THE DETERMINATION OF CONDUCTOR CLEARANCES-TO-GROUND FOR EHV AC AND DC TRANSMISSION LINES

by

ARTHUR JOHN STREMLAW

B.A.Sc., University of Waterloo, 1966

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF THE

REQUIREMENTS FOR THE DEGREE OF

MASTER OF APPLIED SCIENCE

in the Department of Electrical Engineering

We accept this thesis as conforming to the required standard

Research Supervisor'

Members of the Committee

Head of the Department

Members of the Department of Electrical Engineering

THE UNIVERSITY OF BRITISH COLUMBIA

May, 1968

In presenting this thesis in partial fulfilment of the requirements for an advanced degree at the University of British Columbia, I agree that the Library shall make it freely available for reference and Study. I further agree that permission for extensive copying of this thesis for scholarly purposes may be granted by the Head of my Department or by hils representatives. It is understood that copying or publication of this thesis for financial gain shall not be allowed without my written permission.

Department of <u>Electrical Engineering</u>

The University of British Columbia Vancouver 8, Canada

Date () 2, 1968

ABSTRACT

The analyses presented in this thesis are based on a consideration of induction effects below transmission lines and the hazards as presented to the public. The rapid increase of transmission voltages has caused a great deal of concern among utilities about these hazards. The induction effects are a function of line height and at present there is conflict concerning these dimensions.

Primarily, this thesis is concerned with the establishment of the minimum line-to-ground clearances of EHV ac and dc transmission lines. These clearances are established in terms of the electric field under the line based on the "electric field recognition level".

Equations are derived for the electric field, and potential at any point below the line in Chapter 2. These equations are then used in Chapter 3 to show the effect of conductor spacing, height and size on the field. Also, the effect of sky wires and bundle conductors is noted. Chapter 4 derives an allowable value of electric field which is used in Chapter 5 to derive the required heights. Chapter 6 considers a reduction of these clearances or induction effects using ground wires below the line conductors for shielding purposes. Experimental readings are obtained in Chapter 7 to verify the equations derived in Chapter 2 and the effects of sky wires and bundle conductors on the electric field below the line. Chapter 8 establishes right-of-way widths based on induction

effects.

(ii)

TABLE OF CONTENTS

ъ

	Tage .
ABSTRAC1	(ii)
TABLE OF CONTENTS	(iii)
LIST OF ILLUSTRATIONS	(v)
LIST OF TABLES	(viii)
LIST OF SYMBOLS	(ix)
ACKNOWLEDGEMENT	(xi)
1. INTRODUCTION	1
<pre>1.1 Development of EHV and Effects on Line Design 1.2 Presentation of the Problem 1.3 Objectives of the Thesis</pre>	1 2 6
2. DERIVATION OF EQUATIONS FOR THE ELECTRIC FIELD AND POTENTIAL DUE TO AN n-CONDUCTOR SYSTEM	8
2.1 General Description of the System 2.2 Assumptions 2.3 Derivation	8 8 10
3. THE EFFECT OF PHYSICAL PARAMETERS, BUNDLE CONDUCTORS AND SKY WIRES ON THE ELECTRIC FIELD BELOW THE LINE	13
3.1 The Effect of Conductor Spacing, Height and Size on the Electric Field 3.2 The Effect of Bundle Conductors on the	13
Electric Field	16
Field	20
4. AN ANALYSIS OF A MODEL OF A HUMAN BEING	22
 4.1 Method of Approach 4.2 Assumptions 4.3 Co-Ordinate System 4.4 Mathematical Analysis 4.5 Dependance of the Surface Value of Electric 	22 22 24 25
4.6 A Practical Approach to the Determination of the Value of a/b for Human Beings 4.7 Evaluation of a Limiting Value of Eox	29 30 32

(iii)

		Page
5.	DETERMINATION OF MINIMUM HEIGHTS FOR AC AND DC SYSTEMS	36
•	5.1 Method of Approach 5.2 AC Cases 5.3 DC Cases	36 37 43
6.	SHIELDING EFFECTS OF GROUND WIRES BENEATH THE LINE CONDUCTORS	47
•	6.1 Shielding Effects of Ground Wires 6.2 Reduction In Line Heights	47 49
7.	MEASUREMENT OF THE POTENTIAL OF AN OBJECT BELOW A TRANSMISSION LINE	54
	 7.1 Method of Measurement 7.2 Instrument Design 7.3 Calculated Values vs Experimental Values 7.4 Experimental Verification of the Effect of Sky Wires 	54 57 60 62
	7.5 Experimental Verification of the Effect of Bundle Conductors	63
8.	ESTABLISHMENT OF THE WIDTH OF RIGHT-OF-WAYS.	66
	 8.1 Right-of-Way Clearances 8.2 Width Requirements Based on Electrostatic Induction Effects 	66 66
AP	PENDIX I Discussion of the Miller Gradient Meter	7.3
RE	FERENCES	77

LIST OF ILLUSTRATIONS

Figure

Figure	9	Page
1.1	C.S.A. and N.E.S.C. Standards for Line-to- Ground Clearances	5
2.1	Derivation of the Electric Field and Potential for an n-Conductor System	·9 ·
3.1	Electric Field Profiles for ac and dc Cases	14
3.2	Variation in Field Profiles with Conductor Height Spacing and Size	15
3.3	Effect of Conductor Spacing, Height and Size on Emax	17
3.4	Effect of Bundle Conductors on the Field	19
3.5	Effect of Sky Wires on the Field	19
4.1	Prolate Spheroid	24
4.2	Conducting Prolate Spheroid in a Uniform Electric Field	26
4.3	Plot of a/b vs Age for Males and Females	33
5.1	230KV ac Cases - 1 Conductor Bundle	38
5.2	345KV ac Cases - 1 Conductor Bundle	38
5.3	345KV ac Cases - 2 Conductor Bundle	39
5.4	500KV ac Cases - 1 Conductor Bundle	39
5.5	500KV ac Cases - 2 Conductor Bundle	40
5.6	500KV ac Cases - 4 Conductor Bundle	40
5.7	735KV ac Cases - 4 Conductor Bundle	41
5.8	345KV dc Cases - 1 Conductor Bundle	45
5.9	345KV dc Cases - 2 Conductor Bundle	45
5.10	500KV dc Cases - 2 Conductor Bundle	46
5.11	500KV dc Cases - 4 Conductor Bundle	46

(v)

Figure

;

6.1	Per Cent Decrease in Emax/V Using 1 to 5 Ground Wires in their Optimum Position	48
6.2	345KV ac Cases with Shielding - 1 Conductor Bunile	50
6.3	345KV ac Cases with Shielding - 2 Conductor Bundle	50
6.4	500KV ac Cases with Shielding - 1 Conductor Bundle	51
6.5	500KV ac Cases with Shielding - 2 Conductor Bundle	51
6.6	500KV ac Cases with Shielding - 4 Conductor Bundle	52
6.7	735KV ac Cases with Shielding - 4 Conductor Bundle	52
7.1	Coupling Capacitances between the Line and an Insulated Object	54
7.2	Schematic Diagram of UBC Instrument	58
7.3	Test Arrangment to Calibrate the Meters	59
7.4	Calibration Curves	59
7.5	Test Results for 230KV Line	61
7.6	Test Results for 360KV Line	61
7.7	360KV Test Line for Sky Wire Effect	62
7.8	230KV Test Line for Bundle Conductor Effect	64
8.1	230KV Cases – l Conductor Bundle Right-of-Way Widths	68
8.2	345KV Cases – 1 Conductor Bundle Right-of-Way Widths	69
8.3	345KV Cases - 2 Conductor Bundle Right-of-Way Widths	69
8.4	500KV Cases - l Conductor Bundle Right-of-Way Widths	70

Figure	
8.5 500KV Cases - 2 Conductor Bundle Kight-of-Way Widths	70
8.6 500KV Cases - 4 Conductor Bundle Right-of-Way Widths	•• 71
8.7 735KV Cases - 4 Conductor Bundle Right-of-Way Widths	71
I.1 Miller Gradient Meter	•• 73

ł

LIST OF TABLES

TABLE	PAGE
4.1 Limiting Values of Eox	34
5.1 Data Summary for ac Systems	37
5.2 Comparison of Line-to-Ground Clearances	42
5.3 Data Summary for dc Systems	44
6.1 Line-to-Ground Clearances with and without Ground Wires	49
7.1 Measurement of Sky Wire Effect	63
7.2 Measurement of Bundle Conductor Effect	65
I.1 Miller Measurements for 345KV Substation Bus	75

