equation 3.7 to first calculate the distance vector r and then input this into equation 3.2 to get the separate magnetic field contribution from each conductor. This magnetic field contribution from each conductor is then summated at the observation point P to get the total magnetic field at the observation point P . This is demonstrated in figure 3.2.

The steps required to implement equation 3.2 and equation 3.7 in a computer algorithm, are listed in table 3.1.

MATLAB version 6.5 was used to implement the steps in table 3.1. For a complete list of the MATLAB code refer to Appendix B. The magnetic flux density calculated by the computer algorithm, for Structure A, is listed in chapter 4.

For the implementation of equation 3.6 to calculate magnetic flux density in non symmetrical fields of Structure B, there are three unknowns which need to be defined or calculated. The conductor in Structure B has a finite length and therefore the calculation is required to be carried out in three dimensions.

The first unknown is the current in the conductor I . In a similar manner to the symmetrical case, this is usually available by direct measurement or can be a derived value based on the applied voltage and connected load. The second unknown is the distance vector r . This distance vector r in equation 3.6 is the distance between the observation point P and the segment of the current carrying conductor $\Delta\ell$. This is demonstrated in figure 3.3. As the current distribution is non symmetrical, the distance vector r must be calculated by applying Pythagorean theorem in turn, to all conductor segments $\Delta\ell$. The last remaining unknown is the length of the conductor segment $\Delta\ell$. This is a direct result of choosing n in equation 3.6. As $n \rightarrow \infty$ in equation 3.6, then $\Delta\ell \rightarrow 0$. Generally it is not practical for $\Delta\ell \rightarrow 0$, however acceptable accuracy can be obtained by choosing $\Delta\ell$ small in comparison to the conductor length.

The next step is to calculate the cross product $\Delta\ell \times r$. This cross product is calculated separately along each axis using the following equations.

$$\Delta\ell \times r(x) = \Delta\ell(y) \times r(z) - \Delta\ell(z) \times r(y) \quad (3.8)$$

$$\Delta\ell \times r(y) = \Delta\ell(z) \times r(x) - \Delta\ell(x) \times r(z) \quad (3.9)$$

$$\Delta\ell \times r(z) = \Delta\ell(x) \times r(y) - \Delta\ell(y) \times r(x) \quad (3.10)$$

adapted from (Hughes-Hallett, Gleason McCallum, et al. 1998)

where,

$\Delta\ell \times r(x)$ = Cross product in x direction

$\Delta\ell \times r(y)$ = Cross product in y direction

$\Delta\ell \times r(z)$ = Cross product in z direction

In Structure B there are three conductors, one for each phase. The magnetic field contribution from each conductor is determining separately, by first calculating the distance vector r , inputting this value into the cross product equations 3.8 to 3.10

and finally inputting this value into equation 3.6. This is repeated for all segments in the conductor. When this is carried out, the magnetic field contribution from each conductor is then summated, to get the total magnetic field at the observation point P .

The steps required to implement equation 3.6 in a computer algorithm, are listed in table 3.2.

MATLAB version 6.5 was used to implement the steps in table 3.2. For a complete list of the MATLAB code refer to Appendix C. The magnetic flux density calculated by the computer algorithm, for Structure B, is listed in chapter 4.

3.4 Chapter Summary

This chapter provides details on Theoretical Models which included identifying structures, equations and algorithms required to verify the numerical results obtained from commercially available EMF software. Key points discussed in this chapter include.

- Identify Structure A which will be used to model symmetrical magnetic fields,
- Identify Structure B which will be used to model non symmetrical magnetic fields,
- Identify equations which will be used to model both symmetrical and non symmetrical magnetic fields,
- Develop Theoretical Models in the form of computer algorithms to calculate the magnetic field emitted by the structures at an observation point using equations identified.

The results of this chapter will be utilised in chapter 4 to carry out experiments which will be used to verify the results of commercially available EMF software.

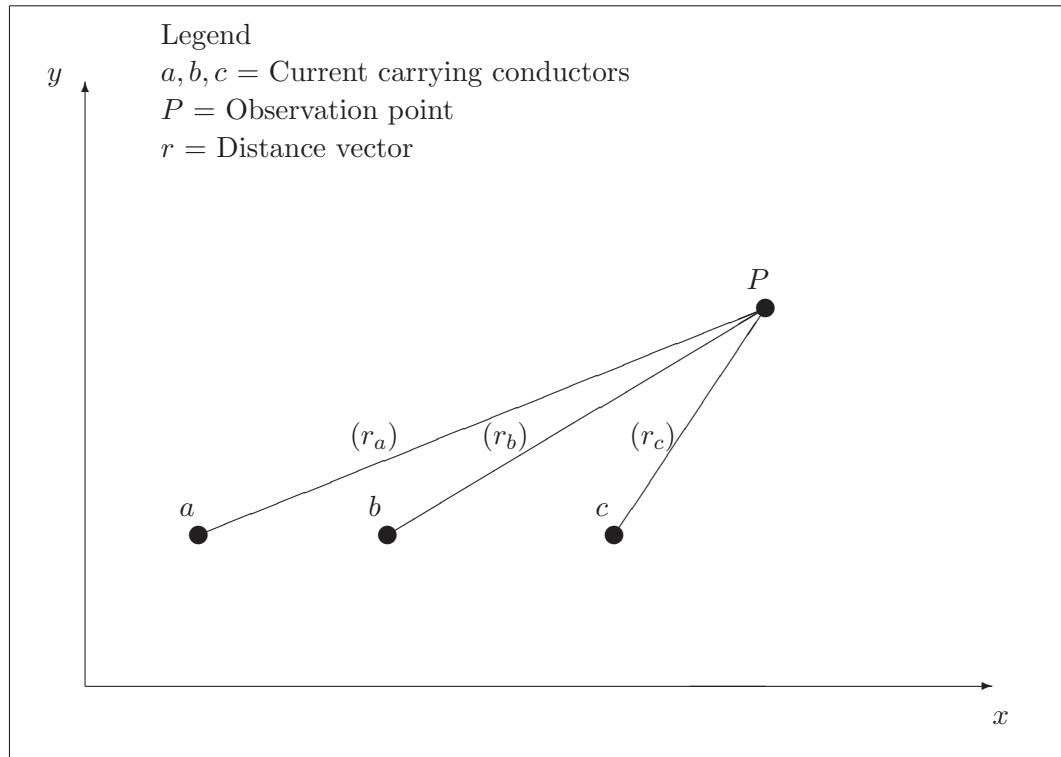


Figure 3.2: Structure A. Calculation of vector r in three conductor, symmetrical magnetic fields

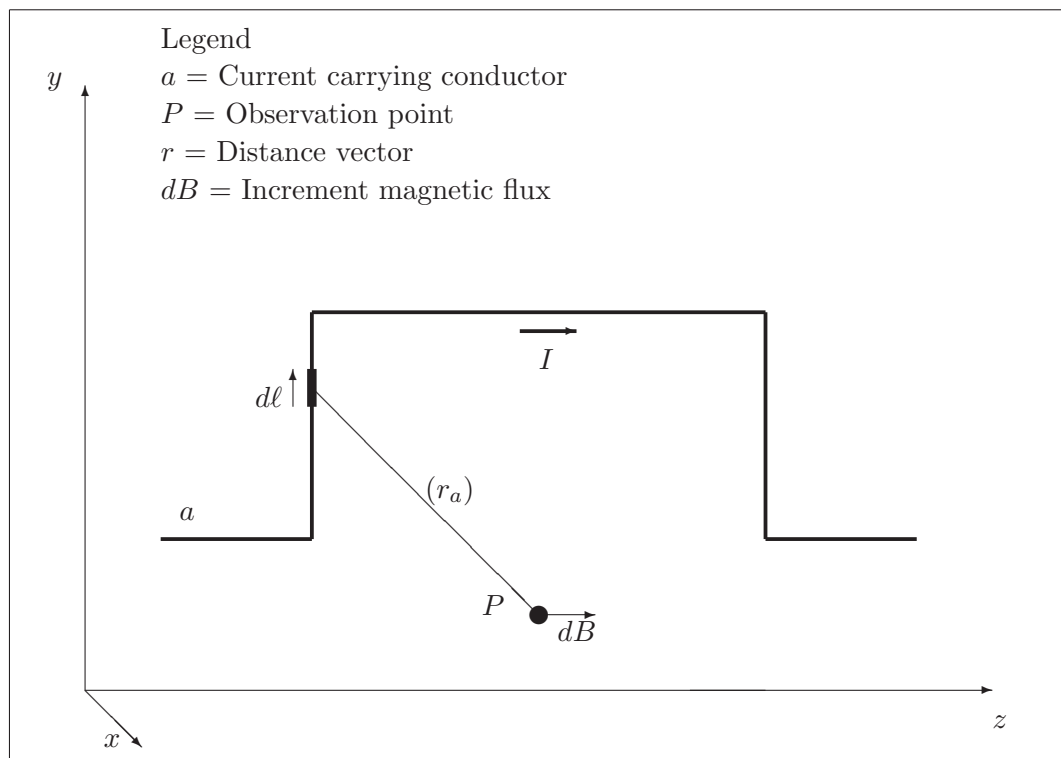


Figure 3.3: Structure B. Calculation of vector r in non symmetrical magnetic fields

Table 3.1: Steps required for generation of computer algorithm to calculate symmetrical magnetic fields using equations 3.2 and equation 3.7

Stage	Details
Step 1	Input data: <ul style="list-style-type: none"> – Specify each conductor horizontal & vertical dimensions – Specify observation point horizontal & vertical dimensions – Specify current flow in each conductor
Step 2	Field strength calculation: <ul style="list-style-type: none"> – Calculate horizontal component of magnetic field strength – Calculate vertical component of magnetic field strength – Repeat calculation for each conductor
Step 3	Net field Strength: <ul style="list-style-type: none"> – Sum individual horizontal magnetic field strength – Sum individual vertical magnetic field strength
Step 4	Convert summated horizontal and vertical magnetic field strength to magnetic flux density
Step 5	Calculate Resultant and Maximum values of magnetic flux density

Table 3.2: Steps required for generation of computer algorithm to calculate non symmetrical magnetic fields using equation 3.6

Stage	Details
Step 1	Input data: <ul style="list-style-type: none"> – Specify each conductor x, y & z dimensions – Specify observation point x, y & z dimensions – Specify current flow in each conductor
Step 2	Determine segments $\Delta\ell$ dimensions: <ul style="list-style-type: none"> – Calculate array with x dimensions for each segment – Calculate array with y dimensions for each segment – Calculate array with z dimensions for each segment – Repeat for each conductor
Step 3	Distance vector: <ul style="list-style-type: none"> – Calculate r for each segment to observation point – Calculate r^3 for each segment to observation point
Step 4	Cross Product: <ul style="list-style-type: none"> – Calculate x direction $I\Delta\ell \times r$ – Calculate y direction $I\Delta\ell \times r$ – Calculate z direction $I\Delta\ell \times r$ – Repeat for each segment and conductor
Step 5	Calculation <ul style="list-style-type: none"> Use results of Step 3 & 4 to implement equation 3.6 Sum calculation for each segment Sum calculation for each conductor

Chapter 4

Experimental Verification

As part of the requirement to develop a systematic procedure for the evaluation and selection of EMF software, it is required to compare the outputs of such software with measurements obtained under controlled laboratory conditions in order to verify that the outputs predicted are accurate. This chapter will use the physical structures identified and the theoretical models developed in chapter 3 in order to carry out this verification of the numerical results obtained from commercially available EMF software. The chapter is organized in the following areas,

- Provide methodology, procedure and results for experiments carried out in the laboratory in order to measure actual magnetic fields emitted by the structures identified in section 3.1,
- Provide results of commercially available EMF software, when modeling magnetic fields emitted by physical structures identified in section 3.1,
- Provide results of MATLAB computer algorithms identified in section 3.3 which model magnetic fields emitted by the physical structures identified in section 3.1,
- Compare the outputs of the commercially available EMF software with the outputs from the MATLAB computer algorithms and actual experiment measurements,
- Summary of key points.

The results of this chapter will be included in the selection criteria developed in chapter 5 in order to evaluate commercially available EMF software.

4.1 Experiments

This section provides method, procedures, construction details and results on experiments carried out in order to measure magnetic fields emitted by physical structures under controlled laboratory conditions.

4.1.1 Experiment Method

In order to measure the magnetic fields for various conditions, five separate experiments were carried out using two different structures identified in section 3.1.

It is essential to ensure that only the magnetic fields radiated from the particular structure is measured and not magnetic fields from external sources. To reduce the impact of magnetic fields from external sources, the following control measures were implemented,

- The experiments were conducted during university holidays. The reasoning of this requirement was to measure the magnetic fields when the building had a low level of occupancy, which reduced radiated magnetic fields from additional sources such as lighting, air conditioning, laboratory equipment and computers.
- The back ground magnetic fields from the general building equipment was measured at regular intervals before and after each experiment. The results varied but were generally within the range of $0.1 - 0.2\mu T$. This relatively low value will have a negligible effect when compared to the magnetic field radiated by each experiment structure.
- The experiments structures with-in the laboratory was located away from any high current sources such as power system sub-main cabling and distribution board. All electrical items which were not required for the experiments were turned off.

The main aim of Experiment 1 and 2 is to obtain a comparison of measured and modeled magnetic fields radiated from Structure A. Structure A consists of three equally spaced

horizontal conductors which result in radiated symmetrical magnetic fields which curl around each conductors as shown in figure 2.2. The construction method of Structure A attempts to reduce errors by ensuring that the current carrying conductors are under tension which reduces sag. The load for Experiment 1 is three phase 415V 12.8A per phase. For Experiment 2 this load is doubled to 415V 24.6A per phase. The magnetic field measurements for Experiment 1 and 2 were taken at 15 observation points along three measurement profiles below the horizontal conductors. Refer to figure 4.1 and photographs located in appendix D for construction details of Structure A.

The main aim of Experiment 3, 4 and 5 is to obtain a comparison of measured and modeled magnetic fields radiated from Structure B. Unlike Structure A, the magnetic fields radiated by Structure B are non symmetrical as the structure consists of a mixture of three equally spaced horizontal and vertical conductors. As per Experiment 1 and 2, the magnetic fields also curl around the conductors as shown in figure 2.2, however there is now both horizontal and vertical magnetic fields which alter the overall net magnetic fields at any particular observation point. Due to construction constraints, it is not practical to build a precise model of Structure B with conductors orthogonal to each other and as such the radiated magnetic field measured will contain some inherent errors when compared to the modeled results. The load for Experiment 3 and 4 is three phase 415V 24.6A per phase. In Experiment 3 the measurement profile is located equal distances from the vertical conductors while in Experiment 4, the measurement profile is located 500mm from the vertical conductors. Experiments 1 to 4 were energised at 415V three phase. In order to gain some comparison of measured and modeled magnetic fields from single phase networks, Experiment 5 was energised at 240V. The load for Experiment 5 is 13.13A. This load is transferred to the load bank by the two outer conductors with the middle conductor not connected. The magnetic field measurements for Experiment 3, 4 and 5 were taken at 15 observation points along five measurement profiles below the horizontal conductors. Refer to figure 4.2 and photographs located in appendix E for construction details of Structure B.

A summary of the above details for each experiment is listed in table 4.1. The equipment used to carry out each experiment is listed in table 4.2. The procedures used to carry out these experiments will be discussed in the next section 4.1.2.

Table 4.1: Specifications for Experiments 1, 2, 3, 4, & 5.

