Live-Line Worker Exposure to EMF on 330kV & 500kV Transmission Towers

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Abstract:

This paper reviews the calculated electromagnetic field (EMF) values of 330kV and 500kV overhead towers for their various operating voltages and energy transfer capability. The calculated values are compared against the current Australian statutory guidelines for occupational limits. Occupational health concerns relating to live line work stem from the theory that biological effects are associated with exposure to power frequency EMF and that these occur as a result of electric current induced in the subject. Safety precautions for these frequencies are thus based on limiting field levels that may induce harmful electric current in the subject. Due to the close proximity of live line working, it is not always possible to limit these EMFs. These fields can be reduced by shielding such as live-line suits.

At the low frequency of 50 Hz, two fields exist that can be studied separately: electric fields and magnetic fields. Magnetic fields are produced by the current flowing (movement of electric charge) along a conductor. Electric current is measured in Ampere (A) and its magnitude varies depending on the power network delivery capability and number of customers (load) supplied by the system. As the load changes, the magnetic field will change. Magnetic fields are measured by both magnetic field strength (MFS) and Magnetic Flux Density (MFD). Reducing 50 Hz magnetic fields requires special engineering techniques and is generally addressed during the design phase of the overhead line. Electric fields may exist without the presence of magnetic fields. This occurs when a transmission line is energised without load – it has an applied voltage but is not conveying current.

The review assesses overhead line structure outlines and tower geometries for compliance to the Public Consultation Draft document issued by the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) – Exposure Limits for Electric & Magnetic Fields – 0 Hz to 3 kHz.

A simulation model was derived overlaying the magnetic and electric field on the structure outline in sufficient resolution to assess occupational exposure at nominated positions on the structure climbing and inspection corridor as well as in other nominated positions for bare hand on conductor and working positions for live stick work. Calculated results are compared against the nominated occupational exposure limits in ARPANSA (2009 revision of draft). Several single circuit, double circuit suspension and strain pole types are provided for a narrative assessment.

1. Background

LineTech Consulting was appointed by an Australian electricity utility (EU) to undertake a narrative review of existing 330kV and newly proposed 500kV overhead towers to recommend the worst case structures from an occupational field exposure point of view. This resulted in the development of a simulation model which overlays both magnetic and electric field on the structure outline in sufficient resolution to assess occupational exposure at nominated positions on the structure. Calculated values are compared against the nominated occupational exposure limits in ARPANSA (2009 revision of draft).

2. Scope of the review

The review assessed overhead line structure outlines and tower geometries for compliance to the Public Consultation Draft document issued by the ARPANSA – Exposure Limits for Electric & Magnetic Fields – 0 Hz to 3 kHz. Worst case structures from an occupational field exposure point of view are to be identified. For the provided structures, a detailed CDEGS model overlaying both magnetic and electric field on the structure outline is provided. This is to assess occupational exposure at nominated positions on the structure climbing and inspection corridor, and in other nominated positions such as bare hand on conductor and working positions for live stick work. In addition, a comparison of the derived fields against measured fields is made.

3. Applied standards

Various local and international standards have been reviewed and a comparison made between the listed standards in Table 1.

Table 1: Standards and guidelines referenced

Standard/Guideline	Document Title
ICNIRP	Guidelines for limiting exposure to time-varying electric and magnetic fields (1 Hz to 100 kHz)
IEEE95.6-2002	IEEE Standard for Safety Levels with Respect to Human Exposure to Electromagnetic Fields, 0-3 kHz
EN50499:2008	Procedure for the assessment of the exposure of workers to electromagnetic fields
ARPANSA	Radiation Protection Standard Exposure Limits for Electric & Magnetic Fields (0 Hz to 3 kHz), Public Consultation Draft, 7 December 2006

The Australian exposure guidelines (described as "interim") were set by the National Health and Medical Research Council (NHMRC) in 1989. Subsequently these guidelines have been rescinded and the ARPANSA have issued a Draft Radiation Protection Standard for Exposure Limits to Electric and Magnetic Fields 0 Hz - 3 kHz on 7 December 2006. Previous guidelines set by the NHMRC are similar to many other countries. In addition to the ARPANSA, the most recent International Commission on Non-Ionizing Radiation Protection (ICNIRP) limits from the published "Guidelines for Limiting Exposure to Time-Varying Electric, Magnetic, and