LIST OF SYMBOLS

a	= semi-major axis of a spheroid
^a ε ^{,a} λ ^{,a} θ	<pre>= unit vectors in the spheroidal co-ordinate system</pre>
Α	= area of the probe
b	= semi-minor axis of a spheroid
b s	= semi-minor axis as determined by surface area
bv	= semi-minor axis as determined by volume
С	= focus of a spheroid
C	= capacitance
C ₁ ,C ₂	= constants
đ	= conductor diameter
D	= conductor phase spacing
е	= eccentricity
ε _ο	= permittivity of free space
E	= permittivity of the person
ε,λ,θ	= prolate spheroidal co-ordinates
E	= electric field
f	= dimensionless factor
h ₁ ,h ₂ ,h ₃	= metric coefficients
H	= conductor height above ground
Hi	<pre>= height of the ith conductor above the ground plane</pre>
Hi	= height of the ith image conductor below the ground plane
\mathbf{J}^{D} .	= displacement current density
I	= conduction current

(ix)

	'n	= number of conductors
	р	= resistivity of a man
	+q _i	= charge per unit length on the ith conductor
	-q _i	<pre>= charge per unit length on the ith image con- ductor</pre>
	r _i	<pre>= distance between the ith conductor and the point P</pre>
	r¦	<pre>= distance between the ith image conductor and the point P</pre>
	R	= conductor radius
	S	= surface area
	t	= time
	\mathbf{T}	= relaxation time
	μ	= permeability of free space
	U ₂ U ₂	= direction vectors
	V	= line-to-ground voltage
	V.m	= volume of a person
	Vs	= volume of a spheroid
	ω	= angular frequency
	W	= weight of a person
	x,y,z	= Cartesian co-ordinates
	ø	= potential function
•	ø	= primary potential function
	Ø	= induced potential function
	α	= angle

(x)

ACKNOWLEDGEMENT

I would like to express thanks to my supervisor Dr. F. Noakes for his guidance and encouragement during the course of my research and for the opportunity to work with him on this project.

My sincere thanks to M.M.Z. Kharadly for his valuable counsel and patience in reading the preliminary draft.

I would like to thank Eugene Lewis and Graham Dawson for reading the final draft. Also, I would like to thank Mr. A. MacKenzie for his assistance, and in particular, my wife for typing both drafts.

Acknowledgement is given to the National Research Council for financial support of the research.

1. INTRODUCTION

1.1 Development of EHV and Effects on Line Design

In order to meet the increasing demand for electrical energy, power utilities are turning more and more to EHV transmission. The need to transmit larger quantities of power and the increasing remoteness of sources underlie this decision. Recent surveys⁽¹⁾have indicated that within the next decade nearly 30,000 circuit miles of EHV lines will be operating in comparison with approximately 8,000 now in existence. A study ⁽²⁾ by the U.S. National Power Surveys on power requirements up to 1980 indicates that the ability to supply more power at a cheaper rate is tied directly to EHV development.

The basic transmission voltage, even as late as 1960, was 230KV. $^{(1),(3)}$ Since then, development of lines operating at 345KV ac or dc and above has become prominent. At present a 735KV line $^{(4)}$ is operational in Canada while research is being conducted at this voltage level in several other countries. $^{(5),(6)}$ The need for higher voltages has already been realized and the next step is felt to be 1,000KV. $^{(7),(8)}$

The advent of extra-high-voltage transmission has not been without its complications. Every facet of transmission line design has been affected. Radio interference and corona losses increased to the point whereby phase clearance and conductor size are now determined by taking these effects into account,

as well as load requirements. The need for higher insulation levels has resulted in increased insulator strings and lineto-structure clearances. As a consequence of the increased clearances, intricate conductor configurations and loading requirements of transmission lines, the towers themselves have become more complex in design and taller. Because of the high cost of towers and installation, span lengths have been increased to help defer total line cost.

1.2 Presentation of the Problem

Due to the complications of analysis of the many factors that affect EHV line design most research at a new voltage level is done experimentally. (9),(10) As more lines become operational every effort is made to present data (11),(12) on every factor of line design as a reference for future designs. This practical approach plus reinforcement by mathematical analysis where possible are responsible for establishing guide-lines that help determine the physical makeup and geometry of the line. The final design is of course subject to economic considerations.

To date, however, insufficient attention has been paid to accurately specifying the minimum clearances of conductors from ground. This factor becomes rather critical at higher voltages for two reasons. The first and more important reason arises from consideration of public safety with respect to the effects of electrostatic induction in objects below the line. The second is for reasons of economy.

Several studies^{(13),(14)} have been carried out in the past

concerning electrostatic induction but these were usually confined to induced voltages in communication networks. The problems of public safety in the vicinity of EHV transmission lines was first put forward by Erith⁽¹⁵⁾ who pointed out that the voltage induced in insulated objects below the lines may reach a lethal value. Further studies of electrostatic induction in objects, based on their coupling capacitance to the line and the hazards presented to humans, was undertaken by Ross.⁽¹⁶⁾ Buchan⁽¹⁷⁾ used the above approach in studying the effects of electrostatic induction as related to the hazards of handling gasoline. His results, however, a were obtained primarily through the use of models in an electrolytic tank. It has been standard practice to date to analyze complicated situations using models in electrolytic tanks or teledeltos paper. A simpler method has recently been devised by Comsa.⁽²⁰⁾ In this case a dry air model is used operating at a high frequency. Its chief advantages are its simplicity and its ability to allow use of larger models.

An appreciation of the magnitudes of potential induced in the vicinity of EHV lines up to and including 735KV was presented by Berg and Noakes.⁽¹⁹⁾ Equations were derived for the potential at any point below the line using an electrostatic approach. A computer was then used to plot the potential profiles. More recent studies by Miller⁽²¹⁾ and Kouvenhover⁽²²⁾ have been concerned with currents induced

in men doing live line maintenance. Evaluation of the strength of the currents passing through the man and the effect on his health has been their main concern.

The underlying motive of each of the above studies is public safety and safety to personnel operating in and around EHV lines. Since the voltage induced in objects is a function of the distance the object is from the source, it becomes obvious that the minimum height of a transmission line is a critical dimension.

At present these line-to-ground clearances are dictated (23) by the Canadian Standards Association in Canada and the (24) National Electrical Safety Code in the United States. However, it should be noted that there is considerable disagreement between these codes as Figure 1.1 indicates. The discrepancies increase significantly as the voltage increases. Each Canadian province and American state loosely interprets the appropriate code and then, based on their own research or regional needs, specify their own requirements. This further complicates the problem.

The codes are based primarily on the mechanical clearances required below the line. Some allowance is made for voltage, however, this allowance varies from region to region. A study by McMurtrie⁽¹⁸⁾ tried to combine the mechanical arguments with a safe limit of approach. The study, however, is limited to voltages below 460KV. With the rapid rise in transmission line voltages it has become obvious that the clearances must





be increased but no one is certain as to how much.

The recent use of EHV dc for transmission has further complicated the problem. No one is certain what heights should be used for dc lines and for the moment the practice is to apply the existing ac standards for the corresponding voltage level. This fact illustrates the need for research with respect to line-to-ground clearances for dc systems as well as ac systems.

1.3 Objectives of the Thesis

It is the main objective of this thesis to determine the minimum height requirements of EHV transmission lines, either ac or dc, based on a consideration of the electric field strength below the line. The purpose of such a study is fourfold:

1) To present a new approach to the problem.

- 2) To determine these heights with a view of establishing an international code.
- 3) To allow more accurate economic studies.
- 4) To reduce the hazards to public safety.

A general description of the system, the assumptions used and the derivation of equations for the electric field and potential at an arbitrary point due to an 'n' conductor system are presented in Chapter 2. The effects of conductor spacing, height and size on the electric field is considered in Chapter 3. The use of bundle conductors and the effect of sky wires are also noted. The derivation of an allowable value of the electric field due to the line with respect to

a human being model is presented in Chapter 4. This value is used in Chapter 5 to plot a set of curves that would enable an engineer to select the proper minimum height based on conductor spacing and size. The plots obtained will cover most practical ranges of conductor spacing and size and they will be obtained for both the ac and dc cases. The use and merits of placing ground wires below the line for shielding purposes are investigated in Chapter 6. The effect of using from 1 to 5 ground wires for shielding is noted and indicates the reduced hazards to the general public when this technique is employed. Also a comparison is made of the required heights as indicated in Chapter 5 with those obtained using the ground wire technique. A general description of the instruments used and the measurements made of the induced potential obtained for two typical systems are presented in Chapter 7. The readings obtained and potential profiles plotted are compared with the calculated values expected as a measure of the accuracy of the analysis used. In addition, measurements are made to experimentally verify the effect of bundle conductors and sky wires on the electric field below the line. A method is proposed in Chapter 8 that is used to determine the width of transmission line right-of-ways based on induction effects. The rationalized FPS system of units is used throughout the thesis.