Exp. No.	Structure	Supply (V)	Load (A)	Comments
1	A	415	12.8	Three phase, Symmetrical fields 3 measurement profiles -250mm below conductors
2	A	415	24.6	Three phase, Symmetrical fields 3 measurement profiles -250mm below conductors
3	B	415	24.6	Three phase, Non Symmetrical fields 5 measurement profiles -250mm below conductors at a distance of 500mm from the vertical sections
4	B	415	24.6	Three phase, Non Symmetrical fields 5 measurement profiles -250mm below conductors located in the centre between vertical sections
5	B	240	13.1	Single phase, Non Symmetrical fields Centre conductor not energised 5 measurement profiles -250mm below conductors at a distance of 500mm from the vertical sections

4.1.2 Experiments Equipment & Procedures

The equipment used to carry out the experiments was sourced mostly from USQ Electrical Laboratory, while the magnetic field meter was supplied by Ergon Energy. This meter was a EMDEX II triaxial meter manufactured by Enertech in California. The meter is a true RMS instrument and derives its name triaxial from its construction, as it contains three separate orthogonally oriented magnetic field sensor coils, one for the X axis, one for the Y axis and finally one for the Z axis. The EMDEX II is widely used for measuring magnetic fields in experiments involving power line frequencies (Swanson 1995, Karipidis, K. & Martin, L. 2005) and is specifically designed to measure AC fields in the 40-800Hz spectrum while rejecting other frequencies outside this range including the earths DC magnetic field (Enertech 2001). The meter was orientated so that the vertical and horizontal measurement profiles were located in the centre of its three sensor coils.

A summary of all equipment used in the experiments is listed in table 4.2.

Table 4.2: List of equipment required to generate and measure magnetic fields for Experiments 1, 2, 3, 4, & 5.

Item	Details	Comments
Power Supply	415V, 50Hz 32A _{max}	Three phase laboratory outlet, protected by residual current device
Load Bank	Donaldson Electric Works 27kW	Resistive heating elements Three banks of 9kW elements, switched separately, three phase cooling fan
Power Measurement	Fluke 43B Power Quality Analyser	Analyser used to measure line volts phase current and power factor
Magnetic field Measurement	EMDEX II	Triaxial meter continuous recording, includes EMCCalc software allows results to be stored and analysed
Conductors	10mm ² PVC	Single insulation, 7 strands of 1.70mm dia.

Although the experiments do have different loads, conductor configuration and measurement profiles, there are similar procedures involved in carrying out these experiments. The procedures are detailed in the table 4.3.

The construction details of the experiments will be discussed in section 4.1.3, while the results recorded will be identified in the next section 4.1.4.

Table 4.3: List of experiment procedures required to carry out Experiments 1, 2, 3, 4, & 5.

Stage	Details
Step 1	This stage involves construction of structure and connection of power supply and load bank. Mark vertical and horizontal profiles to enable accurate location of EMF meter. Measure and record background magnetic field noise.
Step 2	Energised structure and select load based on table 4.1. Switch on ventilation fans on load bank.
Step 3	Measure and record current and power factor in each phase using the power analyser. Prior to recording measurements ensure load current has stabilised by allowing the load bank resistive heater elements to warm up.
Step 4	Using the magnetic field meter, measure the magnetic field along each horizontal profile. At each cross section with a vertical profile record an event on the magnetic field meter. Monitor voltage, current and power factor.
Step 5	Transfer results from magnetic field meter to EMCCalc software. From the EMCCalc software, obtain the magnetic field results at each event and store in excel data base for processing.

4.1.3 Experiments Construction Details

The construction details of Structure A used in Experiments 1 & 2 is as per figure 4.1. This construction involves three parallel horizontal conductors supported on timber supports. Figure 4.1 is a cross section of the conductors at the vertical measurement profile. Magnetic fields are recorded along three horizontal profiles with each profile located at increments of $250mm$ below the conductors. A total of 15 magnetic field measurements are taken on each horizontal profile, with each measurement $100mm$ apart. To improve the accuracy of Experiments 1 & 2, the conductors are installed under tension and secured to horizontal supports using fasteners to ensure that there is minimum sag.

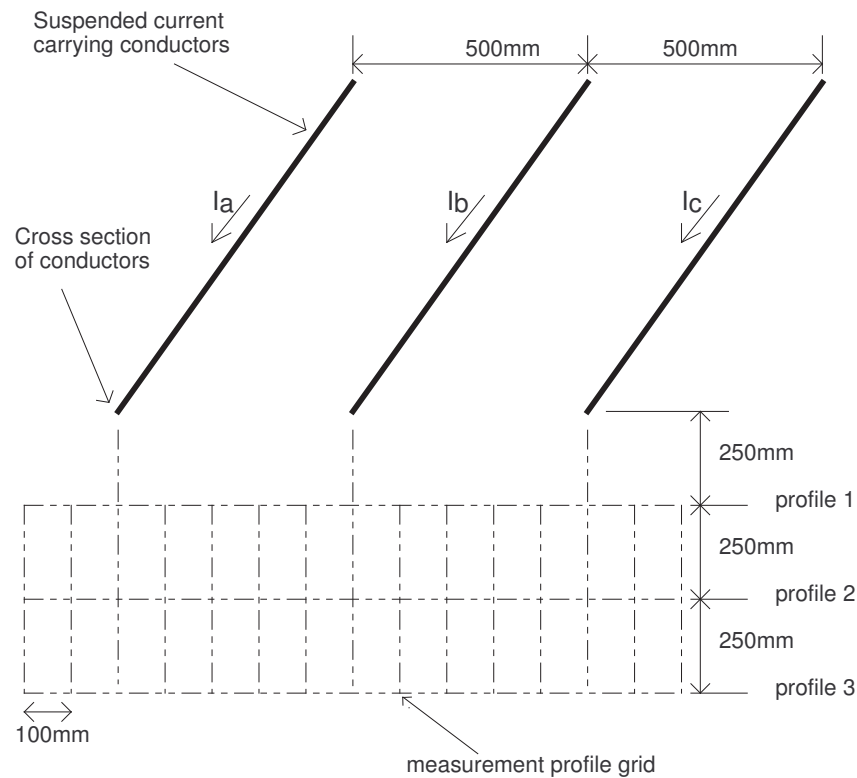


Figure 4.1: Sectional view of Structure A used to generate symmetrical magnetic fields. Measurement of magnetic fields taken at 15 observation points which are equal spaced along three horizontal profiles (1, 2 & 3) below conductors.

The construction details of Structure B used in Experiments 3, 4 & 5 using Structure B is as per figure 4.2. This construction involves three parallel horizontal and vertical conductors supported on timber supports. Figure 4.2 is a isometric view of the conductors and measurement profiles. As indicated in figure 4.3, the horizontal measurement profiles are located at 1500mm from the vertical conductors for Experiment 4 while they are located 500mm from the vertical conductors for Experiments 3 & 5. Similar to Structure A, a total of 15 magnetic field measurements are taken on each horizontal profile, with each measurement 100mm apart, although there are now five horizontal profiles with each profile increments of 250mm below the highest conductors.

The results recorded along each of the horizontal measurement profiles will be identified in section 4.1.4.

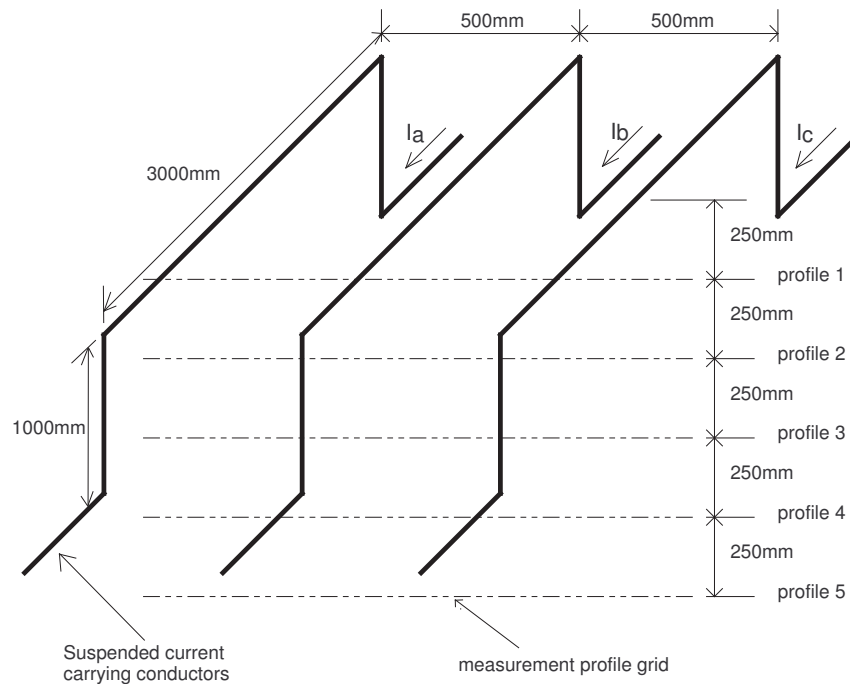


Figure 4.2: Isometric view of Structure B used to generate non symmetrical magnetic fields. Measurement of magnetic fields taken at 15 observation points which are equally spaced along five horizontal profiles (1, 2, 3, 4 & 5) below conductors. (Vertical profiles omitted for clarity)

4.1.4 Measured Magnetic Fields Results

This section provides the results of measurements obtained from Experiments 1, 2, 3, 4, & 5. As there are three horizontal profiles for Experiments 1 & 2, and five horizontal profiles for Experiments 3, 4, & 5 it is not practical to include all results in this section. Therefore only the magnetic fields measured along the $-750mm$ horizontal profile are included, with all other results listed in appendix F.

The measurements obtained along the $-750mm$ horizontal profile for each experiment are listed in table 4.4.

The Measured results in table 4.4 will be discussed in section 4.4.

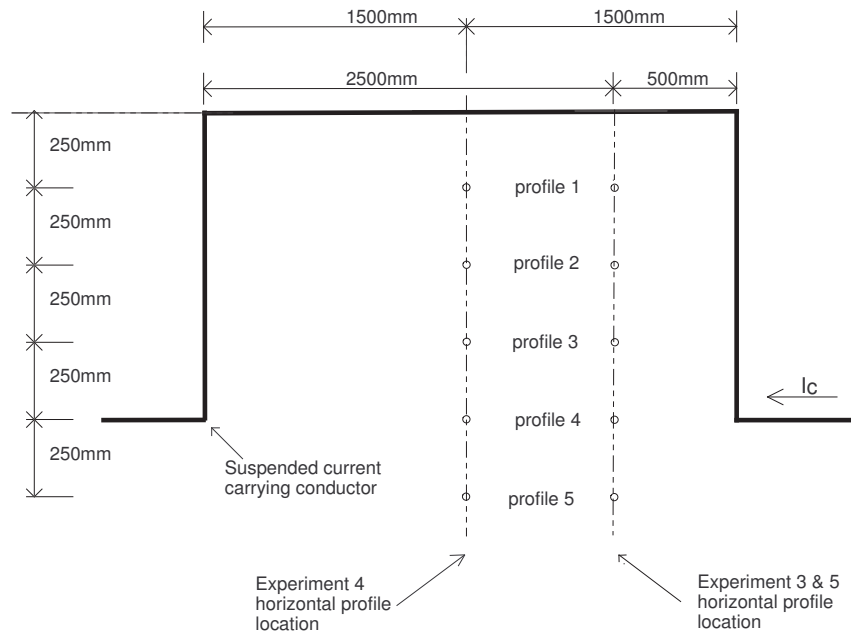


Figure 4.3: Side elevation view of Structure B phase C, used to generate non symmetrical magnetic fields. Horizontal measurement profiles for Experiment 3 & 5 is located 500mm from vertical conductors while Experiment 4 is located in the centre of vertical conductors.

4.2 Commercial EMF Software results

This section will provide the magnetic fields estimated by three commercially available EMF software programs. The three commercial EMF software programs are from the following manufacturers,

- Electric Power Research Institute (EPRI), and
- Safe Engineering Services & Technology (CDEGS), and
- Narda Safety and Test Solutions (Narda).

Additional details on each manufacturer and various software attributes will be discussed in chapter 5.

Table 4.4: Measured magnetic fields for Experiments 1, 2, 3, 4, & 5. Measurements are taken at equal distances along -750mm horizontal profile.

Profile <i>mm</i>	Magnetic Fields Measured μT				
	Exp 1	Exp 2	Exp 3	Exp 4	Exp 5
-700	2.18	4.12	7.10	4.92	4.26
-600	2.68	4.48	8.14	5.48	4.78
-500	2.88	5.08	8.86	5.82	5.10
-400	2.86	5.52	9.14	6.18	5.34
-300	3.00	5.80	9.12	6.62	5.34
-200	3.02	5.98	9.28	6.76	5.26
-100	3.06	6.06	9.52	6.82	5.20
0	3.16	6.02	9.46	6.90	5.22
100	3.06	6.06	9.52	6.80	5.20
200	3.02	5.98	9.28	6.74	5.26
300	3.00	5.80	9.12	6.46	5.34
400	2.86	5.52	9.14	6.20	5.34
500	2.88	5.08	8.80	5.82	5.10
600	2.68	4.66	7.96	5.38	4.64
700	2.22	4.20	7.00	4.84	4.14

4.2.1 Narda Model Results

The Narda results which are located in table 4.5 and appendix F are generated from a demonstration copy of Narda EFC-400 low frequency software version 2006 Build (2567) LF. The demonstration copy allowed the user to enter the majority of details and run the program. As it is a demonstration program, the outputs generated could not be saved or exported. When the calculation process was started, the program produced a warning message advising that 'Calculation results of demo are false'. The magnetic field results produced were extracted off contour plots by placing the cursor at each profile location and recording the magnetic field values identified. Magnetic field values were then stored on an excel database.

Table 4.5: Narda Modeled magnetic fields for Experiments 1, 2, 3, 4, & 5. Modeled results are estimated at equal distances along $-750mm$ horizontal profile.

Profile <i>mm</i>	Magnetic Fields Modeled μT				
	Exp 1	Exp 2	Exp 3	Exp 4	Exp 5
-700	2.08	4.05	7.00	2.84	6.07
-600	2.27	4.42	7.86	3.41	6.36
-500	2.45	4.76	8.49	4.04	6.46
-400	2.60	5.05	8.81	4.63	6.29
-300	2.71	5.27	8.96	5.13	5.93
-200	2.80	5.42	9.10	5.50	5.53
-100	2.85	5.51	9.23	5.70	5.24
0	2.86	5.54	9.29	5.77	5.13
100	2.85	5.50	9.19	5.69	5.24
200	2.80	5.39	9.02	5.48	5.53
300	2.71	5.23	8.85	5.12	5.93
400	2.60	5.00	8.66	4.62	6.29
500	2.45	4.70	8.31	4.01	6.46
600	2.27	4.36	7.69	3.39	6.36
700	2.08	3.99	6.83	2.81	6.07

The Narda results in table 4.5 will be discussed in section 4.4.

4.2.2 EPRI Model Results

The EPRI results located in table 4.6 and appendix F are generated from EMFWorkstation Subcalc module. This is a demonstration model version 2.01 dated July 24 1996. The demonstration copy allowed the user to enter the majority of details only. No outputs could be generated, but a tool option allowed the magnetic field values to be measured by placing the cursor at each profile location and recording the magnetic field values provided. Magnetic field values were then stored on an excel database.

Table 4.6: EPRI Modeled magnetic fields for Experiments 1, 2, 3, 4, & 5. Modeled results are estimated at equal distances along -750mm horizontal profile.

Profile <i>mm</i>	Magnetic Fields Modeled μT				
	Exp 1	Exp 2	Exp 3	Exp 4	Exp 5
-700	2.12	4.02	7.03	4.47	4.10
-600	2.33	4.40	7.83	4.80	4.55
-500	2.51	4.75	8.36	5.08	4.83
-400	2.67	5.04	8.62	5.30	4.91
-300	2.79	5.27	8.72	5.47	4.85
-200	2.88	5.44	8.81	5.57	4.73
-100	2.93	5.54	8.92	5.63	4.63
0	2.95	5.58	8.96	5.63	4.59
100	2.93	5.55	8.88	5.59	4.63
200	2.88	5.47	8.73	5.51	4.73
300	2.79	5.31	8.59	5.38	4.85
400	2.67	5.09	8.45	5.20	4.91
500	2.51	4.81	8.17	4.96	4.83
600	2.33	4.46	7.62	4.66	4.55
700	2.12	4.09	6.83	4.33	4.10

The EPRI results in table 4.6 will be discussed in section 4.4.