Electromagnetic Fields (1 Hz to 100 kHz)”[1] has been reviewed. The former guideline has been internationally accepted. Of particular relevance from the guideline are Table 6[2] and Table 7[3] within the ICNIRP guideline. Power grid frequency of 50 Hz falls within the 0.025-0.8 kHz frequency range. For occupational exposure a limit of 500/f (where f = frequency) is specified for the Electric Field Strength (referred to E-field strength) and measured in units of V/m (or kV/m) and the Magnetic Field (B-field) limit is 25/f. For general public exposure a limit of 250/f is specified for the Electric Field Strength (referred to E-field strength) and measured in units of V/m (or kV/m) and the Magnetic Field (B-field) limit is 5,000/f. The above low frequency publication of 1998 has been replaced during 2010. A summary of the recent ICNIRP reference level guidelines for 50 Hz are listed in Table 2.

Table 2: Reference levels for exposure to time-varying electric and magnetic fields (unperturbed rms values for 50 Hz)

Exposure Category	Electric Field Strength E (kV/m)	Magnetic Field Strength H (A/m)	Magnetic Flux Density B (µT)
Occupational	10	800	1,000
General Public	5	160	200

Both the Australian ARPANSA and European EN 50499 standards are similar and set the reference levels listed in Table 3 and Table 4 for exposure to magnetic and electric fields at power system frequencies.

Table 3: Reference levels for exposure to magnetic fields (unperturbed rms values for 50 Hz)

Exposure Category	Magnetic Field Density (µT rms)	‘Controlled Activity’ Magnetic Field Density (µT rms)	‘Controlled Activity’ - Exposure to regions other than head Magnetic Field Density (µT rms)
Occupational	500	1,500	1,800
General Public	100	300	Not Applicable

Table 4: Reference levels for exposure to electric fields (unperturbed rms values for 50 Hz)

Exposure Category	Electric Field Strength (kV/m)	‘Controlled Activity’ - Electric Field Strength (kV/m)
Occupational	10	20
General Public	5	10

[1] Health Physics December 2010, Volume 99, Number 6 (pages 818 – 836)
[2] ICNIRP Table 6: Reference Levels for Occupational Exposure to Time-Varying Electric & Magnetic Fields
[3] Table 7: Reference levels for general public exposure to time-varying electric and magnetic fields (unperturbed RMS values)

Both standards define ‘Controlled Activities’ applying where certain controls can be in place, such that a ‘Controlled Activity’ set of reference levels with higher values can be allowed. These are derived from the Basic Restrictions incorporating appropriate safety margins. If Reference Levels are to be exceeded by showing compliance with the Basic Restrictions shown in the above tables, then the activity will be deemed to be a ‘Controlled Activity’ and the administrative controls for a ‘Controlled Activity’ (as defined in the relevant standards) will apply.

4. Qualifications & Assumptions

The study realises limitations in accurately modelling insulator end fittings and conductor assembly hardware in CDEGS. More accurate modelling can be attained by applying 3D electric field design and analysis software such as COULOMB which is particularly well suited for insulator and hardware applications and where exact modelling of overhead line hardware is required. A further limitation is the modelling of multiple conductor bundles which is based on calculating the equivalent Geometric Mean radius (GMR) of the conductors. This has limitations when the conductor configuration is considered as illustrated in Figure 1. The modelled components (dark grey area) are only a sub-component of the total area (light grey area).