2. DERIVATION OF EQUATIONS FOR THE ELECTRIC FIELD AND AND POTENTIAL DUE TO AN n-CONDUCTOR SYSTEM

2.1 General Description of the System

The system under study consists of 'n' separate conductors arbitrarily arranged over a perfectly conducting ground plane. The situation is illustrated in Figure 2.1 where the conductors are considered to be parallel to the ground. The electric field or the voltage induced at any point in space may be found in terms of the known voltages of the conductors and their distances from this point.

2.2 Assumptions

The analysis to be carried out will be applicable to either balanced 3 phase ac cases or dc cases. For ac cases the electric field at any point in space is the phasor combination of the fields induced by each line. The resultant phasor at any point in space is fixed in magnitude and rotates at sixty Hertz. As such the ac case can be analyzed as a set of phasors 120 electrical degrees apart and fixed in time. The values derived in this thesis indicate the maximum value that the resultant phasor can achieve. The factor cos(wt) is omitted.

In order to simplify the derivation several assumptions will be made.

- 1) The earth is taken to be homogeneous and perfectly conducting.
- 2) The conductors are assumed to be uniform and infinite in length.



- 3) The charge on the conductors is assumed to be
 - uniformly distributed along and around the conductor.
- 4) Because of the relative dimensions involved the charge on the conductor can be considered as a line source located on the axis at the center of the conductor.
- 5) The ground potential plane is taken at the surface of the earth to represent a worst case situation.

The solution can be further simplified by using the method of images to consider the effect of the earth and by using the principle of superposition to obtain the total field. 2.3 <u>Derivation</u>

Consider Figure 2.1. The total electric field Et_i due to conductor 'i' and its image at the point P can be written as:

$$\underline{E}t_{i} = \underline{E}r_{i} + \underline{E}r_{i}'$$

 $|\mathrm{Er}_{\mathbf{i}}'| = \frac{-\mathbf{q}_{\mathbf{i}}}{2\pi \mathbf{r}_{\mathbf{i}}' \mathbf{e}}$

where (25) $|\text{Er}_i| = \frac{+q_i}{2\pi r_i \epsilon_o}$

and

The total x component of the electric field at the point P is:

$$Ex_{i} = \frac{q_{i}}{2\pi\epsilon_{o}} \left[\frac{\sin\alpha_{i}}{r_{i}} - \frac{\sin\alpha_{i}'}{r_{i}'} \right]$$
 2.2

But $\sin \alpha_i = -(H_i - X)/r_i$ and $\sin \alpha'_i = (H'_i + X)/r'_i$ and $H_i = H'_i$ In general then for an n-conductor system the total electric

10

field at an arbitrary point P can be written as:

$$Ex = \sum_{i=1}^{n} \frac{-q_i}{2\pi\epsilon_0} \left[\frac{H_i - X}{r_i^2} + \frac{H_i + X}{r_i^2} \right] 2.3$$

Since $\underline{E} = -$ grad V it is also possible to write an expression for the potential at point P relative to the ground plane where V=0 as:

$$Vp = V(X) = \int_{0}^{X} grad V dX$$
$$Vp = \frac{1}{2\pi\epsilon_{0}} \sum_{n=1}^{n} q_{1} \ln \frac{r'_{1}}{r_{1}}$$

i=1

r_i

$$Vk = \frac{1}{2\pi\epsilon_{0}} \sum_{i=1}^{q_{i}\ln\frac{r_{ik}}{r_{ik}}}$$

n

expression can be written for each line. Solution A similar of the problem involves n simultaneous equations and is best

11

2.4

 $= \frac{1}{2\pi\varepsilon_{0}} \begin{vmatrix} | \\ | \\ | \\ \ln \frac{r_{nl}}{r_{nl}} \end{vmatrix}$ ln

or in abbreviated form:

$$\begin{bmatrix} V_{i} \end{bmatrix} = \begin{bmatrix} PC_{ij} \end{bmatrix} \begin{bmatrix} Q_{j} \end{bmatrix} \quad i=1,n \quad j=1,n \qquad 2.7$$

The matrix PC is known as the potential coefficient matrix and the entries are known as Maxwell's Potential Coefficients.⁽²⁶⁾ The inverse of the PC matrix allows derivation of the charge on each conductor.

$$\begin{bmatrix} Q_j \end{bmatrix} = \begin{bmatrix} PC_{ij} \end{bmatrix}^{-1} \begin{bmatrix} V_i \end{bmatrix}$$

Equation 2.3 or 2.4 can then be used to solve for the field or the potential. Thus if the line-to-ground voltages of a system are known the potential or electric field at any point can be specified by determining the PC Matrix which is based solely on the geometry of the system.

handled in matrix form. Writing the equations this way gives:

2.6

3. THE EFFECT OF PHYSICAL PARAMETERS, BUNDLE CONDUCTORS AND SKY WIRES ON THE ELECTRIC FIELD BELOW THE LINE

3.1 The Effect of Conductor Spacing, Height and Size on the Electric Field

Usually, a transmission line assumes a definite symmetry about an axis. Only horizontal configurations are dealt with in this thesis as most EHV lines in existence today are of this type. Due to the physical symmetry, only the coefficients on and above the diagonal of the PC matrix need be calculated. Many lines lie in high isokeranic areas and as such sky wires are added for protection. In the analysis presented in Chapter 2 these lines are handled as line conductors whose voltage is zero.

The shape of the profile for the electric field at X=0 for a single pole and double pole dc case and a three phase ac case is shown in Figure 3.1. The profiles were computed for a line height of 20'0" and conductor size of 1024MCM in each case. The electric field is normalized with respect to line-to-ground voltage. Inspection of equation 2.3 indicates that these profiles can be altered by either varying the line voltage or conductor position. The position can be varied by altering either the conductor's spacing or its height. The field can also be altered by using a different sized conductor. The effect of each of these factors on the electric field at X=0 for an ac case is illustrated in Figure 3.2. The range of parameters selected is indicative of those in use today. The height and spacing both have a significant effect on the shape of the profile,



Electric Field Profiles for ac and dc Cases Figure 3.1





while the radius does not. In all cases the maximum electric field lies in a region near the outer conductor. The point at which it actually occurs is dependent upon the ratio of the conductor spacing to height, but normally it lies at a distance between 1.0 and 1.5 times the conductor spacing. Only if the ratio of D/H<1/2 will Emax occur beyond 1.5.

The curves contained in Figure 3.3 were derived for the range of parameters used above. The value of the E-field plotted represents the maximum obtained at ground level for the particular configuration. (The expression Emax will be used throughout this thesis to represent the maximum field intensity calculated for any field profile below the line unless otherwise stated.) A direct comparison of the relative per cent change in Emax for a 100% change in any one parameter can be made while the others are held constant. The results of such a change in each parameter on Emax are in the order of magnitudes tabulated below.

Voltage	+100%
Height	- 65 %
Spacing	+ 30 %
Radius	+ 10%

The most important parameter aside from system voltage, is conductor height and its importance is clearly established above. This fact helps demonstrate the need for accurate determination of conductor height in view of public safety. 3.2 <u>The Effect of Bundle Conductors on the Electric Field</u> It was stated previously that the trend of conductor



Figure 3.3 Effect of Conductor Spacing, Height and Size on Emax

design for EHV lines has been towards the use of bundle conductors for reasons for economy, radio interference and The use of bundle conductors in place of large corona. single conductors greatly alters the value of the electric This fact is illustrated in Figure 3.4 where the value field. of E has been normalized with respect to V. Although each sytem is capable of transmitting the same power, the use of bundle conductors results in a higher maximum electric field near the surface of the earth. The increase in the field could be as high as 40% for the bundle conductor case vs the single conductor case. The minimum heights, which at present do not differentiate between conductor configurations, but are based solely on system voltage and mechanical clearance, would specify the same clearance for each of these lines. In view of electrostatic induction this would seem incorrect.

In this thesis, bundle conductor configurations are handled by using a Geometric Mean Radius (27) (GMR) technique. This technique can be used to reduce a vertical, horizontal or triangular configuration of 'n' conductors to a simple 3 conductor horizontal configuration equivalent. This method allows a substantial savings in time and calculations with no loss in accuracy. An exact solution would have required calculating the center of charge displacements that result from the proximity effects of bundle conductors and then employing the standard solution using a PC matrix far in excess of a 3x3. Even if the proximity effects are ignored,







consideration of the charge on each conductor results in a large PC matrix and increases solution time. The GMR technique is sufficiently accurate in comparison with the other methods for the range of conductor sizes and configurations under study in this thesis.