4.2.3 CDEGS Model Results

The CDEGS results located in table 4.7 and appendix F are generated from CDEGS software using the HiFREQ module. This is a licensed copy version 12 dated 2006. Magnetic field values were extracted from profile plots and stored on an excel database.

Table 4.7: CDEGS Modeled magnetic fields for Experiments 1, 2, 3, 4, & 5. Modeled results are estimated at equal distances along $-750mm$ horizontal profile.

Profile <i>mm</i>	Magnetic Fields Modeled μT				
	Exp 1	Exp 2	Exp 3	Exp 4	Exp 5
-700	2.40	4.40	7.40	4.60	4.16
-600	2.60	4.80	8.20	4.90	4.61
-500	2.75	5.10	8.70	5.20	4.91
-400	2.90	5.40	9.00	5.40	4.98
-300	3.00	5.60	9.10	5.55	4.91
-200	3.10	5.80	9.20	5.70	4.81
-100	3.15	5.90	9.30	5.78	4.71
0	3.20	5.95	9.40	5.80	4.69
100	3.15	5.90	9.30	5.78	4.71
200	3.10	5.80	9.20	5.70	4.81
300	3.00	5.60	9.10	5.55	4.91
400	2.90	5.40	9.00	5.40	4.98
500	2.75	5.10	8.70	5.20	4.91
600	2.60	4.80	8.20	4.90	4.61
700	2.40	4.40	7.40	4.60	4.16

The CDEGS results in table 4.7 will be discussed in section 4.4.

4.3 MATLAB Results

The MATLAB results located in table 4.8 are generated using two different algorithms developed in section 3.3, which are used to model magnetic fields emitted by physical structures under controlled laboratory conditions.

Table 4.8: MATLAB modeled magnetic fields for Experiments 1, 2, 3, 4, & 5. Modeled results are estimated at equal distances along $-750mm$ horizontal profile.

Profile <i>mm</i>	Magnetic Fields Measured μT				
	Exp 1	Exp 2	Exp 3	Exp 4	Exp 5
-700	2.10	4.01	2.07	1.61	1.29
-600	2.30	4.40	2.27	1.71	1.41
-500	2.48	4.75	2.48	1.80	1.54
-400	2.64	5.06	2.69	1.88	1.67
-300	2.77	5.29	2.86	1.95	1.79
-200	2.85	5.46	3.00	2.01	1.88
-100	2.91	5.56	3.08	2.04	1.93
0	2.92	5.60	3.11	2.05	1.95
100	2.91	5.56	3.08	2.04	1.93
200	2.85	5.46	3.00	2.01	1.88
300	2.77	5.29	2.86	1.95	1.79
400	2.64	5.06	2.69	1.88	1.67
500	2.48	4.75	2.48	1.80	1.54
600	2.30	4.40	2.27	1.71	1.41
700	2.10	4.01	2.07	1.61	1.29

The MATLAB results in table 4.8 will be discussed in section 4.4.

4.4 Discussion of Results

This section will compare and discuss the results of the following,

- Magnetic fields measured during experiments under controlled laboratory conditions detailed in section 4.1.4,
- Magnetic fields estimated by Narda software listed in section 4.2.1,
- Magnetic fields estimated by EPRI software listed in section 4.2.2,
- Magnetic fields estimated by CDEGS software listed in section 4.2.3,
- Magnetic fields estimated by computer algorithms executed in MATLAB code listed in section 4.3.

The discussion is carried out separately for three phase symmetrical magnetic fields (Experiment 1 & 2), three phase non symmetrical magnetic fields (Experiment 3 & 4) and finally for single phase non symmetrical fields (Experiment 5).

4.4.1 Experiments 1 and 2

The combined results of magnetic fields measured and estimated for Experiment 1 is located in figure 4.4 and for Experiment 2 is located in figure 4.5. The main difference between these two experiments is the load of Experiment 1 is $12.8A$ per phase and this load is doubled in Experiment 2 to $24.6A$ per phase. These two experiments are designed to generate symmetrical magnetic fields radiated from Structure A, which is constructed to a high degree of accuracy. This allows the conductor dimensions entered into each model to be a close approximation of what was actually constructed which reduces error and thus improves the accuracy of the estimation.

Inspection of figure 4.4 reveals that the magnetic field measured in Experiment 1 along the $-750mm$ horizontal profile varies from $2.18\mu T$ to $3.16\mu T$. In general the results produced from the CDEGS, Narda and EPRI models for Experiment 1 are an accurate representation of the measured values and similar to each other for all measurement

points along the -750mm horizontal profile. The CDEGS results for Experiment 1 is the most precise estimate of the measured values. There is a small difference between the CDEGS values and the outputs from the MATLAB, Narda and EPRI results of approximately $0.3\mu\text{T}$ for all measurement profiles. This difference between the the CDEGS results and the MATLAB, Narda and EPRI results is attributed to the calculation method. The CDEGS method uses a calculation method which approximates Maxwell equations. A detailed analysis of this calculation method is outside the scope of this project, however the calculation method is described in detail by the manufacture SES (Dawalibi, F. & Selby, A. 1993). In comparison the MATLAB, Narda and EPRI methods all use a calculation method based on the Biot-Savart Law detailed in section 3.3.

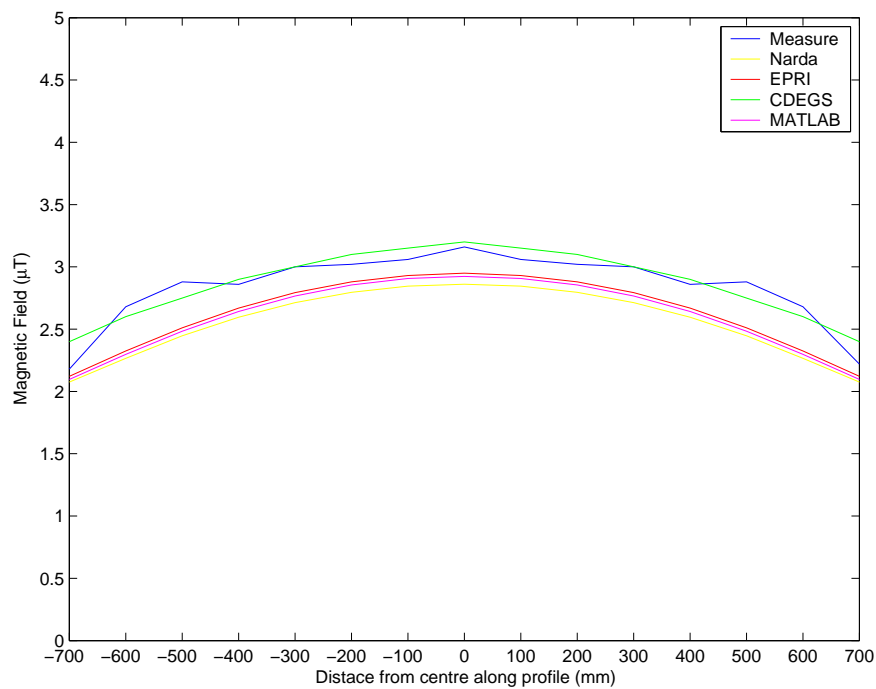


Figure 4.4: Comparison of Experiment 1, Structure A, symmetrical magnetic fields results based on a load of 415V 12.8A per phase. Measurement of magnetic fields taken at equally spaced distances along horizontal profile 750mm below conductors.

In accordance with equation 3.2 for symmetrical magnetic fields, the magnetic flux density B , is directly proportional to the current I . The current in Experiment 2 is double that of Experiment 1 so therefore in accordance with equation 3.2, there must be a doubling of the range of measured magnetic flux density. Inspection of figure 4.5 reveals that the magnetic field measured in Experiment 2 along the -750mm horizontal

profile varies from $4.12\mu T$ to $6.02\mu T$. As expected, this is approximately double the magnetic field from the previous experiment. In general the results produced from the CDEGS, Narda and EPRI models for Experiment 2 are an accurate representation of the measured values and similar to each other for all measurements points along the $-750mm$ horizontal profile. There is a difference between the CDEGS values and the outputs from the MATLAB, Narda and EPRI results of approximately $0.45\mu T$, which once again is attributed to the calculation method. As in Experiment 1, the CDEGS results for Experiment 2 is the most precise estimate of the measured values.

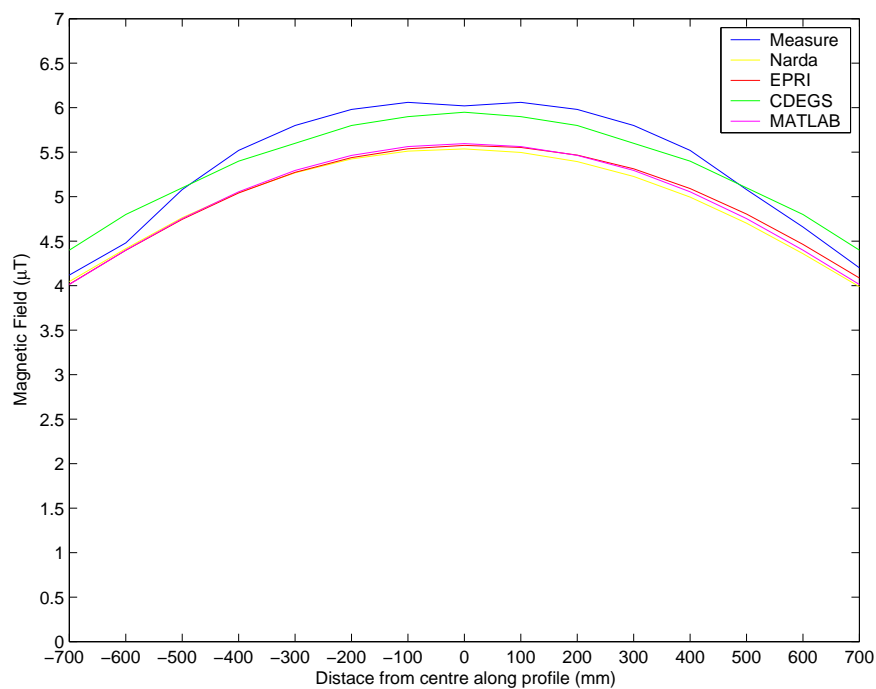


Figure 4.5: Comparison of Experiment 2, Structure A, symmetrical magnetic fields results based on a load of $415V$ $24.6A$ per phase. Measurement of magnetic fields taken at equally spaced distances along horizontal profile $750mm$ below conductors.

4.4.2 Experiments 3 and 4

The combined results of magnetic fields measured and estimated for Experiment 3 is listed in figure 4.6 and for Experiment 4 is listed in figure 4.7. The load for these two experiments is fixed at $24.6A$ per phase. The difference between Experiment 3 and 4 is the location of the measurement profile. This is detailed in figure 4.3 which shows that Experiment 3 has the measurement profile located $500mm$ from the vertical conductors, while Experiment 4 has the measurement profiles located in the centre of the vertical conductors. These two experiments are designed to generate non symmetrical magnetic fields radiated from Structure B. Due to construction constraints of Structure B, there will be some inaccuracies between the measurements observed and predicted.

Inspection of figure 4.6 reveals that the magnetic fields measured in Experiment 3 along the $-750mm$ horizontal profile varies from $7.10\mu T$ to $9.52\mu T$. This range of values measured in Experiment 3 is approximately 3 to $3.5\mu T$ higher than the values measured in Experiment 2 for the same load current and the same distance from the horizontal conductors. This increase is attributed to the close location of the vertical conductors to the measurement profile as shown in figure 4.3. In general the results produced from the CDEGS, Narda and EPRI models for Experiment 3 are an accurate representation of the measured values and similar to each other for all measurement points along the $-750mm$ horizontal profile. In a departure from the results observed in Experiment 1 and 2, the Narda and EPRI results do vary from each other close to the centre of the conductors despite using the same computation method. Inspection of figure 4.6 reveals that the Narda results are more accurate than the EPRI results. The MATLAB results are not an accurate representation of the magnetic fields measured. This is attributed to polarity errors in the MATLAB algorithm. In this experiment there is a larger difference between the measured values and the various software estimates compared to Experiments 1 & 2. This is attributed to inconsistencies between the structure constructed and the conductor dimensions entered into the various models. As in Experiment 1 and 2, the CDEGS results for Experiment 3 is the most precise estimate of the measured values.

Inspection of figure 4.7 reveals that the magnetic fields measured in Experiment 4

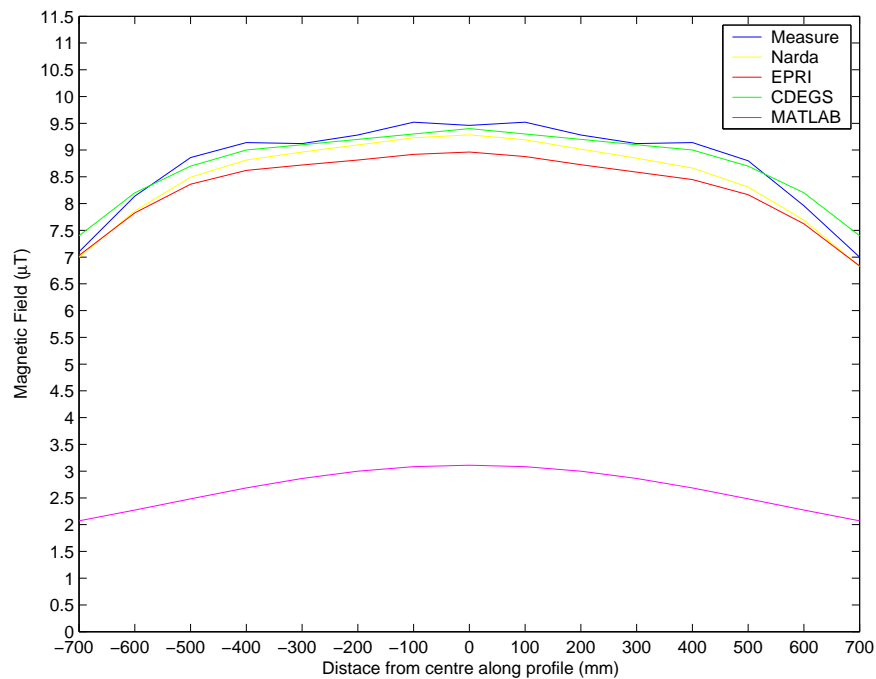


Figure 4.6: Comparison of Experiment 3, Structure B, non symmetrical magnetic fields results based on a load of $415V$ $24.6A$ per phase. Measurement of magnetic fields taken at equally spaced distances along horizontal profile $750mm$ below conductors. Profile located $500mm$ from vertical conductors.

along the $-750mm$ horizontal profile varies from $4.92\mu T$ to $6.90\mu T$. When compared to Experiment 2, the range of values measured is approximately equal for the same load current and the same distance from the horizontal conductors. Inspection of figure 4.3 shows that for experiment 4, the vertical conductors are equal distances from the location of the measurement profile. As the current is traveling up one vertical section and down the other vertical section, by using the right hand rule the magnetic fields from the two vertical sections will effectively cancel each other out. This effectively leaves only the magnetic fields from the horizontal sections which for this conductor configuration, reduce the non symmetrical fields to a symmetrical fields situation similar to Experiment 2.