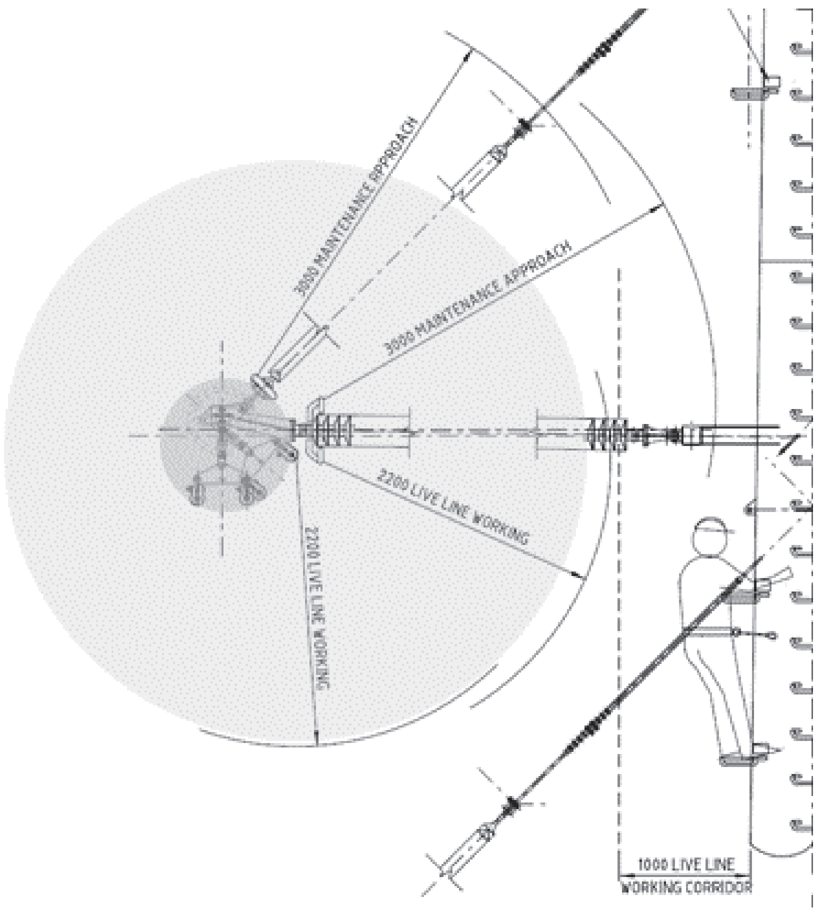
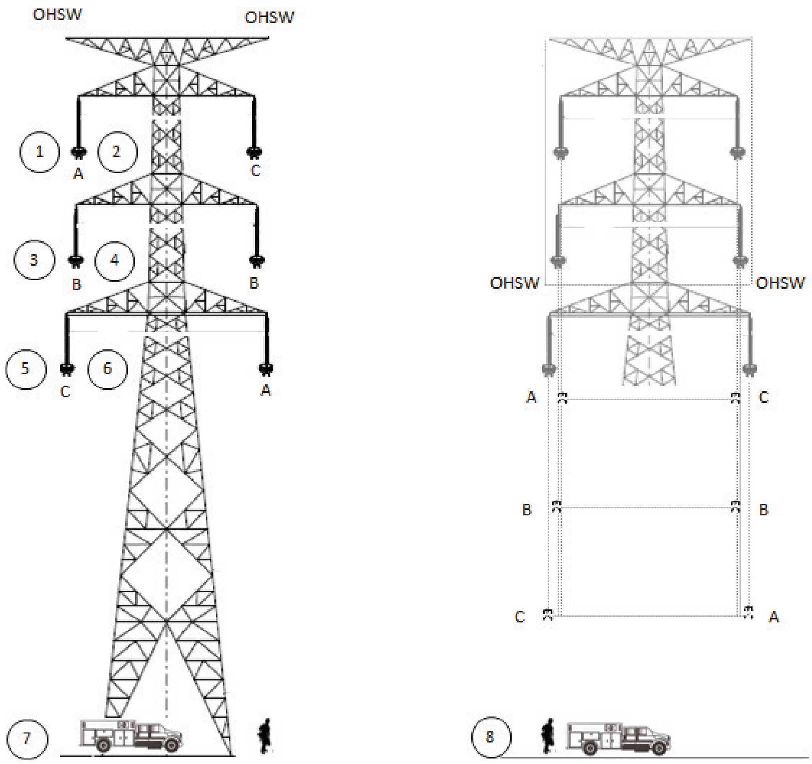


Figure 1: Conductor hardware

Time consuming and costly modelling will more accurately predict the actual EFS and MFD. Alternatively, laboratory tests and field measurements would provide a correction factor for more reliable calculated results. There are other short term safety considerations regarding transmission lines. In the event of a fault occurring on the transmission line, an abnormally high current flows which magnifies the magnetic field in the short time duration. This time duration depends how long it takes the power network to isolate the fault. This study does not consider the short term fault current condition as this abnormally high EMF is insignificant from a health point of view due to its short duration. Studied transmission poles and towers are considered as transposed and the phasing for double circuit towers is taken as ABC and CBA. The safe insulating distance for live line working is to ensure flashover does not occur while at the highest voltage. For this reason the study is based on the maximum operating voltage (U_m).