3.3 The Effect of Sky Wires on the Electric Field

Sky wires are used on transmission lines as a protection against direct strikes by lightning. They are positioned above the line conductors and attached directly to ground. Usually only two wires are used and their exact location is dependent upon the isokeranic level of the region. In the past these wires were normally positioned using direct stroke theory ⁽²⁸⁾at a protective angle of 30[°] midway between the two line conductors. Present practice has been to move the sky wires closer to the outer conductors. An investigation of the effect of these wires on the field below the line conductors shows it to be negligible. This fact is illustrated in Figure 3.5. These results were obtained independent of conductor spacing, height or size.

The spacing of the sky wires was varied from 1/4 to 5/4 that of the line conductors spacing. They were located in the range 20 to 40 degrees above the conductors. The shape of the profiles is altered negligibly and the greatest variation in Emax was less than 5% for the range of positions tried. It should be noted that the change in the electric

field as compared to the case without ground wires was at worst an increase of less than 0.5% and a decrease of 4%. These facts indicate that the sky wires have a negligible effect on the field below the line Since the effect is usually a slight decrease in the field thus favouring greater safety, analysis can be further simplified by not taking sky wires into account.

4. AN ANALYSIS OF A MODEL OF A HUMAN BEING

The corona losses and radio interference presented by a transmission line are due to the electric field set up about the line conductors. It is felt therefore, that derivation of minimum height should be determined in relation to this field.

4.1 Method of Approach

It has been found experimentally⁽²⁹⁾ that a human being is able to sense an induced electric field when the field strength is 6KV/in. This corresponds to a surface current density of 0.5μ A/sq. in. The sensation produced at this level is like a "cooling breeze blowing across the skin". As the intensity increases the sensation increases. It is to be noted that this effect does not present an immediate shock hazard or health hazard on a short term basis. The effect of long range exposure to such a field is at present unknown.

It is felt that individuals passing near or working in the uniform field of a transmission line should not have to experience this sensation. By assuming a prolate spheroidal model for a human, an expression for the electric field at its surface can be derived. If the value of this field is to be limited to 6KV/in: then this fact can be used to determine the line height.

4.2 Assumptions

In order to simplify analysis the following assumptions are made regarding the prolate spheroid model:

- 1) The currents induced in it are assumed to have no effect on the source.
- 2) It is assumed to be homogenious, isotropic, and has the following constants.⁽³⁷⁾
 - p = ln-m (Interior) $p = l0^4 n-m$ (exterior)
 - e = 80e₀
- 3) The relaxation time for charge induced on the spheroid is:

 $\mu = \mu_0$

- $$\begin{split} \mathbf{T} &= \mathbf{\varepsilon}\mathbf{p} \\ \mathbf{T}_{\mathbf{s}} &= 7.1 \ \mathbf{x} \ 10^{-6} \ \mathrm{sec} \qquad (\mathrm{on \ surface}) \\ \mathbf{T}_{\mathbf{i}} &= 7.1 \ \mathbf{x} \ 10^{-10} \ \mathrm{sec} \qquad (\mathrm{inside \ the \ man}) \\ \mathrm{Since \ the \ line \ frequency \ is \ 60 \ Hertz \ the \ redistribution} \\ \mathrm{of \ charge \ over \ the \ spheroid \ can \ be \ assumed \ to \ take \ place} \\ \mathrm{instantly. \ Thus, a \ quasistatic \ situation \ is \ assumed \ to \ exist.} \end{split}$$
- 4) In view of the above constants the spheroid can be treated as a good conductor at line frequency and hence the conduction current can be assumed much larger than the displacement current.
- 5) The field in the vicinity of the spheroid is assumed to be uniform, directed in the negative X-direction, and due to sources located at infinity. Its magnitude is taken equal to the largest field value occurring over the man's height when he is not present. The analysis is carried out for that instant of time at which E is a maximum.

Analysis can be further simplified if a prolate spheroidal co-ordinate system is used.

4.3 <u>Co-Ordinate System</u>

A prolate spheroid as shown in Figure 4.1 is obtained by rotating an ellipse about its major axis. Let $\varepsilon,\lambda,\Theta$ be the new co-ordinates. When the ellipse is rotated the co-ordinate ε defines prolate spheroidal surfaces, whose orthogonal surfaces are confocal hyperboloids of two sheets defined by λ . The measure of rotation from the Y axis in the Y-Z plane is defined as Θ . The perpendicular distance from the X axis to the point in question is defined as r.



Figure 4.1 Prolate Spheroid
The relations between cartesian co-ordinates and prolate spheroidal co-ordinates are:

$$\begin{aligned} \mathbf{x} &= \mathbf{c}\lambda\varepsilon \\ \mathbf{y} &= \mathbf{c}\sqrt{(\varepsilon^2 - 1) (1 - \lambda^2)} \cos \theta \\ \mathbf{z} &= \mathbf{c}\sqrt{(\varepsilon^2 - 1) (1 - \lambda^2)} \sin \theta \end{aligned}$$

The metric coefficients are:

$$h_{1} = c \underbrace{\left(\frac{\epsilon^{2} - \lambda^{2}}{\epsilon^{2} - 1}\right)}_{\left(\frac{\epsilon^{2} - \lambda^{2}}{\epsilon^{2} - 1}\right)}$$
$$h_{2} = c \underbrace{\left(\frac{\epsilon^{2} - \lambda^{2}}{\epsilon^{2} - \lambda^{2}}\right)}_{\left(1 - \lambda^{2}\right)}$$

$$h_3 = c (\epsilon^2 - 1) (1 - \lambda^2)$$

4.4 Mathematical Analysis

The analysis of a conducting spheroid in a uniform electric field is a simple inhomogeneous boundary value problem. If a uniform parallel field Eox is applied along the X axis as shown in Figure 4.2 the potential of the applied field at X is:

> Ø₀ = - EoxX ≣ - Eoxcλε

This primary potential ϕ_{\bullet} , is a solution of Laplaces equation in the form of a product of two functions. That is:

$$\phi_{0} = C_{1}F_{1}(\epsilon)F_{2}(\lambda)$$

4.1

4.2

4.3

where $C_1 = -Eoxc$, $F_2(\lambda) = \lambda$, and $F_1(\epsilon) = \epsilon$. It is not regular at infinity.



Figure 4.2 Conducting Prolate Spheroid in a Uniform Electric Field

If the boundary conditions are to be met then the potential \emptyset_1 due to the induced distribution of charge on the spheroid must vary functionally over every surface of the family $\varepsilon = \text{constant}$ in exactly the same manner as \emptyset_0 . It differs from \emptyset_0 in that it must be regular at infinity. A solution for \emptyset_1 can assume the form:

$$\phi_{1} = C_{2}G_{1}(\epsilon) : F_{2}(\lambda)$$

4.5

where $F_2(\lambda) = \lambda$ as before. But \emptyset_1 must satisfy Laplace's equation. Substituting for \emptyset_1 from equation 4.5 into Laplace's equation and noting that $d\emptyset_1/d\Theta=0$ one obtains:

$$\frac{d^2G}{d\epsilon^2} + \frac{2\epsilon}{(\epsilon^2 - 1)} \frac{dG}{d\epsilon} - \frac{2G}{(\epsilon^2 - 1)} = 0 \qquad 4.6$$

Equation 4.6 is a second order differential equation and possesses two solutions. One is already known from 4.4. Using this known solution and noting the form of 4.6 it is possible to write (31)

$$G = \varepsilon \int \frac{e^{-\int \frac{2\varepsilon}{\varepsilon^2 - 1}} d\varepsilon}{\varepsilon^2} d\varepsilon} = \varepsilon \int \frac{d\varepsilon}{\varepsilon^2(\varepsilon^2 - 1)} d\varepsilon}$$
4.7

By substituting 4.7 and $F_2^{}(\lambda)$ from 4.4 into 4.5 the following result is obtained:

$$\emptyset_{1} = \emptyset_{0} \frac{C_{2}}{C_{1}} \int_{\varepsilon} \frac{d\varepsilon}{\varepsilon^{2} (\varepsilon^{2} - 1)}$$
4.8

The constant C_2 may be determined from the condition that the potential at any surface ε_0 is a constant. That is:

$$\begin{split} \phi_{s} &= \phi_{1} + \phi_{0} \\ &= \phi_{0} + \phi_{0} \frac{c_{2}}{c_{1}} \int_{\varepsilon} \frac{d\varepsilon}{\varepsilon^{2} (\varepsilon^{2} - 1)} \\ &= \phi_{0} \left[1 + \frac{c_{2}}{c_{1}} \int_{\varepsilon} \frac{d\varepsilon}{\varepsilon^{2} (\varepsilon^{2} - 1)} \right] \varepsilon = \varepsilon_{0} \end{split}$$

therefore:



The potential at any point in space can be written as:

A knowledge of the potential of the spheroid and evaluation of the integrals in the above expression completely defines the potential at any point in space. In this case $\phi_s = 0$ because the spheroid is on the ground. The integrals can be evaluated and written in the form:⁽³²⁾

$$\int \frac{\mathrm{d}\varepsilon}{\varepsilon^2(\varepsilon^2 - 1)} = \frac{1}{\varepsilon} + \frac{1}{2} \ln\left(\frac{\varepsilon - 1}{\varepsilon + 1}\right)$$

Substitution of the limits of the integrals into equation 4.11 allows equation 4.10 to be rewritten as:

But $\emptyset_{0} = -$ Eoxcle thus:

$$\emptyset = -\operatorname{Eoxcle} + \operatorname{Eoxcleo}\left[1 + \frac{\varepsilon}{2} \ln\left(\frac{\varepsilon - 1}{\varepsilon + 1}\right)\right]$$
$$\left[1 + \frac{\varepsilon_{0}}{2} \ln\left(\frac{\varepsilon_{0} - 1}{\varepsilon_{0} + 1}\right)\right]$$

4.12

4.10

The solution for the electric field at the surface ϵ_{0} is found from the relation:

$$\mathbf{E}_{\mathbf{a}=\mathbf{a}} = -\nabla \phi_{\mathbf{a}=\mathbf{a}}$$

Substituting 4.12 into 4.13 and noting that $d\phi/d\theta = 0$ the value of the electric field is found to be:

$$E_{\varepsilon_{0}} = \lambda E_{0} \sqrt{\frac{\varepsilon_{0}^{2} - 1}{\varepsilon_{0}^{2} - \lambda^{2}}} \left\{ 1 - \varepsilon_{0} \left[\frac{\frac{\varepsilon_{0}}{\varepsilon_{0}^{2} - 1} + \frac{1}{2} \ln \frac{\varepsilon_{0}^{-1}}{\varepsilon_{0}^{+1}}}{\frac{\varepsilon_{0}}{1 + \frac{0}{2} \ln \frac{\varepsilon_{0}^{-1}}{\varepsilon_{0}^{+1}}} \right] \right\}^{a_{\varepsilon}}$$

$$4.14$$

The above expression defines the electric field at the surface of the spheroid in terms of the original field.

4.5 <u>Dependence of the Surface Value of Electric Field on the</u> <u>Ratio of a/b</u>

It was noted in section 4.1 that the electric field recognition level occurs at 6KV/in. If equation 4.14 is rearranged it is possible to determine an allowable value of Eox based on $E_{\epsilon_{a}} = 6KV/in$. That is:

$$Eox = \frac{\frac{E_{\varepsilon_0}}{\frac{\varepsilon_0^2 - 1}{\frac{\varepsilon_0^2 - \lambda^2}{\frac{\varepsilon_0^2 - \lambda^2}}} f$$

where
$$f = 1 - \varepsilon_0 \frac{\varepsilon_0^2 - 1}{1 + \frac{\varepsilon_0}{2} \ln \frac{\varepsilon_0 + 1}{\varepsilon_0 + 1}}{1 + \frac{\varepsilon_0}{2} \ln \frac{\varepsilon_0 - 1}{\varepsilon_0 + 1}}$$

4.15

In the above equation E_{ε_0} is known and if λ is taken to be unity then determination of Eox is dependent on the value of f. Since $\varepsilon_0 = 1/e$, where e is the eccentricity, its value is given by:

$$\varepsilon_{o} = \frac{1}{1 - (b^{2}/a^{2})}$$

The value of ε_0 and hence of f is dependent upon the ratio of a/b. In the lower limit when a/b = 1 the spheroid reduces to a sphere and the value of f is unity. The limit on Eox would be 6KV/in. in this case. However, in the upper limit as the value of a/b approaches infinity, the value of f approaches infinity. In this case the allowable electric field Eox approaches zero.

4.6 <u>A Practical Approach to the Determination of the Value of</u> <u>a/b for Human Beings</u>

The value of 'a' corresponds to a persons height and is easily obtainable. On the other hand 'b' must be determined. It can be evaluated through a consideration of the volume and surface area of the person.

If the specific gravity for humans is taken as 1.0 then the volume occupied by a person can be found as:

$$Vm = 27.7 W$$
 cu. in 4.17

where W represents the weight of the individual. The volume of a spheroid is given by:

 $Vs = \frac{4}{3} \pi ab^2$

30

4.16

Equating Vs/2 to equation 4.17 a solution for b follows if a person's height and weight are known. In this case:

$$b_v = 3.64 [W/a]^{1/2}$$
 in. 4.19

where b_v is the value of b based on the volume consideration. It is also possible to determine the surface area of a person from biological considerations: (33)

$$Sm = (71.84W^{0.425} a^{0.725} 0.155) sq. in.$$
 4.20

The surface area of a spheroid is given by:

$$S = 2\pi b^2 + \frac{2\pi b^2 a}{e} \sin^{-1} e$$
 4.21

If S/2 is equated to equation 4.20 another solution for b results which can be denoted as b_s . In general the value of b_s is larger than the value of b_v . If 'b' is taken as the average of b_s and b_v both conditions are reasonably satisfied. Therefore:

$$p = \frac{b_v + b_s}{2}$$
 4.22

The above equations demonstrate quite clearly that the value of 'b' is primarily dependent upon the weight of an individual. At any fixed height therefore, a thin person is far more affected by the field than a heavy person. A determination of the worst case condition for Eox reduces to finding the minimum weight a person achieves at some arbitrary height and then comparing the ratios of a/b for the various heights.

4.7 Evaluation of a Limiting Value of Eox

The derivation of a meaningful limit on Eox is dependent upon the relation between people's heights and weights. Statistical data on this relationare available in many biological handbooks. (34), (35) In this thesis two cases are considered on the basis of these data. First the worst possible case is assumed by combining maximum heights with minimum weights at any age level. The second case is based on combining average heights with average weights. The results are illustrated in Figure 4.3.

The curves of the worst case indicate that a/b is a maximum for a 13 year old male or a 12 year old female. The values of Eox for these cases are considerably lower than for the case of a man over 25 years of age. The results based on averages indicate lower values of a/b in all cases but still points out that people in their teens are most susceptible. The value of Eox corresponding to each of the above cases is tabulated in Table 4.1. The case of a man 25 years and over is included for a comparison.

According to Table 4.1 the limiting value of Eox should be taken as 0.8KV/ft. However, use of this value may prove more stringent than required, since the probability of achieving maximum height and minimum weight simultaneously is deemed small. A more meaningful value may be found by considering



the clearances specified by the values of Table 4.1 for a given voltage level.

Table 4.1 Limiting Values of Eox

Case		MALE	•	. ·	FEMALE	· .
(Age (Yrs)	Eox (KV/ft)	Height (Ins)	Age (Yrs)	Eox (KV/ft)	Height (Ins)
Average	e 15	1.383	65.6	12	1.365	59.0
	25	1.528	68.3			
Worst	13	0.809	66.8	12 [.]	0.800	64.7
`	25	1.081	73.1	• • •		

The sensation produced by excessive electric fields is unrecorded for 230KV lines now in existence. In an area accessible to pedestrians only, most codes in Canada specify a line clearance of 22'0" to 24'0". The line heights required for the values of Eox in Table 4.1 can be computed for a range of 230KV cases and compared against the accepted values. The results listed below are obtained using conductor spacings and sizes of 22'0" to 32'0" and 606MCM to 1277MCM respectively.

Eox	X	Height
0.800	64.7	31.0' - 35.0'
0.809	66.8	30.8' - 34.8'
1.091	73.1	26.1' - 29.1'
1.365	59.0	22.4' - 24.8'
1.383	65.6	22.4' - 24.8'
1.528	. 68.3	21.3' - 23.3'

In consideration of accepted practice and the number of cases covered, the allowable value of Eox is taken to be:

$$E_{max} = 1.365 KV/ft.$$
 at 4'11"

Using this value it is now possible to compute the required line clearances for systems at any voltage level.