Experiment 4 has produced vastly different results. The CDEGS, Narda and EPRI models produced similar results towards the centre of measurements but these results are approximately $1.3\mu T$ below the value measured. The CDEGS and EPRI results are similar to each other for all measurements points along the $-750mm$ horizontal

profile. The difference between the CDEGS and EPRI modeled and measured results reduces to approximately $0.5\mu T$ at the outer measurement points. This is attributed to inconsistencies between the structure constructed where excess sag of the conductors causes higher fields to be measured compared to models which assumes ideal conditions. The difference between the Narda and measured results increases from an initial $1.13\mu T$ to approximately $2.08\mu T$ at the outer measurement points. This is attributed a combination of inconsistencies between the structure constructed and the conductor dimensions entered into the Narda model and may also be attributed to the demonstration version of the software producing false results. The MATLAB results are not an accurate representation of the magnetic fields measured. This is once again attributed to polarity errors in the MATLAB algorithm.

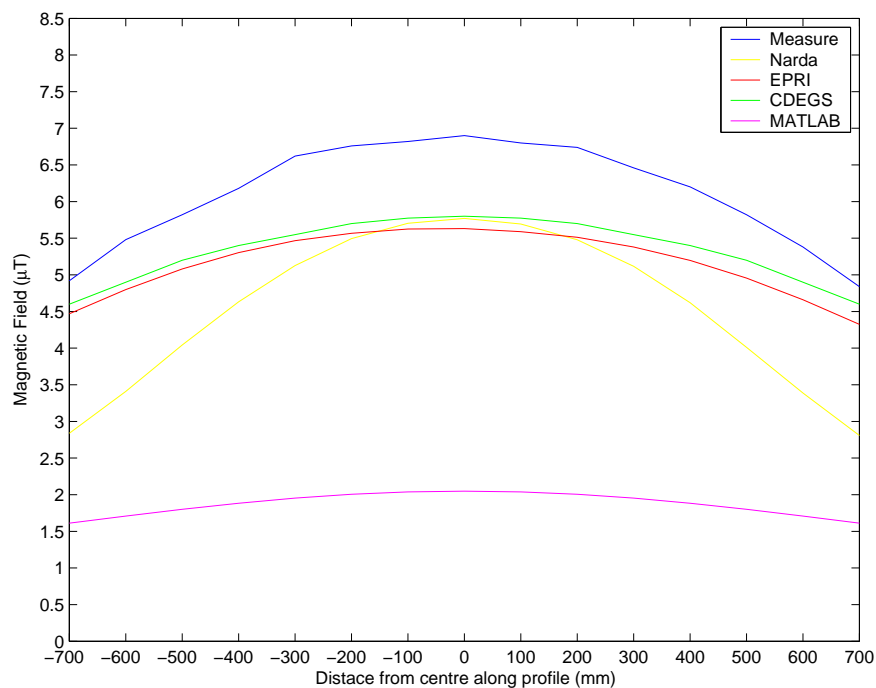


Figure 4.7: Comparison of Experiment 4, Structure B, non symmetrical magnetic fields results based on a load of 415V 24.6A per phase. Measurement of magnetic fields taken at equally spaced distances along horizontal profile 750mm below conductors. Profile located equal distances from vertical conductors.

4.4.3 Experiment 5

The results of magnetic fields measured and estimated for Experiment 5 are listed in figure 4.8. Experiment 5 is a single phase load energised at $240V$ with $13.13A$ flowing in the two outer conductors of Structure B. The middle conductor is not energised and does not form part of the experiment. The measurement profile is detailed in figure 4.3 which shows that Experiment 5 has the measurement profile located $500mm$ from the vertical conductors. Experiment 5 is designed to generate non symmetrical magnetic fields radiated from Structure B. Due to construction constraints of Structure B, there will be some inaccuracies between the measurements observed and predicted.

Inspection of figure 4.8 reveals that the magnetic field measured in Experiment 5 along the $-750mm$ horizontal profile varies from $4.26\mu T$ to $5.34\mu T$. This experiment is energised by a single phase voltage and contains conductors spaced $1000mm$ apart, therefore there is no direct comparison between the results obtained from Experiment 1–4 and Experiment 5.

Experiment 5 has produced vastly different results. The results from the CDEGS and EPRI models are similar to each other but have a difference of approximately $1.0\mu T$ higher when compared to the measured results. The Narda results are similar to the measured values towards the centre of the structure, but are vastly different at the edges of the structure. The various inaccuracies in this experiment are attributed to inconsistencies between the structure constructed where excess sag of the conductors causes higher fields to be measured than the conductor dimensions entered into the various models. The Narda inconsistencies are also attributed to the demonstration version of the software producing false results. It is considered that the errors associated with the CDEGS and EPRI inaccuracies are increased, especially towards the centre of the structure, as the middle conductor is not energised. The current carrying conductors are located $\pm 500mm$ along the horizontal profile and inspection of figure 4.8 reveals that the error between the measured value and CDEGS and EPRI results in this area is relatively small at approximately $0.2\mu T$. As in experiments 2 & 3, the MATLAB results are not an accurate representation of the magnetic fields measured. This is once again attributed to polarity errors in the MATLAB algorithm.

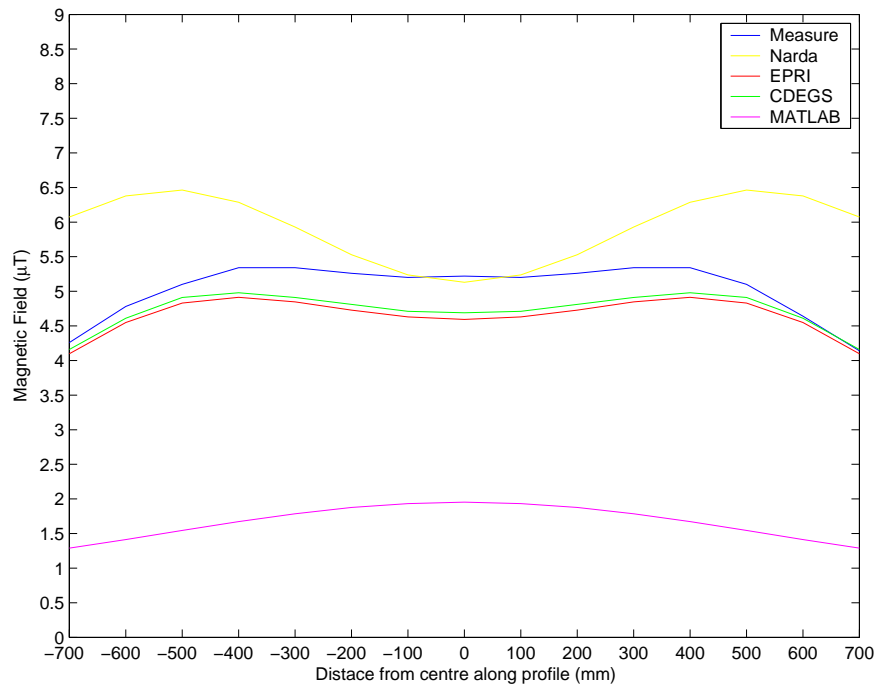


Figure 4.8: Comparison of Experiment 5, Structure B, non symmetrical magnetic fields results based on a load of 240V 13.13A. Middle conductor is not energised. Measurement of magnetic fields taken at equal spaced distances along horizontal profile 750mm below conductors. Profile located 500mm from vertical conductors.

4.5 Chapter Summary

This chapter provides details and results of five experiments carried out under controlled laboratory conditions in order to verify the numerical results obtained from commercially available EMF software. The outputs of the commercially available EMF software are compared against actual measured values. A comparison and subsequent discussion of results indicates the following key points,

- For the three phase symmetrical magnetic fields of Experiments 1 & 2, the results produced from the CDEGS, Narda and EPRI software are an accurate representation of the measured values. The MATLAB algorithms for symmetrical magnetic fields is able to verify that the results measured and modeled by the commercially available EMF software is accurate and reliable.
- For the three phase non symmetrical magnetic fields of Experiment 3, the results

produced from the CDEGS, Narda and EPRI software are an accurate representation of the measured values. Differences between the measured and modeled results are attributed to inconsistencies between the structure constructed and the conductor dimensions entered into the various models. The MATLAB algorithms for non symmetrical magnetic fields is not able to verify the results. This is attributed to polarity errors within the MATLAB algorithm.

- For the three phase non symmetrical magnetic fields of Experiment 4, the results produced from the CDEGS and EPRI software are generally an accurate representation of the measured values although these results produce a larger error when compared to the results of previous experiments. As in Experiment 3 this error is attributed to inconsistencies between the structure constructed and the conductor dimensions entered into the CDEGS and EPRI models. The Narda software results are not an accurate representation of the measured values. The Narda inconsistencies are attributed to the demonstration version of the software producing false results. The MATLAB algorithms for non symmetrical magnetic fields is not able to verify the results. This is attributed to polarity errors in the MATLAB algorithm.
- For the single phase non symmetrical magnetic fields of Experiment 5, the results produced from the CDEGS and EPRI software are generally an accurate representation of the measured values although these results produce a large error closer to the centre of the structure. As in Experiments 3 & 4, this error is attributed to inconsistencies between the structure constructed and the conductor dimensions entered into the CDEGS and EPRI models. The Narda software results is not an accurate representation of the measured values. The Narda inconsistencies are attributed to the demonstration version of the software producing false results. The MATLAB algorithms for non symmetrical magnetic fields is not able to verify the results. This is attributed to polarity errors in the MATLAB algorithm,

The results of this chapter will be utilised in chapter 5 to evaluate commercially available EMF software.

Chapter 5

Commercial EMF Software Evaluation and Selection

This chapter will identify three commercially available EMF softwares and develop a selection criteria in order to evaluate each software program. The selection criteria developed is designed to solve the main aim of this project which is to develop a systematic procedure for the evaluation and selection of EMF software, in order to estimate the EMF generated by High Voltage Sub Stations and Distribution, Sub-Transmission and Transmission Networks. Part of the selection criteria will use the results of the experiments undertaken in chapter 4. The selection criteria and subsequent evaluation is developed based on Ergon Energy needs and requirements. Other prospective purchasers may need to modify this section to suit their own particular requirements. The chapter is organized in the following areas,

- Identify commercially EMF software solutions and provide background information which will allow an understanding and appreciation of the manufactures experience and attributes,
- Develop a selection criteria in order to identify the strengths and weakness of each software program, and
- Formulate a response to each item of the selection criteria,

- Recommend the purchase of a software program
- Summary of key points.

5.1 EMF Software Solutions

The three commercially EMF modeling software solutions that have been identified are from the following manufactures,

- Narda Safety and Test Solutions (Narda),
- Electric Power Research Institute (EPRI),
- Safe Engineering Services & Technology (CDEGS).

There is a vast difference between each software program and the experience of each particular manufacturer. The following section provides a general introduction to each software program offered along with background information on each manufacturer and associated agents.

5.1.1 Narda EFC 400

Narda Safety Test Solutions was created in 2000 when Narda, a Division of L-3 Communications, based in New York, acquired Safety Test Solutions, a German manufacturer. Narda are predominately a manufacturer and retailer of EMF measuring devices and instruments. They also market and sell a suite of EMF modeling software called EFC-400. Narda currently have an Australian agent called Airmet Scientific who are suppliers of equipment dedicated to the protection of personnel in the workplace. Airmet are predominately a hazardous equipment sales and support company.

The EMF modeling software EFC-400 is marketed and sold by Narda, but was actually developed by another German organization called Forschungsgesellschaft fuer Energie und Umwelttechnologie GmbH (FGEU). FGEU was founded in 1992 and state their objectives are research analysis and provider of information in the field of environmental protection.

Narda offer two EMF program solutions namely the EFC-400LF and EFC-400ST. The EFC-400ST is a scaled down package suitable only for high voltage substations while

the EFC-400LF package carries out all the functions of the EFC-400ST and also models the transmission and distribution lines. As the main aim of this project is to estimate the EMF generated by High Voltage Sub Stations and Distribution, Sub-Transmission and Transmission Networks, the restricted EFC-400ST solution will not satisfy the main aim of the project and therefore will not be considered.

The EFC-400LF software advantages and disadvantages will be compared against the selection criteria in section 5.3. (adapted from (Narda Safety and Test Solutions 2006)).

5.1.2 EPRI EMF Workstation SUBCALC

The Electric Power Research Institute (EPRI), established in 1973, is an independent not for profit US based research institute with a main purpose to carry out research in energy and environmental areas as directed by its funding members.

Its members are mostly electric utilities from the US but has 18% of members coming from outside the US. It carries out research in a wide variety of electrical areas. As a result of this research and the needs of its members, it produces EMF modeling software called EMF Workstation 2005 which has a SUBCALC component specifically designed for calculating EMFs from high voltage substations.

EPRI has licensed a company called Enertech Consultants to develop and market the EMF Workstation Software to any interested parties except electric utilities, which includes Ergon Energy. A electric utility may only purchase the software directly from EPRI or become a member of one of the EPRI EMF Programs which grants unlimited licenses of the software as a membership entitlement.

EPRI WorkStation consists of various software modules for modeling the EMF generated in residential environments, powerlines and substations. There are currently six modules available which are listed in table 5.1.

The EPRI WorkStation software advantages and disadvantages will be compared against the selection criteria in section 5.3. (adapted from (Electrical Power Research Institute 2006))

Table 5.1: List of EPRI sub packages and modules

Item	Details
RESICALC	Calculate EMF around the home
SUBCALC	Calculate EMF radiated from HV substations
EMFX	Provides information on field sources & measurements Power Line Calculator Determines the electric characteristics of power lines
Enviro	Estimates lateral EMF profiles
Expocalc	Exposure Assessment Program for Transmission Line Electric & Magnetic Fields

5.1.3 SES CDEGS - HiFREQ

The Safe Electric Services and Technologies (SES) is a Canadian owned solution provider specialising in grounding, earthing, lightning, electromagnetic interference and EMC analysis & mitigation problems. It was founded in 1979 by its current President, Dr Farid Dawalibi, who is heavily involved in the training and development of the software. CDEGS have an Australian agent called Power Earth who are based in New South Wales.

SES produce a software package called Current Distribution, Electromagnetic Fields, Grounding and Soil Structure Analysis (CDEGS) which they describe as a powerful set of integrated engineering software training tools designed to accurately analyse problems involving grounding and electromagnetic fields. CDEGS is essentially a user interface that accommodates various input processors, output processors and engineering modules. This allows flexibility in the configuration, but can add complexity to the operation of CDEGS.

There are two main methods of purchasing the CDEGS software package. The first method is to purchase the complete range of CDEGS software and associated modules. The second method is to purchase various sub-packages which appear to be focused on three activities, Grounding, Power Line and EMF calculations. There are currently nine sub-packages available which are listed in table 5.2.

Table 5.2: List of CDEGS sub-packages

Area	Sub-package
Grounding Calculations	Multiground
	Multiground +
	Multiground Z
	Multiground Z+
Power Line Calculations	Multilines
	Multilines +
EMF Calculations	Multifields
	Multifields +

The above sub-packages are bundled with various input and output processors. Ergon Energy currently own a sub-package called Multiground (Malz option). This is currently used by Ergon Energy's Substation Design Engineers to design high voltage substation earth grids and estimate resultant step and touch voltages under fault conditions.

Generally it was considered that the HIFREQ engineering module attached to the Multifields sub-packages would provide the best solution. If the Multifields sub-packages was added to the existing sub-packages, approximately 80% of the total software would be purchased. It is considered that it would be prudent to purchase the remaining 20% and therefore the full range of CDEGS software was included in the evaluation.

The CDEGS software advantages and disadvantages will be compared against the selection criteria in section 5.3. (adapted from (Safe Engineering Services & Technologies 2006))

5.2 Selection Criteria

This section will develop a selection criteria which will allow commercially available EMF software to be evaluated based on the requirements identified in consultation with the key users and stake holders.

The consultation included Ergon Energy Design, Information Technology (IT) and Environment Groups. It is not intended that the selection criteria will develop an exhaustive list of each software attributes, but will allow each software to be judged on its ability to address or solve key needs identified by the stake holders. There is a large range of product material available for each commercial EMF software, particularly for the CDEGS and Narda options which can be consulted for further and more indebt analysis.