Eight of the most important working position locations are considered. These are typically illustrated in Figure 2. Locations 7 and 8 are not considered in the study as these locations are relevant to general public limits which are below the occupational limits.



(a) Location at Tower (b) Location at Midspan[4]

Figure 2: Location of Working Position Measurement Locations[5]

Breakdown of air gap insulation occurs when the strength of the electric field exceeds a certain critical value and the air itself loses its insulation property. The electric field strength at this moment is called critical electric field strength E_{kp}. To ensure safety in high voltage live-line working, we should make the possible electric field strengths at the worksite below E_{kp}. The electric field of the worksite is irregularly distorted by the metal parts on the live-line working tools. It is necessary to calculate the electric field strength at the worksite and to find whether

[4] Assuming horizontal ground & maximum conductor span
[5] Not to scale

it could go beyond the critical value. The former consideration is assumed to be allowed for in the minimum approach distances utilised by the EU. The minimum approach distances (safety distance) for each voltage category have been provided by the EU and are listed below in Table 5.

Table 5: Live Line Safe Approach Distances

System Voltage (kV)			
110/132	275	330	500
1.2	2.0	2.2	2.9

For review purposes, the minimum clearances assumed from ground is taken to be the EU's internal standard which is marginally higher (6 to 12%) than ENA C (b)1 for voltages 110 to 330 kV; and substantially higher (58%) for 500 kV. These are listed below in Table 6.

Table 6: Minimum Live Conductor Clearance from Ground

	System Voltage (kV)			
	110/132	275	330	500
EU Standard ENA C (b)1[6] (% Variation)	7.5 6.7 (+12%)	8.0 7.5 (+7%)	8.5 8.0 (+6%)	14.2 9.0 (+58%)

5. Methodology

6.1 Study model

The solution methodology for electric field calculation is based on the charge simulation method. This approach consists of the calculation of the equivalent charges per unit length of conductor and the calculation of the electric field produced by these charges. The general relationship used to calculate the charges on a multi conductor system is presented in matrix form in:

[Q] = [P]-1 [V] (1)

Where: [Q] is a column vector of the linear charge on each conductor
[V] is a column vector of the potentials of the conductors
[P]-1 is the inverted matrix of the Maxwell potential coefficients of the conductors

Current Distribution Electromagnetic Interference Grounding and Soil Structure Analysis Software (CDEGS[7]) software is applied in this study – more specifically TRALIN and HIFREQ modules. A set of image conductors is used with charges opposite to those of the transmission line. The actual conductors and their images are characterized by real and

[6] ENA C(b)1 – 2006 Guidelines for the Design and Maintenance of Overhead Distribution and Transmission Lines: Table 2 above depicts the maximum values (over the carriageway of roads) from Table 8.1 Clearance From Ground, Lines Other Than Insulated Service Lines – Section 8 p 54
[7] Application & SESTECH Installation Version 13.4.28.0 – Professional Version

imaginary voltages and diameters. Overhead shield wires are also included in this method (and assumed to be at zero potential).

For bundled conductors, a single conductor with an equivalent diameter is used, on the basis of the following formula:

$$R_{eq,i} = \sqrt[n]{n.r_i.(r_b)^{n-1}}.$$

Where: n is the number of conductors

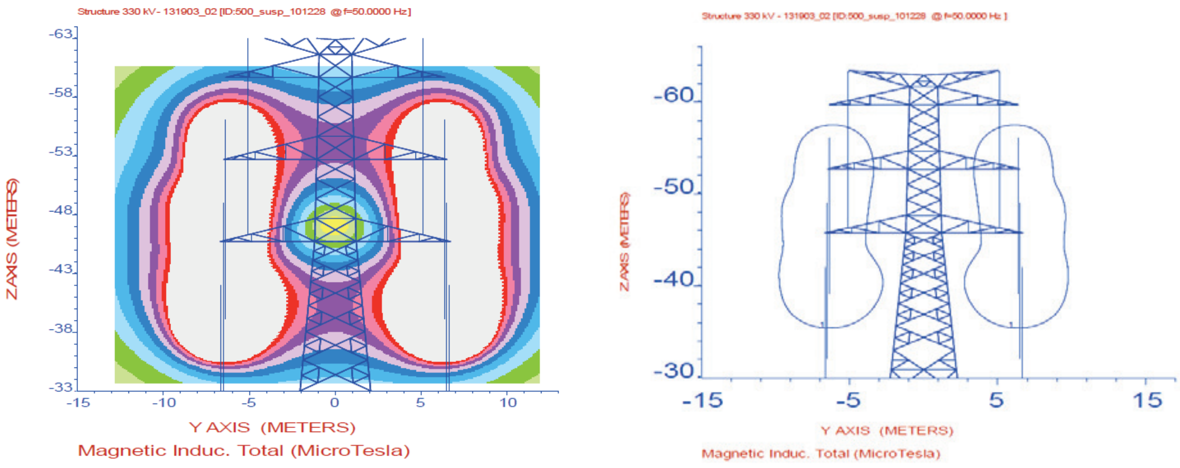
r_i is the conductor radius

r_b is the radius of the bundle

All studies are based on a supporting tower in the centre of two 500 m spans.

6. Analysis & Results

The results for locations 1 to 12 are depicted graphically in two different forms. Tower locations are illustrated by means of *contours*. These contours represent the maximum allowable MFS and MFD for "controlled environment". Various ways of representing the compliance or non-compliance was considered. Considering the limitations of CDEGS, it was deemed appropriate to represent the results graphically & not quantitatively in a table. Various plotting options are considered for representing the CDEGS results. These are illustrated in Figure 3.



(a) Spot Plot (b) Contour Plot

Figure 3: Plotting options

The most appropriate representation of the above are considered to be the contours. This represents the approach boundary around each conductor (or bundled conductors). In addition, contours of the occupational exposure limits are indicated for each structure. These are illustrated in Figure 4.

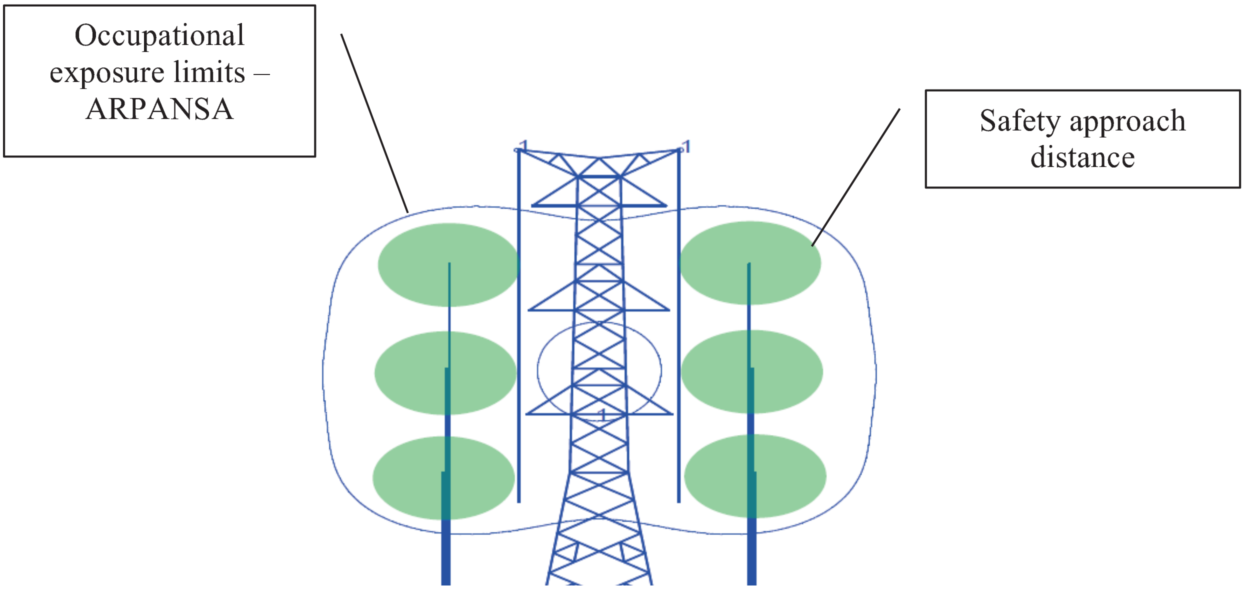


Figure 4: Exposure limit & safety approach distance representation.