5. DETERMINATION OF MINIMUM CONDUCTOR HEIGHTS FOR AC AND DC SYSTEMS

5.1 Method of Approach

It was pointed out in Chapter 3 that the electric field is affected by system voltage, conductor size, height and separation. A general expression can be written for the electric field as:

$$E = \sum_{i=1}^{n} q_i F(Hi, Xi, di)$$

The charge, as determined from 2.8 can be written as:

$$q_i = \sum_{i=1}^{n} G(Hi, Di, di)$$
 Vi

Substituting 5.2 into 5.1:

$$E = \sum_{i=1}^{n} Vi F(Hi, Xi, di) G(Hi, Di, di)$$

where Xi=Di+x. At any voltage level Vi is known. If E is fixed at 1.365KV/ft. it is then possible to use equation 5.3 to solve for any one parameter holding the other two fixed by an iterative technique. Since height is desired it must be solved for any combination of conductor spacing or size that may occur for any voltage level. It should be pointed out that the iterative process lends itself quite readily to use of a digital computer. The results listed below were obtained using an IBM 7044 computer with an

5.1

IBFTC Compiler in Fortran IV language.

5.2 AC Cases

In order to make the results obtained as useful and as general as possible a survey of existing EHV systems was undertaken. A number of phase spacings and conductor sizes are possible for any one voltage level. The results obtained below cover most possible combinations that are in existence today. The range of values used is shown in Table 5.1.

Voltage KV	Spacing Ft.	Conductor MCM	Conductors Per Phase	Bundle Spacing	GMR Ft.
230	22 - 32	605 - 1034	1	-	
345	22 - 34	1351- 2355	1	· –	-
345	22 - 36	795 Min. 1277 Max.	2 ^{° ·} 2	12" 18"	0.215 0.290
500	32 - 42	2800-3120	1	· _	-
500	26 - 42	1780-2493	2	18"	0.3-0.4
500	38 - 54	520 - 795	4	18"	0.5-0.7
735	44 - 60	795 Min. 1277 Max.	4	18" 20"	0.7 0.9

Table 5.1 Data Summary for ac Systems

The curves of Figures 5.1 to 5.7 all meet the required constraint on Emax specified by equation 4.23 for the spacings and radii indicated. The radii appearing on the curves cover the most common conductor sizes in use today for the system indicated and are expressed in feet. Any value of







Figure 5.2 345KV ac Cases - 1 Conductor Bundle





radius not indicated directly is obtainable through interpolation with negligible error. As an example of this, consider the use of a 1024MCM-24/13 strand ACSR cable with an O.D. of 1.165 inches, on the 230KV system at 30'0" spacing. By interpolation the expected height of this line would be 24 feet. Actual calculation specifies a height of 24.1 feet. The error is less than 0.5%.

The curves contained in Figure 5.7 are based on estimated values that may be used at this level. To date only one system in the world is operating at this voltage level, however, the principle of bundle conductors will continue to be employed at this voltage level and at any immediate higher levels. Bundle spacing and conductor size is expected to increase if altered at all.



The conductor clearances derived above are based on a voltage consideration and are completely independent of mechanical requirements. The values in Figures 5.1 to 5.7 are in excess of any mechanical clearance as specified to date. Since existing codes are based primarily on mechanical clearances this would seem incorrect in view of induction effects. Table 5.2 lists the heights required at present by the C.S.A. and N.E.S.C. electrical codes for each voltage level, in addition to the range of values derived above. Land accessible to pedestrians indicates the minimum required clearance while land accessible to vehicles indicates the maximum clearance required. Only present standards are compared. The voltages listed below are line-to-line and all clearances are in feet.

Voltage KV	Conductors Per Phase	Minimum Derived	Clearance to C.S.A.	Ground N.E.S.C.
230	I	22.4-24.8	21.7-27.7	29.0-34.0
345	1 2	29.4-34.4 33.8-40.0	22.3-28.3	33.8-38.8
500	1 2 4	41.5-46.0 45.4-52.9 54.0-61.1	23.0-29.0	40.4-45.4
735	4	73.8-81.9	24.0-30.00	50.0-55.0

Table 5.2 Comparison of Line-to-Ground Clearances

The values of acceptable clearance as stated by C.S.A. are extremely low in comparison with the derived values. Lines being built at present using these values can be

termed hazardous in view of public safety. As shown in Figure 1.1 these values are being upgraded to correspond more to industries view of higher clearances. However, the present proposed revisions do not appear to be sufficient when compared with the derived values. On the other hand, the present N.E.S.C. standards appear to be adequate for most lines up to 500KV and 2 conductor bundles. Above this voltage level and for 4 conductor bundles the values appear low. The proposal to reduce these values seems undesirable and will only increase the induction hazards to the public.

In both cases the need to specify clearances based on accessibility seems irrelevant in view of the derived heights. Since most land in and around transmission lines will eventually become accessible to vehicles the present system of definition is only relative and hence meaningless. It is therefore recommended that line clearances be derived from electrical considerations, as was done in this thesis. In view of the clearances specified above it is suggested that these heights be accepted as a guide for future designs. 5.3 DC Cases

Use of high voltage dc transmission has had only limited application in North America. Because of this fact, only a few lines have been built or proposed to date. A broad survey as was carried out for the ac cases is difficult. As such, some of the parameter ranges used are based on existing dc test configurations⁽³⁶⁾ and the author's own judgement as to possible values that may be used. Only double pole lines were considered in this thesis as most single pole lines are used for crossing large bodies of water. As such, the short distance, they are above ground is negligible. The parameter ranges for double pole systems are listed below in Table 5.3.

Table 5.3

Data Summary for dc Systems

Voltage KV	Spacing . Ft.	Conductor MCM	Conductors Per Phase	Bundle Spacing	GMR Ft.
345	<u> 30 - 46</u>	1780-2300	l	-	-
345	30 - 46	2156 Min. 2574 Max.	2 2	16" 18"	0.2 '0.3
500	40 - 56	2300 Min. 3120 Max.	2 2	16" 18"	0.12
500	40 - 56	954-1780	4	18"	0.3-0.7

Using the technique listed in section 5.1 results for the dc cases are obtained and shown in Figures 5.8 to 5.11. Only two voltage levels were considered as most cases at present are either operating at these levels or within 10% of these values.

Comparison of ac systems with dc systems at any voltage level shows that the latter requires as much as 15% less clearance. This is another factor in favour of using dc at higher voltage levels and it also points out the possible error in applying ac clearances to dc lines as is now the case.







Figure 5.9 345KV dc Cases - 2 Conductor Bundle





6. SHIELDING EFFECTS OF GROUND WIRES BENEATH THE LINE CONDUCTORS

6.1 Shielding Effects of Ground Wires

It is suggested that the electric field at ground level may be reduced by placing ground wires underneath the line conductors. If the field intensity is reduced by a significant amount it might result in a reduction in the heights as derived in Chapter 5. This could result in large economic savings if the reduction in height is significant. Alternatively, if shielding is employed at the same height, induction hazards might be reduced.

In order to speed analysis of the effect of ground wires on the field, a test case was computed with 1,2,3 and 5 ground wires placed beneath the line. The test line was assumed to have a 50'0" spacing, a 40'0" height and an effective radius of 0.3 feet. The results are normalized with respect to voltage. A survey of existing systems indicates that the minimum line to structure clearance at any voltage level is 7'0". Thus the ground wires cannot lie closer than this distance to a line conductor. Also, because of mechanical considerations the minimum height of ground wires was taken as 20'0". To locate the optimum position of the ground wires their spacing was varied from D/4 to 5D/4 while their height was varied from 20'0" to 33'0" at each spacing increment. The following points were noted:

1) The maximum variation in Emax/V was less than 4% for the range of heights tried at each spacing and for each

case. This would tend to indicate that the ground wires are independent of height above ground for the region tried.

2) The shielding effect of the ground wires was reduced as they were moved horizontally closer to the center of the configuration. The optimum position with respect to spacing occurred in all cases when the ground wires were directly below the line conductors.

3) The electric field profiles are altered negligibly over the range of positions tried.

The per cent decrease in Emax/V at ground level with the ground wires in their optimum position for 1 to 5 ground wires is shown in Figure 6.1.



Figure 6.1 Per Cent Decrease in Emax/V Using 1 to 5 Ground Wires in Their Optimum Position

The decrease in Emax obtained using ground wires should be investigated with respect to the effect in reducing line height. However, before such an attempt is made it should be noted that the effect of a single ground wire is almost negligible, while using 5 is impractical because of expense. It would appear that the use of 3 ground wires in their optimum position is worth consideration. Only ac cases will be investigated.

6.2 <u>Reduction in Line Heights</u>

735

The curves shown in Figure 6.2 to 6.7 are obtained by meeting the required allowable: value on Emax given in section 4.7 with 3 ground wires present as part of the line configuration. A direct comparison of the heights derived for identical cases with and without ground wires, based on the parameter ranges of Table 5.1, is shown in Table 6.1 where all dimensions are in feet.