Criteria 1: Provide a general description on operation of the software.

Key points include,

- how easy is it to build a model including ease of data input,
- facilities available when working on the software such as different views, shortcuts, component libraries, grouping facilities, background maps, measurement tools

Criteria 2: Base Calculation

Does the software calculate electric and magnetic fields and what is the theory on which the computation is based?

Criteria 3: Can the software model electric and magnetic fields in High Voltage substations and their components in three dimensional (3D)?

Specific components of interest include,

- high voltage busbar
- currents in earth mat
- high and low voltage circuit breakers
- high and low voltage transformers
- capacitor banks
- air core reactors
- structural elements

Criteria 4: Can the software model Transmission, Sub-Transmission and Distribution Power Lines with or without overhead earth wire (OHEW)?

- Criteria 5:** Can the software model underground cables with different earthing arrangements?
- Criteria 6:** Can the software model electric fields based on various distribution voltages including neutral return, unbalanced systems including Single Wire Earth Return (SWER), Multiple Earth Neutral (MEN), Active compensation, ABC, multiple voltages on one structure?
- Criteria 7:** Can the software model different EMF shielding including different materials, shapes and edges?
- Criteria 8:** Can the software import data in Computer Aided Drafting (CAD) format? Can it interface to CAD packages such as Microstation or AutoCAD?
- Criteria 9:** Does the manufacturer provide training on use of the software?
- Criteria 10:** Will the software operate on Ergon Energy computer Wide Area Network (WAN)?
- Criteria 11:** Does the software provide a combination of technical and non technical outputs suitable for insertion into an environmental report? Can the outputs be easily modified to match existing report formats. Can the outputs be exported and integrated into a third party software such as Coral Draw, Matcad, MATLAB or Excel.
- Criteria 12:** What level of technical support is available from the software manufacturer or local agent?
- Criteria 13:** Is there any supporting references from existing users to support the software?
- Criteria 14:** How do the costs of each software program compare with each other?
- Criteria 15:** Based on experiments carried out in chapter 4, are the results of the softwares reliable?

5.3 Response to Selection Criteria

Each of the three EMF modeling software solutions identified is vastly different in both operation and interface. As such the final software selection will most likely be a compromise of conflicting needs and requirements. This section of the report will formulate a response to the selection criteria developed in section 5.2 by using the experience gained while carrying out the modeling tasks in section 4.2 and information freely available from each manufacturer.

Criteria 1: General description on how the software works, ease of data input, facilities available such as different views, shortcuts, libraries, grouping facilities, background maps, measurement tools etc.

- Narda EFC-400LF is a ‘drag and drop’ model based EMF calculation program, where the user selects and places a model of the object from a library. New libraries can be added or imported from the manufactures web site. Existing tower and cables library models can be edited using the inbuilt line editor. The overall site model is built based on a combination of separate library items which are inserted into the workspace.
- EPRI EMF Workstation is also a model based EMF calculation program. It uses a ‘drag and drop’ method to generate a model, where the user selects a model such as a circuit breaker or a transmission tower and places it in a scaled model of the area to be investigated. Edit tools are available to modify each model to suit particular requirements.
- CDEGS provides more of a hands on approach than a ‘drag and drop’ operation. The user builds up a model of the site by drawing items such as busbars, conductors, fence, underground pipes and entering data such as voltages, current, soil resistivity etc. One of the input processors SESCAD, which is a computer aided drafting toolbox, allows to user to carry out basic CAD operations such as copying, pasting stretching etc, as well as assign properties such as current sources and insulation properties. Then the user inputs this data into an engineering model which carries out the required calculations. Finally an output processor is used to interpret the results and

to create and export plots.

Criteria 2: Does the software calculate electric and magnetic fields and what is the theory on which the computation is based?

- Narda EFC-400LF will calculate electric and magnetic fields based on a maximum 32000 x 32000 points of calculations. It also has other limits which include 50000 conductors, 100 transmission lines and 1000 buildings. Narda software bases its calculations on the Biot-Savart Law.
- EPRI EMF Workstation will only calculate magnetic fields based on a maximum area of $832m^2$. It also bases its calculations on the Biot-Savart Law.
- CDEGS will calculate both electric and magnetic fields based on 7000 elements. The different modules in the CDEGS uses mathematical techniques which are in generally based on Maxwell equations.

Criteria 3: Can the software model EMF in substations and their components in 3D?

- Narda EFC-400LF is ideal for drawing in 3D. It uses models of substation components in a similar way to the EPRI SUBCALC. Narda have advised that their basic library of substation elements can be easily supplemented with new elements as required
- EPRI EMF Workstation has a SUBCCALC module that is ideal for drawing and modeling EMF substations in 3D. It comes with a large library of components such as transformers, circuit breakers busbars etc. These components are available as a menu item and can be selected and dropped onto a model.
- The CDEGS software can model all substation components such as the transformer and reactors. The components have to have their current carrying conductors dimensions entered onto the model. A wide range of drafting tools are available to limit the work required. The transformer and reactors are represented as lumped impedances or can be represented as coils. Building items and switchboard frames can be represented in the model as a mesh where EMF reduction values can be included in the model.

Criteria 4: Can the software model Transmission, Sub-Transmission and Distribution Power Lines with or without overhead earth wire (OHEW)?

- Narda EFC-400LF can model these power lines and also automatically calculate ground currents. Library items can be modified to include earth conductors if not already included.
- EPRI EMF Workstation can model these power lines with an OHEW. The manufacturers state the program has the ability to also model ground currents from items such as water pipes, service cables and ground wires.
- CDEGS can model these power lines including all types of grounding wires, conductor paths and pipes.

Criteria 5: Can the software model underground cables with different earthing arrangements?

- Narda EFC-400LF can model EMF generated from cables. From the information available it is considered that different types of earthing arrangements would require a specific block to be generated by the manufacturers.
- Based on the information available, it is not considered possible for EPRI to model underground cables.
- CDEGS Multilines can model residual and fault current distributions between a central grounding system including neutral, shields wires and metallic sheaths. It is considered that by using the various CDEGS energisation types, different earthing arrangements can be included in a model to calculate the EMF radiated.

Criteria 6: Can the software model electric fields based on various distribution voltages including neutral return, unbalanced systems including SWER, MEN, Active compensation, ABC, multiple voltages on one structure?

- Narda EFC-400LF can compute electric fields, and from the manufacturers literature provided it is assumed that the above voltage configurations can be modeled.
- EPRI EMF Workstation can not model electric fields.
- CDEGS can model electric from on overhead or underground conductors energized by any number of current and voltage sources. It is considered that by using the various CDEGS energisation types, all of the above voltage configurations can be modeled.

Criteria 7: Can the software measure different EMF shielding including different shapes and edges?

- Narda EFC-400LF assumes buildings are a ground wire grid and assumes negligible radiation inside the building. It is considered that this feature is predominately used in antenna calculations such as mobile phone signal strength models.
- EPRI EMF Workstation Expocalc has the ability to perform electric field shielding calculations from objects such as transmission towers, buildings and trees.
- CDEGS can model structures by identifying them as a mesh. This process requires various details about the composition of the materials to be known.

Criteria 8: Can the software import data in Computer Aided Drafting (CAD) format? Can it interface to CAD packages such as Microstation or AutoCAD?

- Narda EFC-400LF can import data including Data Exchange Format (DXF) which is a two dimensional graphics file format, created by the manufactures of AutoCad and is supported by virtually all computer based CAD products including Microstation and AutoCAD. It can also export data such as isolines, hatch patterns and solids in DXF format.
- EPRI EMF Workstation does not have the ability to import or export data in CAD format.
- CDEGS can also import and export data from most CAD packages in DXF format.

Criteria 9: Does the manufacture provide training?

- Narda EFC-400LF training can be provided by the manufactures FGEU in Europe. It is a two day course and FGEU can come to Australia to deliver specific training as required. However FGEU advise that training is generally not required as the program is easy to use.
- EPRI regular holds 3-day training session on the software. It is assumed that this training takes place in the United States.

- CDEGS regularly undertakes training in Canada and has recently completed training in Brisbane and Sydney. The training course is titled Power System Grounding & Electromagnetic Interference Analysis and is a five day course that covers all aspects of the CDEGS software.

Criteria 10: Will the software operate on Ergon Energy computer Wide Area Network (WAN) and able to be accessed from all offices?

- Narda EFC-400LF can only be located on a local area network within a building. The manufacturer has reported that it is not suitable for installation on a wide area network although it is considered that this could possibly be overcome with appropriate network management tools similar to the existing CDEGS configuration.
- EPRI will not operate on a computer network. It is loaded onto a single computer. If Ergon become a full member, then there is no restriction on the number of licences. If Ergon only purchase one or two copies, then they are fixed to a particular machine.
- Ergon Energy currently operates a CDEGS sub-package called Multiground on the Ergon Energy computer network. The new software would operate in the same manner where a third party network management software restricts access, based on the exact licence configuration.

Criteria 11: Does the software provide a combination of technical and non technical outputs suitable for insertion into an environmental report? Can the outputs be easily modified to match existing report formats. Can the outputs be exported and integrated into a third party software such as Coral Draw, Matcad, MATLAB or excel.

- Narda EFC-400LF can produce a wide range of colour graphics that can be superimposed onto area maps. The outputs are suitable for insertion in both technical and non-technical reports. Narda can produce a range of 2D and 3D contour plots which are very professional in appearance.
- EPRI can produce multi coloured magnetic fields graphs with infrastructure superimposed on the graph. Calculated magnetic field values can be exported in a low level ASCII format.

- CDEGS output processor GRServer can provide a range of technical and non-technical outputs for engineering technical reports and more general reports suitable for the public. In addition the graphics can be saved in common format which can be cut and pasted in word documents. CDEGS can also produce a range of text reports which detail results of calculations.

Criteria 12: What level of technical support is available from the software manufacturer or local agent?

- Narda EFC-400LF technical support is carried out by a separate German company called FGEU. With the time difference between Australia and Germany it is considered that the technical support will be carried out mostly by email. This will require a separate contract with FGEU.
- EPRI support is free if Ergon become a full member. If Ergon does not become a full member, then any support is available on a per cost basis.
- CDEGS offer both general support and engineering support and have a free phone number available. With the time difference between Australia and Canada, there is a 3 to 4 hour window available, to contact SES. The Engineering support service offered by SES will allow Ergon Energy Engineers to talk directly to SES Engineers to solve problems and if required CDEGS files can be emailed directly to SES where they can check for potential problems.

Criteria 13: Is there any supporting references from existing users to support the software?

- Narda also have a large range of customers. References from the National Grid in the UK spoke highly of the software. SPI in Victoria have also purchased the software but are in the early stages of using it.
- EPRI advised they have a large range of users, however contact details are confidential.
- CDEGS also have a large range of users. Current Ergon Energy internal staff who operate the earthing program advise that in general the program is suitable. Powerlink Queensland also use the program for earthing and EMF studies and in general are happy with it.

Criteria 14: How does the cost of each software program compare with each other?

The cost options presented in this section are based on offers received by Ergon Energy from each manufacture. The prices quoted in table 5.3 are based on a relative percentage range of the most cost effective option in order protect the confidentiality of offers received and to ensure probity in future software purchasing. A review of prospective users within Ergon Energy indicated that a single concurrent user license would be restrictive and access for two concurrent users would be favorable. The various pricing information listed in table 5.3 includes options for one or two license systems. Also included in table 5.3 is a yearly cost for any available ongoing support service.

Table 5.3: Details of commercially available EMF software prices. Prices are based on a relative percentage range with the most cost effective single license option rated at 100% and all other prices scaled to this amount. Costing based on exchange rate of AU\$1 to US\$0.75 and AU\$1 to €0.60.

Option	Manufacture	Single License	Two License	Comments
1	Narda EFC-400LF Support	100% 10%	175% 12%	First 12 months support from FGEU included.
2	EPRI EMF Workstation Support	762% As req.	914% inc.	Support for non members based on as required contract. Two License cost based on full membership of EPRI.
3	SES CDEGS Support	286% 37%	286% 57%	First 12 months support included in purchase price. Price for CDEGS upgrade to existing earthing modules.

Criteria 15: Based on experiments carried out in chapter 4, are the results of the software reliable?

- A review of figures 4.4 to 4.8 indicates that the Narda software is able to accurately model the magnetic fields emitted in Experiments 1 to 3. The

software is not able to accurately model the magnetic fields emitted in Experiments 4 & 5 although this could be attributed to random false calculations associated with the evaluation version of the software used. Based on these experiments carried using an evaluation version of the software, it can not be determined if the results produced from the Narda software are reliable.

- A review of figures 4.4 to 4.8 indicates that the EPRI software is able to accurately model the magnetic fields emitted in Experiments 1 to 5. The results produced are within an acceptable tolerance, however they do have a lower precision when compared to the results from the CDEGS software, but have a higher precision when compared to the results produced by the Narda software. Based on these experiments, it is considered that the results produced from the EPRI software are reliable.
- A review of figures 4.4 to 4.8 indicates that the CDEGS software is able to accurately model the magnetic fields emitted in Experiments 1 to 5. The results produced are within an acceptable tolerance, have a higher precision when compared to the results from both the EPRI and Narda software. Based on these experiments, it is considered that the results produced from the CDEGS software are reliable and CDEGS is more precise compared to the EPRI or Narda software.

The choice of software will largely depend on what type of modeling and investigation activities Ergon Energy want to undertake and the ability of the person entering the data. In order to assist with this decision the following points, based on the response to the selection criteria, are noted.

- EPRI EMF Workstation program appears to be fairly easy to use. However this ease of use can result in an inflexible program which will operate in fixed confines of the software substation model. The pricing structure of the EPRI SUBCALC is not attractive as the cost is a direct multiple of the number of licenses required which is geared towards encouraging Ergon Energy to become a member of an EPRI EMF work group rather than a one off purchase of the software. Ergon Energy has previously considered membership of EPRI and has judged that there is no strategic advantage to Ergon Energy joining EPRI.

- Ergon Energy substation design currently use almost a third of the CDEGS options. It is considered that by including the remainder of the CDEGS modules, it will facilitate a more holistic approach to Substation Electrical Engineering design and investigation. This however is an disadvantage to the casual user which can be overcome by training and in house support.
- The existing CDEGS software is already supported by Ergon IT service provider. This provides an advantage as the remaining CDEGS modules can operate in a familiar configuration.
- The CDEGS software and processes can appear complicated compared to the drag and drop style of the EPRI SUBCALC and the Narda EFC-400LF. Existing Ergon Energy users of CDEGS have reported that the software is user friendly once the user is familiar with the operation and configuration of the software. As the users of the selected software will most likely be of professional or para-professional qualifications, it is considered that with appropriate training and a range of resources such as help manuals, 'How To' engineering guides and 'Cheat Sheets' Ergon Energy can develop and maintain a CDEGS knowledge base with expertise and skills to assist casual users.
- The EPRI EMF Workstation and the Narda EFC-400LF are both EMF modeling programs and designed solely for this task. The CDEGS software is a broader electrical engineering software that is used to solve electric fields, grounding and power line calculations. The CDEGS software can also perform additional tasks such as, model faults in transmission lines and induced EMF in metallic pipelines or fences, residual and fault current distributions in cables and shields, power line corona effects and audible noise. The CDEGS software comes with a package called SES-Enviro which is specifically aimed at Electromagnetic Environmental Impact Analysis of overhead Transmission Lines. Also included are packages called Autogrid-Pro and AutoGroundDesign for grounding calculations and SES-TLC for power line calculations. It is considered that these tools will be a valuable asset to Ergon Energy during the planning and design of new electrical infrastructure.
- The support service offered by CDEGS although of a higher cost is considered

superior to the service provided by Narda/FGEU and EPRI.