The results reveal that in most instances, the safety approach distances are within (or marginally outside) the occupational exposure limits. This means that when live-line operators approach the safety approach distance, they will be exposed to EFS & MFD levels that exceed those stipulated within ARPANSA guidelines. The approach distance includes any affected area while gaining access along climbing devices. It is reasonable to question the feasibility in applying these guidelines to live-line workers as personnel protective equipment in the form of conductive suits do provide shielding against both EFS and MFD. To quantify the level of protection with a degree of accuracy would require measurements in field or laboratory conditions.

The effects of various profiles for tension structures are taken into account as illustrated in Figure 5. This has been applied to 330 kV structure.

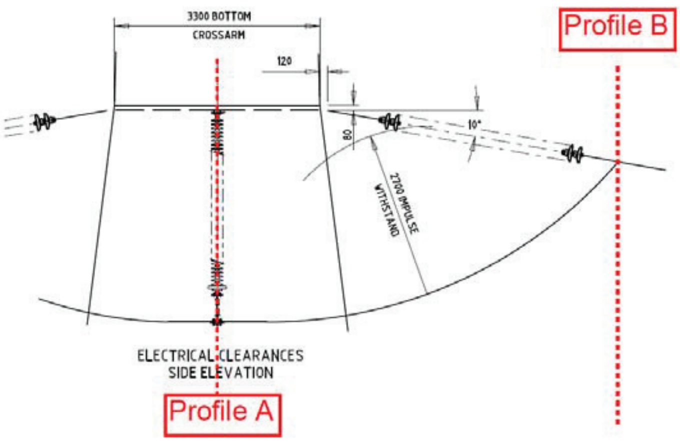


Figure 5: Profile A & B for tension structures

As field measurements were obtained for the 330kV tower, these towers were studied in more detail for comparison purposes. The measurements of electric and magnetic fields near a 330 kV tower were carried out. It is important that measurement instruments are applied within their specified measurement ranges. Measurement were carried out with two different instrument manufacturers. Confidence is obtained in the measurements recorded that were within the calibration range of the magnetic and electric field meters (0-600μT and 0-10kV/m respectively). From the field measuring data it is noted that an instrument capable of measuring fields higher than 25kV/m is best suited.

7. Summary

This study acknowledges the limitation in accurately modelling insulator end fittings and conductor assembly hardware in CDEGS. Accurate modelling can be attained by software particularly well suited for insulator and hardware applications. A further limitation is the modelling of conductor bundles which is based on calculating the equivalent Geometric Mean radius (GMR) of the conductors.

The results of the study reveal that in most instances approach distances are within (or marginally outside) the EMF contours demarcating the occupational exposure limits. This means that when live-line operators approach the safety approach distance, they may be exposed to EFS & MFD levels that exceed those stipulated within ARPANSA guidelines. Despite this “non-compliance”, it is reasonable to question the feasibility of applying these guidelines to live-line workers as personnel protective equipment (PPE) in the form of conductive suits do provide mitigation by shielding against both EFS and MFD. To accurately quantify the level of EMF exposure, field or laboratory measurements will need to be performed.

A comparison between measured and calculated results were carried out on the 330 kV towers. A good correlation between the computed and measured values is found at two locations. At two other locations, the correlation is not as close. Further investigation is required.

8. References

1. ELF Electric and Magnetic Fields Exposure Assessment of Live-Line Workers for 132 kV Transmission Line of SEC I.O. Habiballah, *Member, IEEE*, T. K. Abdel-Galil, *Member, IEEE*, M. M. Dawoud, *Senior Member*, *IEEE*, C. A. Belhadj, *Member, IEEE*, M. Arif Abdul-Majeed, and T.A. Al-Betairi 2006 IEEE PES Transmission and Distribution Conference and Exposition Latin America, Venezuela.
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3. Health Physics December 2010, Volume 99, Number 6 (pages 818 – 836)
4. ICNIRP Table 6: Reference Levels for Occupational Exposure to Time-Varying Electric & Magnetic Fields, Table 7: Reference levels for general public exposure to time-varying electric and magnetic fields (unperturbed RMS values)
5. Comparison of Measured and Computed Electric Fields near a 330 kV Tower Winston Ruan and Simon Fortin *Safe Engineering Services & technologies Ltd, Montreal, Canada.* Tony Auditore *LineTech Consulting Ltd, Hamilton, New Zealand.*