Table 6.1 Line-to-Ground Clearances with and without Ground Wires Voltage Conductors Clear. To Height Minus Height with Per Cent Per Phase Structure Shielding Decrease KV Shielding '345[.] 1 9 29.4-34.4 24.1-27.5 18-20 2 33.8-40.0 28.6-32.9 15-18. 500 1. .11 41:5-46.0 34.6-37.9 17-17 45.4-52.9 39.0-44.9 14-16 2 4 54.0-61.1 45.5-51.4 16-16

73.8-81.9

63.1-70.2

14-14

Since the line to structure clearance is of the order of 9'0" for 345KV systems it would seem highly unlikely that

18









ground wires would be used at this voltage level because of the required mechanical clearances. However, at all higher voltage levels it would appear that a useful reduction in line height can be achieved through the use of 3 ground wires placed below the line conductors. This reduction in height on the average is in the order of 17%. Since conductor vibration problems increase with tower height it is desirable to keep the lines as close to the ground as possible. In view of this the savings in height using ground wires may prove useful.

The savings in tower costs versus the installation cost of the ground wires would, of course, be the deciding factor in incorporating this technique. In any case, it is felt that this shielding technique could still be applied in populous areas to reduce electrostatic induction effects where this is important. It is noted that use of 3 ground wires below the line conductors reduces the electric field by approximately 30%. This means that induction effects would also be directly reduced by a similar amount. Such a safety factor cannot be overlooked. Incorporation of this idea might allow greater utilization of area laying in the rightof-way of the transmission lines.

7. MEASUREMENT OF THE POTENTIAL OF AN OBJECT BELOW A TRANSMISSION LINE

7.1 Method of Measurement

In this chapter a method to measure the potential below a transmission line is presented. Using this method experimental results are obtained for several lines and compared against the theoretical values predicted by the equations of Chapter 2. In addition, readings are taken to verify the effect of bundle conductors and sky wires.

In Figure 7.1 the potential induced in an object located at the point P(x,y) due to any one line can be written as:

$$V(x,y) = \frac{V C_{io}}{(C_{og} + C_{io})}$$
7.1

where C_{io} = the line to object capacitance C_{og} = the object to ground capacitance



Figure 7.1 Coupling Capacitances between the Line and

The charging current flowing through C_{io} to the object can be written as:

$$\left| \mathbf{I} \right| = \frac{\left| \mathbf{V}_{\mathbf{i}} \right| \, \omega \, \mathbf{C}_{\text{og}} \, \mathbf{C}_{\text{io}}}{\mathbf{\cdot}^{\mathbf{C}}_{\text{io}} + \mathbf{C}_{\text{og}}}$$
7.2

If a measurement of V(x,y) is taken this is analogous to closing switch S_1 through a metering circuit. In this case:

$$|I| = \frac{V_{i} \omega C_{io}(1 + j\omega RC_{og})}{1 + j\omega R(C_{io} + C_{og})}$$
7.3

and

$$|V(x,y)| = \frac{V_{i} \omega C_{i0} R}{1 + j\omega R (C_{i0} + C_{og})}$$
7.4

Equation 7.4 indicates that the potential at P will be greatly affected by the resistance of the metering circuit. Since C_{io} and C_{og} are of the order of a few picofarads, R would have to approach 10^{12} ohms or better in order that V(x,y) is independent of the circuit. In this case equation 7.4 reduces to 7.1. Although the value of V_i and C_{io} will differ for each line, the effect of the metering circuit is the same in each case. An indirect method has been devised to measure V(x,y) since a high impedance meter capable of reading up to 20KV was not readily obtainable.

If the object is grounded, then the net charge appearing on it will give rise to a secondary field. The potential at

the surface of the object due to the line and this secondary field must be zero. By choosing the object to be a sphere whose radius is 'a', it is possible to write:

$$V(x,y) + \frac{q}{4\pi\epsilon_0} \left(\frac{1}{a} + \frac{1}{2x}\right) = 0$$

or upon rearranging:

$$q = \frac{V(x,y) 4\pi\varepsilon_{0}}{\left(\frac{1}{a} + \frac{1}{2x}\right)}$$

In the case of an ac system the current flowing to the sphere to maintain it at zero potential would be:

$$I = \frac{V(x,y) \ 4\pi\omega\varepsilon_{0}}{\left(\frac{1}{a} + \frac{1}{2x}\right)}$$
7.6

The value of I will be of the order of microamperes for V(x,y) of the order of KV. Therefore, by connecting a microammeter in series between the sphere and ground this charging current can be measured. Since ω , x, a and ε_0 are known then V(x,y) can be computed and compared against the expected value. It is important that the sphere's dimensions should be small with respect to the distance of the sphere from the source so that the distortion it introduces will not affect the source.

7.2 <u>Instrument Design</u>

An instrument is required to read the charging current that flows through the probe to the ground. An ac microammeter with a capability of reading 1.0 to 20µA would be desirable but such movements are extremely expensive and were not readily available.

Instead an operational amplifier was used to allow measurements in a range more suited to already existing meters. -Because it-was necessary to measure the charging current under actual lines, the instrument designed had to be portable, flexible and battery operated.

A schematic of the circuit is shown in Figure 7.2. The input resistance varies from 200 ohms in the 50K range to 1 in the 10 megohms range. Some of the design features of the instrument are:

- 1) It has a full scale deflection of 0.1 to $20\mu A$ by using the proper scale setting.
- 2) It can be biased to compensate for current offset in the operational amplifier.
- 3) It uses mercury cell batteries for longer life and stable output.
- 4) An inexpensive panel type ac voltmeter with a O-IV --full scale is used as an indicator.

The instrument was calibrated using the set-up shown in Figure 7.3. The results of the tests are shown in

5-WAY SWITCH

P

ABLE



Figure 7.2. Schematic Diagram Of UBC Instrument



Figure 7.3. Test Arrangement To Calibrate Meters



Figure 7.4

A second method for reading the charging current was proposed by Miller⁽²¹⁾ in the design of his gradient meter. This involved rectifying the ac signal by means of a diode bridge and using a O-15µA full scale dc microammeter. The Miller meter was also built and was tested using the arrangement shown in Figure 7.3. The results of these tests are shown in Figure 7.4. It should be noted that the Miller meter accurately measures charging current but his technique of reading the voltage gradient under transmission lines is incorrect. A discussion of this technique and the gradient meter is presented in Appendix I.

7.3 <u>Calculated Values vs Experimental Values</u>

A measure of the induced potential was made by reading the charging current through a grounded 1'0" diameter aluminum sphere. The position of the sphere was moved horizontally from y=-2.5D to y=+2.5D in 10 foot increments from the centre of the configuration, while vertically situated at a fixed level above ground. Measurements were taken under two different lines operating at different voltage levels. The parameters of these lines are given below.

Voltage KV	Spacing Ft.	Height	Conductor MCM	No. Per Phase	Bundle Spacing
235	18	39.3	795	l	· _
360	35	54.0	795	2	12"


Figure 7.6. Test Results For 360KV Line

A comparison of the calculated and measured values for --each of these lines is shown in Figure 7.5 and 7.6. The measured values are an average of the Miller and UBC Instrument readings. The resulting discrepancies were less than 5% in most cases. The readings were higher than expected for the 230KV case and lower than expected for the 360KV case. These effects could result if a slight voltage --unbalance occurred between the conductors. The good agreement between calculated values and measured values verifies the validity of the equations in Chapter 2. The induced potential at any level can be found by employing the technique outlined above and using either the Miller meter or the UBC instrument. 7.4 Experimental Verification of the Effect of Sky Wires

Tt was pointed out in section 3.6 that the presence of sky wires above the line conductors has virtually no effect on the electric field and hence the potential below the line. As a check on this, an actual 360KV line was selected having the configuration shown in Figure 7.7.



Using the technique presented above, a measure of the induced ---potential at the 4'O" level was made. A comparison of the measured values and those that would be expected if no sky wires were present is shown in Table 7.1.

Feet	Miller Meter KV	UBC Instrument KV	Computed Values KV	Average Error In Per Cent
0 .	1.043	1.051	0.960	+9.0
10	1.295	1.320	1.204	+8.6
20	1.765	1.733	1.705	+2.6
30	2.153	2.136	2.175	-1.4
40	.2.447	2.405	2.451	-1.0
50	2.473	2.462	2.487	-0.8
60	2.220	2.187	2.329	-5.4
70	2.018	1.985	2.063	-3.1
80	1.749	1.733	1.765	-1.4
90	1.413	1.413	1.481	-4.6

Table 7.1 Measurement of Sky Wire Effect

The difference on the average was within 4%, which is within experimental error. It is thus justifiable to ignore the effect of sky wires.