5.4 Recommendation

In investigating the above software programs it is apparent that the three solutions identified are vastly different to each other and manufactured by companies of completely different interests and backgrounds.

The software from EPRI, EMF Workstation, does produce reliable results, does allow for EMF shielding to be considered, appears to be easy to use and has user friendly models already built in. However EMF workstation does not calculate electric fields. This coupled with the high cost when multiple licences are required and the fact that it is not compatible with CAD software effectively eliminates EPRI from further consideration.

The software from Narda EFC-400LF and the software from CDEGS are considered as the two viable options. The Narda software is easier to use and has very good output graphics. The Narda also has a very systematic procedure for entering conductors, where it asks for the start point, stop point and attributes for each conductor. This allows a casual operator with very low level training to enter data; however this can also lead to disadvantages, such as lack of flexibility in the program and skills used in fault finding.

The CDEGS software has a more hands on approach compared to the drag and drop of the Narda EFC-400LF and thus allows the user to be more involved in the model generation and gain an appreciation of the calculation process. The CDEGS option also provides Ergon Energy with greater options as the software can be used to supplement the currently owned CDEGS software and allows Ergon Energy to build on existing design skills and processes where the introduction of a Narda EFC-400LF will require a new range of skills and processes to be developed and managed both from a operator and system maintenance aspect.

Both the Narda and the CDEGS options will interface with the existing CAD packages

used by Ergon Energy. The Narda option may be easier to use for the casual user when compared to the CDEGS option, however this is offset as the key users will be required to carry out existing earthing studies on CDEGS and already have a working knowledge of CDEGS operations.

The CDEGS software is supported already on the Ergon Energy computer network and will be easily integrated into the existing network arrangements where there is a risk that the Narda software may not integrate into the computer network. CDEGS support arrangements, although more expensive than Narda/FGEU services, do provide greater advantages to Ergon Energy.

Based on the experiments carried out it is considered that the CDEGS software is able to accurately model the magnetic fields radiated by the various structures. Using the evaluation version of the Narda software, it could not be determined if the results produced from the Narda software are reliable.

When taking these items into consideration, it is therefore recommended the purchase of two licence version of the CDEGS software for a cost of 286%.

5.5 Chapter Summary

This chapter provides details on three commercially available EMF software programs. As part of the systematic procedure for the evaluation and selection of the EMF software, a selection criteria was developed in order to identify each software advantages and disadvantages which resulted in a recommendation to purchase CDEGS software. Key points discussed in this chapter include.

- Identify three commercially available EMF software programs from from EPRI, SES and Narda,
- Identify background information on each of the manufactures,
- Develop a selection criteria in order to evaluate the advantages and disadvantages of each software program,

- Develop a response to the selection criteria based on the experience gained while carrying out the modeling experiments and information available from each manufacturer,
- Discussion of the advantages and disadvantages identified in the response to the selection criteria,
- Recommend the purchase of two licence version of the CDEGS software for a cost of 286%.

Chapter 6

Conclusions and Further Work

The main aim of this project is to develop a systematic procedure for the evaluation and selection of commercial EMF software, which will provide a recommendation for the purchasing of EMF modeling software in order to estimate the EMF generated by High Voltage Sub Stations and Distribution, Sub-Transmission and Transmission Networks.

This systematic procedure was applied to commercial EMF software programs from three manufacturers. A comparison of the results from commercial EMF software compared against measurements obtained from five experiments and predications from theoretical models developed indicated that the results from EPRI and CDEGS are reliable and accurate. The Narda results were obtained using an evaluation version of the software which introduced errors and therefore it could not be determined if the results produced from the Narda software were accurate.

The theoretical models developed for calculating symmetrical fields was accurate when compared to the measurements produced. However, the theoretical models developed for non symmetrical fields was not able to reproduce accurate results when compared to the experiment measurements. This is attributed to coding errors which will require further development and testing.

In addition to achieving the main aim of the project it also allowed an understanding

of EMF research, standards, theory, modeling procedures and evaluation skills to be developed.

6.1 Achievement of Project Objectives

The following objectives have been addressed:

Literature Review Chapter 2 presented background information on EMF. Items identified included the source of EMF, properties and units of measurement. Australian and International Standards & Guidelines were also identified. This chapter presented information on research into adverse health effects associated with exposure to EMF and identified the policy which is commonly used to manage this exposure. The chapter concluded by identifying laws which are used to calculate electric and magnetic fields.

Theoretical Models Chapter 3 presented two structures which enable symmetrical and non symmetrical magnetic fields to be measured. Laws identified in Chapter 2 were developed into equations and expanded into Theoretical Models in the form of computer algorithms to predict the magnetic fields emitted from these structures.

Experimental Verification Chapter 4 presented details and results of five experiments carried out in order to verify the numerical results obtained from commercially available EMF software by comparing them against actual measured values and predications from Theoretical Models.

Commercial EMF Software Evaluation and Selection Chapter 5 presented details on the three commercially available EMF software programs. A selection criteria was developed in order to evaluate each software by identifying there advantages and disadvantages. This resulted in the recommendation to purchase CDEGS software.

6.2 Further Work for CDEGS EMF Software

The main aim of this project was to develop a systematic procedure for the evaluation and selection of EMF software, which ultimately led to the purchase of CDEGS software. Due to coding errors associated with the MATLAB Biot Savart algorithm, it was not possible to verify the accuracy of the results for the non symmetrical magnetic fields. These coding errors are possibly attributed to polarity errors. Further work is required to fine tune this algorithm with a view to improving accuracy and repairing the coding errors. Future projects could revise the code and include items such as a input interface to prompt the user for the number of conductors, dimensions, current and observation points. The code could also be amended to include a compliance checker where the magnetic field estimated at an observation point is compared against maximum exposure values specified. A useful addition would be to add a section to calculate the electric field at the observation points.

The experiments carried out involved measuring the magnetic fields measured along various horizontal profiles below current carrying conductors. On hindsight only one set of measurements along the $700mm$ horizontal profile was used in the evaluation. It would have been more benefit to only obtain results of one measurement horizontal profile but increase the type of measurements by using a single element instrument and orientate the instrument to measure both the X, Y and Z axis and also the maximum or peak value.

The selected software will need to be further verified, from the effective but relatively simple experiments carried out in this project, to include a comparison of real life scenarios involving both High Voltage Substations and power lines. The main aim of these additional experiments is to allow the user to have confidence in the results and to determine the range of tolerances to be included with future EMF predications. A follow up project is already underway to compare the CDEGS magnetic fields predication with measurements obtained from a $66kV$ to $11kV$ substation containing two $40MVA$ transformers, two $11kV$ capacitor banks and a indoor $11kV$ switchboard with feeder cables.

The CDEGS software has to be integrated into existing design procedures, standards

and quality assurance systems. CDEGS design standards need to be developed to ensure that all models, where possible, are carried out on a similar work space and configuration. Items that need to be standardized include grouping of conductors, scales, modeling of transformers, air core reactors, capacitor banks, allocation of colours in plots and type of plots produced. Standard report templates if developed, will also provide consistent modeling practices and allow efficient use of resources.

For these reasons the EMF software project can be considered an on going project.

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Appendix A

Project Specification

University of Southern Queensland
Faculty of Engineering and Surveying

**ENG 4111/2 Research Project
PROJECT SPECIFICATION**

FOR: Sean Joseph Mc Guinness
TOPIC: Evaluation of commercial EMF Software
SUPERVISOR: Dr. Tony Ahfock, USQ
SPONSORSHIP: Ergon Energy Pty Ltd
ENROLMENT: ENG4111 – S1, D, 2006;
ENG4112 – S2, D, 2006;
PROJECT AIM: The aim of this project is to develop a systematic procedure for the evaluation and selection of commercially available EMF software.
PROGRAMME: **Issue A, 16 March 2006**

1. To carry out a literature review on the requirement for EMF monitoring, electromagnetic modelling on which EMF software is based and EMF standards.
2. To develop a number of theoretical models based on principles such as Maxwells Laws and Biot-Savart Law to verify numerical results from commercially available EMF software simulating simple conductor configurations.
3. To carry out Laboratory tests on simple conductor configurations and compare test results with predictions by theoretical modelling and commercial software.
4. To develop a list of criteria against which commercial EMF software could be evaluated.
5. To carry out an evaluation of a small number of software packages according to the criteria developed above.

ASSESSMENT CRITERIA:

The requirement for a 'B' grade is successful completion of objectives (1), (3), (4) and (5). For a grade better than 'B' a good attempt at objective (2) is needed.

AGREED: Se. Guinness (Student) A. Ahfock (Supervisor)
DATED: 17 / 9 / 2006 13 / 9 / 2006

Appendix B

MATLAB code for symmetrical Magnetic Field

Listing B.1: MATLAB m file for symmetrical magnetic fields.

```

% ampere- Works out magnetic flux density at arbitrary
% point in x-y plane due to 3 infinitely long
% (in z direction) conductors quasi-static
% conditions assumed; superposition of equations
% based on Maxwell's Equation(Ampere's law).
% modified by Sean Mc Guinness (0019621304)
% from code developed by Dr Tony Ahfock (USQ)
clear all; help ampere; % Clear memory; print header
%
%-----
% User Input Data, define currents and conductor dimensions
%-----
% current in first conductor (a, b & c)
% position relative to origin (m)
ia=24.6*cos(0)+i*24.6*sin(0); xa=-0.5 ; ya=1 ;
ib=24.6*cos(-120*pi/180)+i*24.6*sin(-120*pi/180);xb=0.0; yb=1;
ic=24.6*cos(120*pi/180)+i*24.6*sin(120*pi/180); xc=0.50; yc=1;
%
xp=0.0;yp=0.25; % position of observation point (m)
%
mu0=4*pi*1e-7; %permeability of free space
%
%-----
%Compute the field strength in (A/m) at observation point
%-----
hax=ia*(xp-xa)/(2*pi*((xp-xa)^2+(yp-ya)^2));% ia x-component
hay=-ia*(yp-ya)/(2*pi*((xp-xa)^2+(yp-ya)^2));% ia y-component
hbx=ib*(xp-xb)/(2*pi*((xp-xb)^2+(yp-yb)^2));% ib x-component
hbys=-ib*(yp-yb)/(2*pi*((xp-xb)^2+(yp-yb)^2));% ib y-component
hcx=ic*(xp-xc)/(2*pi*((xp-xc)^2+(yp-yc)^2));% ic x-component
hcy=-ic*(yp-yc)/(2*pi*((xp-xc)^2+(yp-yc)^2));% ic y-component
%
hx=(hax+hbxs+hcx); % net field strength in the x-direction
hy=(hay+hbys+hcy); % net field strength in the y-direction
%
%-----
%Compute the magnetic field density in (uT)
%-----
bx=mu0*hx*1000000 % x-component of flux density(uT) at xp,yp
by=mu0*hy*1000000 % y-component of flux density(uT) at xp,yp
%
rbx=real(bx);% real part of bx
ibx=imag(bx);% imaginary part of bx
rby=real(by);% real part of by
iby=imag(by);% imaginary part of by
%
%-----
%Compute the resultant magnetic field density in (uT)
%-----
% finding the major of the 'polarization ellipse'
th=[0:pi/180:2*pi];
%loop for all points
for ii=1:361
    bth(ii)=(rbx*rbx+ibx*ibx)*(cos(th(ii)))*cos(th(ii));
    bth(ii)=bth(ii)+(rby*rby+iby*iby)*(sin(th(ii)))*sin(th(ii));
    bth(ii)=bth(ii)+2*(ibx*iby+rbx*rby)*(sin(th(ii)))*cos(th(ii));
end
%find maximum value to the 'polarization ellipse'
maxb=sqrt(max(bth))
%calculate the resultant

```

```
absbx=abs(bx);  
absby=abs(by);  
resultantb=sqrt(absbx*absbx+absby*absby)  
%EOF
```

Appendix C

MATLAB code for non symmetrical Magnetic Field

Listing C.1: MATLAB m file for Non symmetrical magnetic fields.

```

% biot_sav  Compute magnetic field for a three conductors
%           using the Biot-Savart law for Structure B.
%           Structure B consists of horizontal & vertical
%           conductors. The coordinate axis for this mfile
%           is taking an imaginary cross section of three
%           parallel conductors, then left to right
%           (or east to west) across conductors is the X axis,
%           top to bottom (or north to south) is
%           the y axis and the depth along the wires is the Z axis.
%           modified by Sean Mc Guinness (0019621304)
%           with the assistance of Dr Tony Ahfock (USQ)
%           original file based on biotsav.m from
%           'MATLAB Projects for Scientists and Engineers'
%           by Fishbane, Gasiorowicz & Thornton
%           Applied Scale: 1 Matlab unit - 1m
clear all; help biot_sav; % Clear memory; print header
%
% User Input Data, define currents and conductor dimensions
%
mu0 = 4*pi*1e-7; % Permeability of free space (T*m/A)
%Current per phase in Amps
Ia = 24.6*cos(0)+i*24.6*sin(0); %A phase
Ib = 24.6*cos(-120*pi/180)+i*24.6*sin(-120*pi/180);%B phase
Ic = 24.6*cos(120*pi/180)+i*24.6*sin(120*pi/180); %C phase
%
% Useful constant
Constant(1) = mu0/(4*pi) * Ia;
Constant(2) = mu0/(4*pi) * Ib;
Constant(3) = mu0/(4*pi) * Ic;
%
%observation point P where results are measured
xP=0;%varies between 0.7m 0 to -0.7m ie 0 is below centre
yP=0.250;%same for experiment 3, 4 & 5
zP=4.500;%exp 4 = 4.5m, exp 3&5 = 5.5m
%
fprintf('Observation point X axis is %g m\n',xP)
fprintf('Observation point Y axis is %g m\n',yP)
fprintf('Observation point Z axis is %g m\n',zP)
%
%@ Loop over the horizontal segments in the conductors in z plane
ZSegments = 9000;%ie segment every 9m/9000=1 mm
%
%
%
%@ Loop over the vertical segments in the conductors in y plane
YSegments = 1000;% ie vertical section is 1000mm high
%
%
%
%@ set up zero arrays for conductor x, y & z values
%(speeds up execution of the program to assign first)
x=zeros(3,ZSegments);
yH=zeros(3,ZSegments);
yV=zeros(3,YSegments);
z=zeros(3,ZSegments);
%
%calculate X values array for parallel conductors 0.5m apart
x(1,1:ZSegments)=-0.5;% ie -0.5m off centre

```

```

x(2,1:ZSegments)=0; %ie centre conductor
x(3,1:ZSegments)=0.5;% ie 0.5m off centre
%for small segments of change in each conductor dlx = zero
dlx(1:3,1:ZSegments)=0;
%
%calculate Y array values for conductors. In this experiment
%the y values vary for both horizontal(yH) and vertical(yV)
%conductors. First array for the horizontal conductors
for k=1:ZSegments
    if (k<3000)|(k>6000)%ie lowest horizontal sections
        yH(1:3,k)=1;%1m off the ground
    elseif (k>3000)&(k<6000)%lowest horizontal sections
        yH(1:3,k)=2;%2m off the ground
    elseif (k==3000)|(k==6000)%vertical sections
        yH(1:3,k)=0;%3m & 6m are vert. conductors
    end
end
%for small segments of horz. conductors change of y = zero
dlyH(1:3,1:ZSegments)=0;
%array for vertical conductors which are located at
%ZSegments 3000 & 6000
for k = 1:3
yV(k,1:YSegments)=[1.001:0.001:2.000];%1m to 2m high
end
%ie small segments of y change by 1mm
dlyV(1:3,1:YSegments)=0.001;
%
%calculate Z array values for conductors
%results in dlz 1mm long
for k = 1:3
z(k,1:ZSegments)=[1:1:ZSegments]/1000;
end
%ie each conductor P has small segments of z change by 1mm
dlz(1:3,1:ZSegments)=0.001;
%
%no user input beyond this point
%
% Loop over each conductor and evaluate B(x,y,z)
%at the observation point
bx = 0; by = 0; bz=0; % Initialize B to zero
% loop for each phase conductor
for xP = 0:0.1:0.700
%loop for horizontal profile points
%from centre to outer edge at 700mm
%initialize B to zero for each measurement point
bx = 0; by = 0; bz=0;
    for p =1:3
%loop for each of the three conductors p (a, b & c)
for k=1:ZSegments %loop over each Z segment
    % Compute components of the r vector (vector between
    %% segment on conductors and observation point)
    rx = xP - x(p,k);
    ry = yP - yH(p,k);
    rz = zP - z(p,k);
    % Compute r^3 from r vector
    r3 = sqrt(rx^2 + ry^2 + rz^2)^3;
    % Compute x,y&z components of cross product dl X r
    % Method for cross product using the Algebraic definition

```

```

% see page 642 of
%(Hughes-Hallett , Gleason , McCallum , etal. 1998)
%calculates x,y&z values seperately
dl_X_rx = dlyH(p,k)*rz - dlz(p,k)*ry;
    dl_X_ry = dlz(p,k)*rx - dlx(p,k)*rz;
dl_X_rz = dlx(p,k)*ry - dlyH(p,k)*rx;
    %@ Increment sum of x, y & z components
bx = bx + Constant(p)*dl_X_rx/r3;
    by = by + Constant(p)*dl_X_ry/r3;
bz = bz + Constant(p)*dl_X_rz/r3;
%3m & 6m are vert. conductors
    if (k==3000)|(k==6000)
        for q=1:YSegments
            %@ Compute components of the r vector
            %(vector between segment on conductors
            %and observation point)
                rx = xP - x(p,k);
                ry = yP - yV(p,q);
                rz = zP - z(p,k);
            %@ Compute r^3 from r vector
                r3 = sqrt(rx^2 + ry^2 + rz^2)^3;
            %@ Compute x,y&z components of cross
            %product dl X r
            %calculates x,y&z values seperately
                dl_X_rx = dlyV(p,q)*rz - dlz(p,k)*ry;
                    dl_X_ry = dlz(p,k)*rx - dlx(p,k)*rz;
                dl_X_rz = dlx(p,k)*ry - dlyV(p,q)*rx;
                    %@ Increment sum of x, y & z components
                bx = bx + Constant(p)*dl_X_rx/r3;
                    by = by + Constant(p)*dl_X_ry/r3;
                bz = bz + Constant(p)*dl_X_rz/r3;
            end
        end
    end
end
end
end
BMag = sqrt(bx^2 + by^2 + bz^2);
obs_M = abs(BMag)*1000000;%1000000 converts to micro Telsa
fprintf('When Observation point is %g meters the \n ',xP)
fprintf('Observation point magnetic field is %g micro T\n',obs_M)
end
%EOF

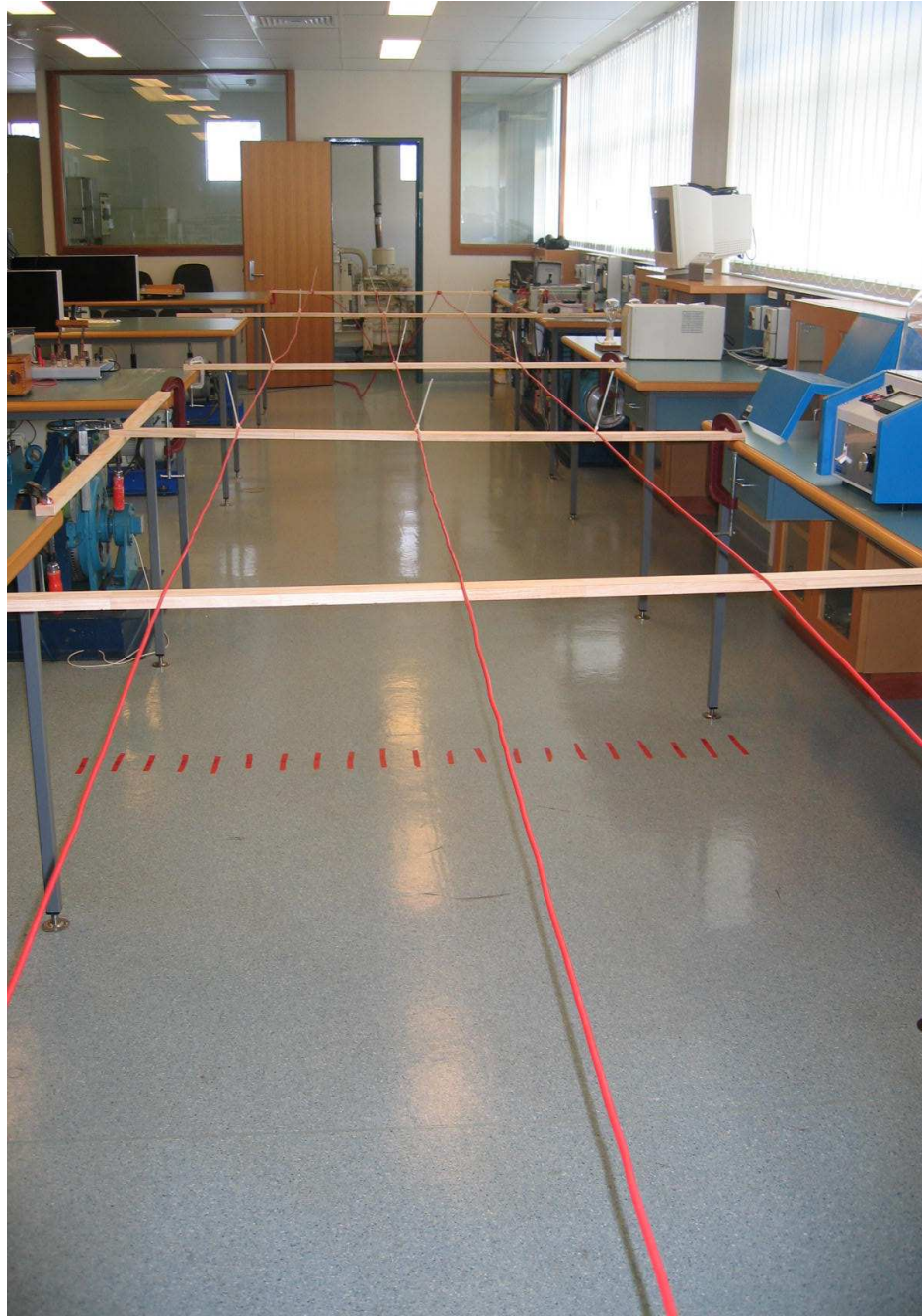
```

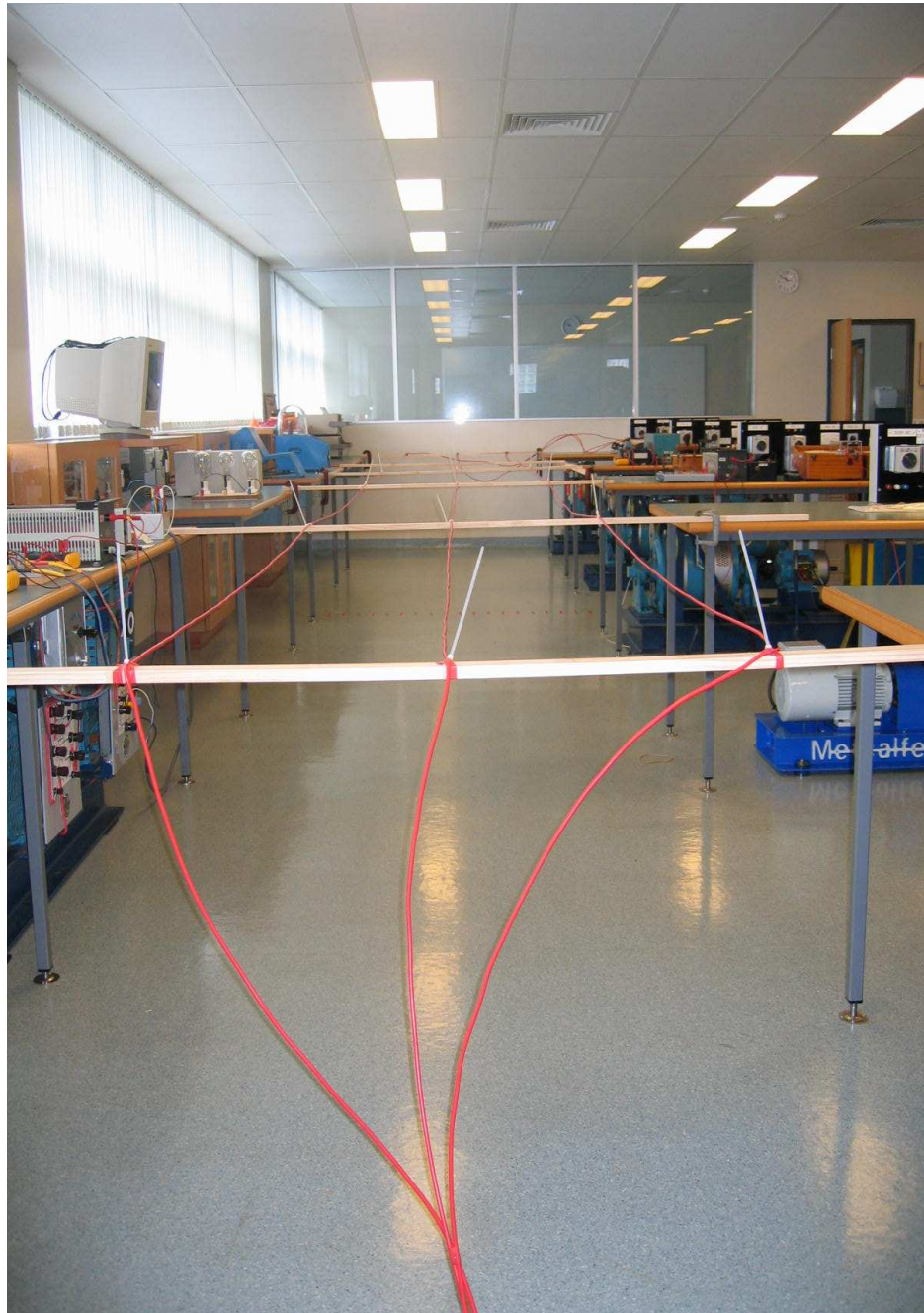
```
%
```

Appendix D

Photographs of Experiments

Structure A

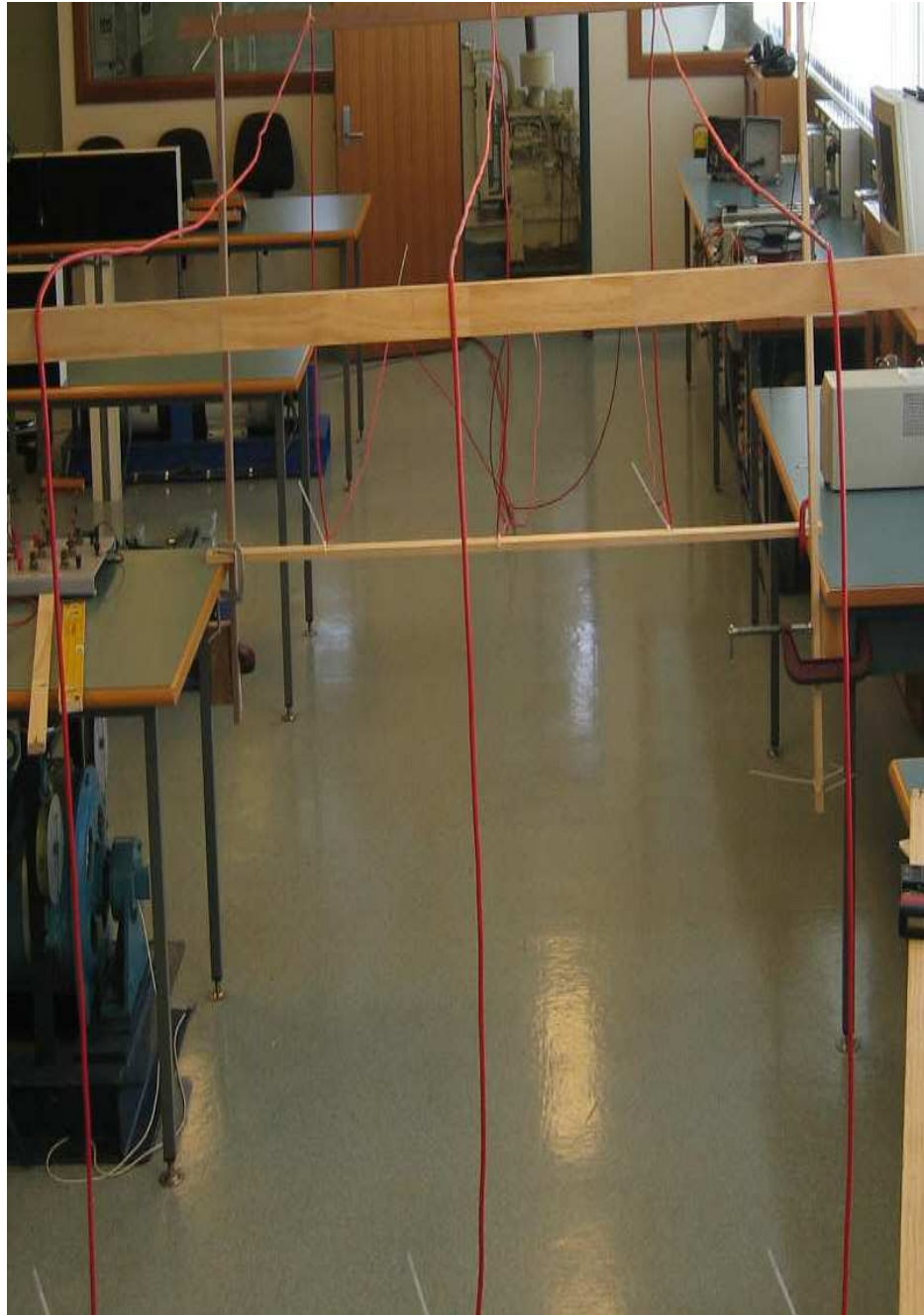




Appendix E

Photographs of Experiments

Structure B





Appendix F

Experiment and Model Results

Magnetic Field (μT) modeled by Narda for Experiment 1

Horizontal Profile (mm)	Vertical Profile (mm)														
	-700	-600	-500	-400	-300	-200	-100	0	100	200	300	400	500	600	700
-250	6.06	7.98	9.66	10.30	10.23	10.24	10.56	10.79	10.56	10.24	10.23	10.30	9.66	7.98	6.06
-500	3.34	3.82	4.26	4.59	4.82	4.96	5.04	5.06	5.04	4.96	4.89	4.59	4.26	3.82	3.34
-750	2.08	2.27	2.45	2.60	2.71	2.80	2.85	2.86	2.85	2.80	2.71	2.60	2.45	2.27	2.08

Magnetic Field (μT) modeled by Narda for Experiment 2

Horizontal Profile (mm)	Vertical Profile (mm)														
	-700	-600	-500	-400	-300	-200	-100	0	100	200	300	400	500	600	700
-250	11.88	15.52	18.79	19.94	19.76	19.75	20.35	20.79	20.29	19.65	19.61	19.74	18.55	15.39	11.77
-500	6.50	7.43	8.29	8.93	9.36	9.62	9.76	9.77	9.73	9.57	9.29	8.84	8.18	7.35	6.42
-750	4.05	4.42	4.76	5.05	5.27	5.42	5.51	5.54	5.50	5.39	5.23	5.00	4.70	4.36	3.99

Magnetic Field (μT) modeled by Narda for Experiment 3

Horizontal Profile (mm)	Vertical Profile (mm)														
	-700	-600	-500	-400	-300	-200	-100	0	100	200	300	400	500	600	700
-250	14.66	19.13	22.33	23.36	21.05	20.97	22.31	23.29	22.21	20.75	20.77	21.96	21.86	18.75	14.35
-500	9.78	11.27	12.20	12.44	12.37	12.48	12.80	12.98	12.75	12.38	12.21	12.22	11.94	11.03	9.57
-750	7.00	7.86	8.49	8.81	8.96	9.10	9.23	9.29	9.19	9.02	8.85	8.66	8.31	7.69	6.83
-1000	4.98	5.56	6.05	6.40	6.63	6.78	6.86	6.88	6.83	6.72	6.55	6.30	5.92	5.43	4.86
-1250	3.52	3.86	4.19	4.46	4.66	4.79	4.86	4.88	4.84	4.75	4.60	4.52	4.10	3.78	3.42

Magnetic Field (μT) modeled by Narda for Experiment 4

Horizontal Profile (mm)	Vertical Profile (mm)														
	-700	-600	-500	-400	-300	-200	-100	0	100	200	300	400	500	600	700
-250	10.70	14.28	17.70	19.21	19.32	19.27	19.94	20.30	19.86	19.26	19.12	18.94	17.35	14.01	10.46
-500	5.03	6.07	7.19	8.16	8.88	9.33	9.54	9.59	9.51	9.28	8.82	8.09	7.08	5.98	4.93
-750	2.84	3.41	4.04	4.63	5.13	5.50	5.70	5.77	5.69	5.48	5.12	4.62	4.01	3.39	2.81
-1000	2.01	2.39	2.80	3.18	3.51	3.80	3.92	3.92	3.92	3.77	3.52	3.19	2.80	2.40	2.01
-1250	1.64	1.90	2.17	2.42	2.63	2.80	2.90	2.94	2.90	2.80	2.64	2.42	2.17	1.91	1.65

Magnetic Field (μT) modeled by Narda for Experiment 5

Horizontal Profile (mm)	Vertical Profile (mm)														
	-700	-600	-500	-400	-300	-200	-100	0	100	200	300	400	500	600	700
-250	10.48	12.27	12.79	11.20	8.67	6.44	5.04	4.56	5.04	6.44	8.67	11.20	12.79	12.27	10.48
-500	7.50	8.02	8.15	7.79	7.08	6.30	5.74	5.53	5.74	6.30	7.08	7.79	8.15	8.02	7.50
-750	6.07	6.38	6.46	6.29	5.93	5.53	5.24	5.13	5.24	5.53	5.93	6.29	6.46	6.38	6.07
-1000	5.04	5.22	5.26	5.16	4.97	4.75	4.60	4.54	4.60	4.75	4.97	5.16	5.26	5.22	5.04
-1250	4.14	4.24	4.27	4.24	4.17	4.09	4.03	4.00	4.03	4.09	4.17	4.24	4.27	4.24	4.14

Magnetic Field (μT) modeled by EPRI for Experiment 1

Horizontal Profile (mm)	Vertical Profile (mm)														
	-700	-600	-500	-400	-300	-200	-100	0	100	200	300	400	500	600	700
-250	6.21	8.28	10.10	10.71	10.53	10.52	10.90	11.20	10.90	10.52	10.53	10.71	10.10	8.28	6.21
-500	3.41	3.92	4.38	4.77	4.97	5.11	5.18	5.21	5.18	4.97	4.77	4.38	3.92	3.41	
-750	2.12	2.33	2.51	2.67	2.79	2.88	2.93	2.95	2.93	2.88	2.79	2.67	2.51	2.33	2.12

Magnetic Field (μT) modeled by EPRI for Experiment 2

Horizontal Profile (mm)	Vertical Profile (mm)														
	-700	-600	-500	-400	-300	-200	-100	0	100	200	300	400	500	600	700
-250	11.94	15.90	19.38	20.53	20.20	20.20	20.98	21.59	21.03	20.30	20.35	20.73	19.62	16.13	12.14
-500	6.52	7.49	8.36	9.03	9.47	9.74	9.90	9.96	9.92	9.79	9.54	9.12	8.46	7.60	6.63
-750	4.02	4.40	4.75	5.04	5.27	5.44	5.54	5.58	5.55	5.47	5.31	5.09	4.81	4.46	4.09

Magnetic Field (μT) modeled by EPRI for Experiment 3

Horizontal Profile (mm)	Vertical Profile (mm)														
	-700	-600	-500	-400	-300	-200	-100	0	100	200	300	400	500	600	700
-250	14.48	18.97	21.77	21.78	20.51	20.36	21.67	22.60	21.59	20.19	20.23	21.38	21.30	18.34	14.10
-500	9.76	11.16	11.99	12.17	12.08	12.15	12.44	12.60	12.39	12.04	11.90	11.94	11.72	10.88	9.50
-750	7.03	7.83	8.36	8.62	8.72	8.81	8.92	8.96	8.88	8.73	8.59	8.45	8.17	7.62	6.83
-1000	5.06	5.58	5.99	6.28	6.46	6.57	6.63	6.64	6.60	6.50	6.36	6.15	5.85	5.42	4.91
-1250	3.60	3.91	4.18	4.31	4.56	4.66	4.71	4.72	4.69	4.61	4.49	4.31	4.08	3.79	3.48

Magnetic Field (μT) modeled by EPRI for Experiment 4

Horizontal Profile (mm)	Vertical Profile (mm)														
	-700	-600	-500	-400	-300	-200	-100	0	100	200	300	400	500	600	700
-250	12.01	15.57	18.62	19.69	19.47	19.44	20.01	20.42	19.23	19.27	19.21	19.34	18.21	15.15	11.65
-500	6.88	7.76	8.52	9.08	9.43	9.63	9.73	9.75	9.68	9.53	9.29	8.90	8.32	7.54	6.66
-750	4.47	4.80	5.08	5.30	5.47	5.57	5.63	5.63	5.59	5.51	5.38	5.20	4.96	4.66	4.33
-1000	3.14	3.28	3.40	3.50	3.56	3.60	3.62	3.62	3.60	3.56	3.50	3.42	3.31	3.18	3.03
-1250	2.27	2.39	2.44	2.48	2.50	2.52	2.52	2.52	2.51	2.49	2.46	2.42	2.37	2.31	2.23

Magnetic Field (μT) modeled by EPRI for Experiment 5

Horizontal Profile (mm)	Vertical Profile (mm)														
	-700	-600	-500	-400	-300	-200	-100	0	100	200	300	400	500	600	700
-250	8.15	10.50	12.04	11.76	10.41	9.14	8.35	8.10	8.35	9.14	10.41	11.76	12.04	10.50	8.15
-500	5.80	6.40	6.87	6.91	6.64	6.28	6.01	5.91	6.01	6.28	6.64	6.91	6.87	6.40	5.60
-750	4.10	4.55	4.83	4.91	4.85	4.73	4.63	4.59	4.63	4.73	4.85	4.91	4.83	4.55	4.10
-1000	2.99	3.27	3.48	3.60	3.64	3.64	3.63	3.62	3.63	3.64	3.64	3.60	3.48	3.27	2.99
-1250	2.15	2.32	2.47	2.58	2.65	2.69	2.71	2.72	2.71	2.69	2.65	2.58	2.47	2.32	2.15

Magnetic Field (μT) modeled by CDEGS for Experiment 1

Horizontal Profile (mm)	Vertical Profile (mm)														
	-700	-600	-500	-400	-300	-200	-100	0	100	200	300	400	500	600	700
-250	6.20	8.00	9.60	10.20	10.18	10.18	10.40	10.63	10.40	10.18	10.18	10.20	9.60	8.00	6.20
-500	3.60	4.00	4.45	4.75	5.00	5.10	5.18	5.20	5.18	5.10	5.00	4.75	4.45	4.00	3.60
-750	2.40	2.60	2.75	2.90	3.00	3.10	3.15	3.20	3.15	3.10	3.00	2.90	2.75	2.60	2.40

Magnetic Field (μT) modeled by CDEGS for Experiment 2

Horizontal Profile (mm)	Vertical Profile (mm)														
	-700	-600	-500	-400	-300	-200	-100	0	100	200	300	400	500	600	700
-250	12.10	15.80	19.00	20.20	20.10	20.10	20.60	21.10	20.60	20.10	20.10	20.20	19.00	15.80	12.10
-500	6.80	7.70	8.60	9.20	9.70	10.00	10.10	10.20	10.10	10.00	9.70	9.20	8.60	7.70	6.80
-750	4.40	4.80	5.10	5.40	5.60	5.80	5.90	5.95	5.90	5.80	5.60	5.40	5.10	4.80	4.40

Magnetic Field (μT) modeled by CDEGS for Experiment 3

Horizontal Profile (mm)	Vertical Profile (mm)														
	-700	-600	-500	-400	-300	-200	-100	0	100	200	300	400	500	600	700
-250	15.00	19.20	22.55	22.60	21.10	21.00	22.60	23.40	22.60	21.00	21.10	22.60	22.55	19.20	15.00
-500	10.20	11.50	12.40	12.50	12.60	12.70	12.90	13.10	12.90	12.70	12.60	12.50	12.40	11.50	10.20
-750	7.40	8.20	8.70	9.00	9.10	9.20	9.30	9.40	9.30	9.20	9.10	9.00	8.70	8.20	7.40
-1000	5.40	5.90	6.30	6.60	6.80	6.90	7.00	7.10	7.00	6.90	6.80	6.60	6.30	5.90	5.40
-1250	4.00	4.20	4.50	4.70	4.90	4.95	5.00	5.10	5.00	4.95	4.90	4.70	4.50	4.20	4.00

Magnetic Field (μT) modeled by CDEGS for Experiment 4

Horizontal Profile (mm)	Vertical Profile (mm)														
	-700	-600	-500	-400	-300	-200	-100	0	100	200	300	400	500	600	700
-250	12.60	16.35	19.40	20.40	22.00	21.50	20.80	21.30	20.80	21.50	22.00	20.40	19.40	16.35	12.60
-500	7.00	7.90	8.60	9.15	9.50	9.70	9.80	9.83	9.80	9.70	9.50	9.15	8.60	7.90	7.00
-750	4.60	4.90	5.20	5.40	5.55	5.70	5.78	5.80	5.78	5.70	5.55	5.40	5.20	4.90	4.60
-1000	3.28	3.42	3.52	3.60	3.66	3.70	3.71	3.72	3.71	3.70	3.66	3.60	3.52	3.42	3.28
-1250	2.44	2.52	2.56	2.60	2.62	2.63	2.64	2.64	2.64	2.63	2.62	2.60	2.56	2.52	2.44

Magnetic Field (μT) modeled by CDEGS for Experiment 5

Horizontal Profile (mm)	Vertical Profile (mm)														
	-700	-600	-500	-400	-300	-200	-100	0	100	200	300	400	500	600	700
-250	8.33	10.74	12.37	12.01	10.62	9.31	8.52	8.27	8.52	9.31	10.62	12.01	12.37	10.74	8.33
-500	5.69	6.51	6.98	7.05	6.78	6.39	6.12	6.05	6.12	6.39	6.78	7.05	6.98	6.51	5.69
-750	4.16	4.61	4.91	4.98	4.91	4.81	4.71	4.69	4.71	4.81	4.91	4.98	4.91	4.61	4.16
-1000	3.00	3.29	3.50	3.63	3.69	3.69	3.67	3.65	3.67	3.69	3.69	3.63	3.50	3.29	3.00
-1250	2.17	2.36	2.48	2.56	2.67	2.72	2.73	2.73	2.73	2.72	2.67	2.56	2.48	2.36	2.17

Magnetic Field (μT) measured during Experiment 1

Horizontal Profile (mm)	Vertical Profile (mm)														
	-700	-600	-500	-400	-300	-200	-100	0	100	200	300	400	500	600	700
-250	6.54	8.44	11.54	11.60	11.48	11.40	11.36	11.32	11.74	11.84	11.96	11.60	11.54	8.44	6.80
-500	3.42	3.90	4.38	5.06	5.18	5.34	5.48	5.50	5.42	5.48	5.42	5.06	4.64	4.02	3.56
-750	2.18	2.68	2.88	2.86	3.00	3.02	3.06	3.16	3.06	3.02	3.00	2.86	2.88	2.68	2.22

Magnetic Field (μT) measured during Experiment 2

Horizontal Profile (mm)	Vertical Profile (mm)														
	-700	-600	-500	-400	-300	-200	-100	0	100	200	300	400	500	600	700
-250	11.80	14.62	17.58	20.26	21.12	21.12	21.12	20.80	21.44	21.76	21.12	20.35	18.56	15.04	12.48
-500	6.48	7.34	8.28	9.18	9.76	10.14	10.28	10.34	10.46	10.46	10.08	9.42	8.58	7.58	6.62
-750	4.12	4.48	5.08	5.52	5.80	5.98	6.06	6.02	6.06	5.98	5.80	5.52	5.08	4.66	4.20

Magnetic Field (μT) measured during Experiment 3

Horizontal Profile (mm)	Vertical Profile (mm)														
	-700	-600	-500	-400	-300	-200	-100	0	100	200	300	400	500	600	700
-250	17.28	20.48	24.32	24.96	24.32	23.68	24.64	24.96	24.64	23.68	24.32	24.96	24.32	19.20	15.04
-500	9.82	11.64	13.06	13.12	13.36	13.48	13.80	13.76	13.92	13.54	13.42	13.12	13.06	10.98	9.72
-750	7.10	8.14	8.86	9.14	9.12	9.28	9.52	9.46	9.52	9.28	9.12	9.14	8.80	7.96	7.00
-1000	5.36	5.74	6.08	6.46	6.74	7.00	7.10	7.16	7.10	7.02	6.86	6.64	6.24	5.78	5.18
-1250	3.88	4.14	4.48	4.72	4.94	5.04	5.16	5.20	5.16	5.10	4.96	4.70	4.46	4.08	3.72

Magnetic Field (μT) measured during Experiment 4

Horizontal Profile (mm)	Vertical Profile (mm)														
	-700	-600	-500	-400	-300	-200	-100	0	100	200	300	400	500	600	700
-250	16.32	22.08	26.56	27.52	27.84	29.44	28.16	28.48	28.16	29.44	27.84	27.52	26.56	22.08	16.32
-500	7.46	9.12	10.10	11.72	12.42	12.58	12.46	12.36	12.32	12.26	11.72	10.78	9.56	8.14	7.26
-750	4.92	5.48	5.82	6.18	6.62	6.76	6.82	6.90	6.80	6.74	6.46	6.20	5.82	5.38	4.84
-1000	3.46	3.64	3.74	3.90	4.10	4.18	4.28	4.32	4.28	4.28	4.18	4.08	3.88	3.72	3.56
-1250	2.56	2.66	2.78	2.86	2.94	2.90	2.96	2.96	2.96	2.96	2.94	2.88	2.78	2.72	2.62

Magnetic Field (μT) measured during Experiment 5

Horizontal Profile (mm)	Vertical Profile (mm)														
	-700	-600	-500	-400	-300	-200	-100	0	100	200	300	400	500	600	700
-250	11.00	12.68	13.34	13.62	12.36	10.60	9.68	9.48	9.86	11.08	12.58	13.62	12.82	10.82	8.46
-500	6.06	6.82	7.30	7.44	7.28	7.04	6.86	6.90	7.10	7.24	7.44	7.40	6.94	6.20	5.38
-750	4.26	4.78	5.10	5.34	5.34	5.26	5.20	5.22	5.20	5.26	5.34	5.34	5.10	4.64	4.14
-1000	3.22	3.50	3.72	3.76	3.84	3.88	3.96	3.96	3.92	3.94	3.84	3.70	3.60	3.42	3.18
-1250	2.38	2.52	2.64	2.82	2.84	2.94	2.90	2.94	2.88	2.88	2.78	2.64	2.50	2.36	2.18