7.5 Experimental Verification of the Effects of Bundle Conductors In section 3.5 it was pointed out that using bundle conductors in place of single conductors greatly increases —the field intensity and hence the potential near the earth's surface. As a check on this an existing 230KV line was selected that used a bundle conductor configuration along one portion of its length and a large single conductor along the remainder. The configurations of the line are shown in Figure 7.8



-Figure 7.8 _230KV Test Line For Bundle Conductor Effect A comparison is made in Table 7.2 between the potential measurements obtained at X = 4'0'' and the values expected using the bundle configuration as well as the single conductor. (A direct comparison by measuring potential values for the bundle and single conductors was not possible.) The readings in Table 7.2 are an average of the Miller meter and the UBC instrument measurements. The measured values are in good agreement with the values expected for the bundle conductor case. The difference between the expected bundle values and the expected single conductor values is much larger than possible experimental Therefore, the readings can be assumed to represent the error. bundle conductor values. As such the anticipated effect of bundle conductors versus single conductors is true.

Table 7.2 Measurement of Bundle Conductor Effect

Feet	Measured kV	Computed Potentia Bundle	al in KV Single	Per Cent Error For Bundle Case
0	1.396	1.453	1.068	-4.0
10	1.539	1.503	1.111	+2.4
20	1.875	1.739	1.293	+8.1
30	2.355	2.144	1.591	+9.8
40	2.759	2.488	1.839	+10.9
50	2.800	2.593	1.912	+8.0
60 ·	2.559	2.449	1.802	+4.4
70	-2.321	2.153	1.583	+1.8
80	1.825	1.810	1.330	+0.8
90	1.551	1.486	1.091	+4.5
100	1.195	1.207	0.886	-1.4

8. ESTABLISHMENT OF THE WIDTH OF RIGHT-OF-WAYS

8.1 Right-of-Way Clearances

The right-of-way of a transmission line is that strip of land the line occupies and the clearing to either side of the line. At present the width of the right-of-way is determined mostly by mechanical requirements. Since, in most cases a line must cross forested land the width of the right-ofway is usually fixed to allow ample room for construction, safety from falling trees, and protection in case of fire. In densely populated areas, land is at a premium and excessive right-of-way widths is undesirable. The utilities are at present reluctant to reduce large right-of-way widths because of possible induction effects that would prove hazardous to public. It is desirable therefore to try and specify this width in relation to induction effects.

8.2 Width Requirement Based on Electrostatic Induction Effects

Danger from electrostatic induction results only when the insulated object is grounded and current flows. It is accepted that the threshold of $perception^{(38)}$ occurs at 1 milliampere and that currents up to 9 milliamperes for men and 6 milliamperes for women constitute no hazard although they may prove exceedingly annoying. A person coming in contact with an insulated object can be viewed electrically as shown in Figure 7.1. In this case R can be taken to be the person's resistance. It was shown previously that the voltage induced in an insulated object due to each line is:

$$V(\mathbf{x},\mathbf{y}) = \frac{V_{i} C_{i0}}{(C_{og} + C_{i0})}$$
 7.5

When $S_{\underline{l}}$ is closed the current flowing through the resistor is:

$$\left| \mathbf{I} \right| = \left| \frac{\mathbf{V}_{i} \boldsymbol{\omega} \mathbf{C}_{i0} \quad (1 + j \boldsymbol{\omega} \mathbf{R} \mathbf{C}_{0g})}{1 + j \boldsymbol{\omega} \mathbf{R} \quad (\mathbf{C}_{i0} + \mathbf{C}_{0g})} \right|$$
7.3

But for R small this reduces to:

$$|I| = |V_i \omega C_{i0}|$$
8.1

For a grounded object the current flowing from ground to maintain it at zero potential can be written as:

$$|I| = |\omega C_{og} V(x, y)|$$
8.2

Substituting for V(x,y) from 7.1 gives:

 $|I| = \frac{\omega V_{i} C_{og} C_{io}}{(C_{og} + C_{io})}$

If $C_{og} >> C_{io}$ then the above expression reduces to equation 8.1. In the case of an object close to the ground with respect to its distance from the line the above assumption is true.

It is shown in equation 8.2 that the charging current to ground is dependent upon the object's capacitance to ground and the potential of the point in space it occupies. In the case of complicated conducting objects this potential may be considered equal to the value that would occur at the object's center of gravity. According to this if a sphere is considered at X=6'0'', its potential will always be V(6,y), independent of its radius.

8.3

The radius would then affect only the sphere's capacitance and increases or decreases the current flow to ground with an increase or decrease of radius respectively.

Using this approach it is possible to find a tolerable level of induced potential by specifying a worst case C_{og} . From previous studies it is felt that C_{og} at worst might reach 5000 pf.⁽¹⁶⁾ If the current is to be limited in the region from 1 to 5 milliamperes this would result in an acceptable range of V(x,y) of from 0.5 to 2.5KV. In view of the above and of the reduced probability of flammable objects to ignite as the voltage is reduced below 1KV it is felt that a tolerable limit on V(x,y) should be taken as 1KV.

The above criterion can be used to specify the width of a right-of-way for any line operating at any voltage. If a vertical height of reach of 6'0" is assumed then the width can be specified by finding the horizontal location from the center of the configuration at which the induced potential is 1KV.



Figure 8.1 230KV Cases-1 Conductor Bundle Right-of-Way Widths













Figure 8.5 500KV Cases-2 Conductor Bundle Right-of-Way Widths







Figure 8.7 735KV Cases-4 Conductor Bundle Right-of-Way Widths

The curves of Figures 8.1 to 8.7 indicate the required width of the right-of-ways, as measured from the center of the configuration for the spacings and line heights indicated. At each voltage level the maximum effective radius as presented in Table 5.1 was used.

Mechanical clearances usually require a 150 foot clearance from the center of the configuration. This clearance is in excess of the value required for most lines operating at 230 and 345KV. This indicates that in populous areas once the line is constructed more land near lines at voltages up to 345KV could be utilized. Above this voltage level the widths required based on induction effects exceed the mechanical requirement. In view of public safety the widths as derived in this thesis would appear more desirable.

It should be noted that a peak occurs in each right of way curve. This point represents the worst case for the configuration under study. Maximum safety for the public results if these values are used for all lines operating at that voltage and spacing.

APPENDIX I: DISCUSSION OF THE MILLER GRADIENT METER

A field intensity, or gradient meter, as illustrated in Figure 1.1, was developed for studies by Miller⁽²⁹⁾ concerning live line maintenance.



A - A

Figure I.l. Miller Gradient Meter

The meter consists of a main circular electrode surrounded by a guard ring to eliminate fringing. The main electrode is connected to a microammeter through a shielded lead and then to the shield of the circuit. The area of the main electrode is so dimensioned as to allow a field intensity of 100 or 1000 volts/in. to drive lµA through the circuit. The gradient meter was used to read the electric flux impinging on the surface of a workman by placing the probe in front of the area being investigated. In addition, the meter itself minus the probe was coupled between a lineman and a suitable reference potential to measure the total induced current flowing through the man. It was also proposed that the gradient meter could be used to measure the low intensity fields that exist a few feet above ground under a HV power line. In this case a large probe was built and supported on a tripod at an arbitrary height above ground and the tripod was moved from y=-2D to y=+2D. The results of these applications are presented in Miller's papers.^{(29),(38)}

The technique to measure electric field intensity and total induced current of a workman while bounded to a bucket, or while standing on the tower is correct as long as the lineman is at the reference potential. In this case the meter measures the electric field emanating (connected to the line) or impinging (connected to the ground) due to the net charge appearing on the workman at any instant. Similarily the total induced current can be measured. If the workman is isolated in space no net charge would appear and no electric field would impinge on him.⁽³⁹⁾ In this case no measure can be made of the induced current or electric field.

In view of this it should be pointed out that the technique to read low intensity fields under transmission lines with the Miller meter is incorrect. This can be seen directly from the results presented in Miller's paper⁽³⁸⁾ concerning a set

of measurements of the voltage gradient made under a 345KV substation bus. These measurements which are in KV/in., are listed below in Table 1.1.

Table 1.1 Miller Measurements for 345KV Substation Bus

Feet	Miller at X=6	Readings At X=0'	Computed Values At X=6' At X=0'		
0	650	90	102	83	
10	650	100	117	107	
20	950	150	168	152	
30	780	110	146	141	
40	500	90	98	99	

Inspection of equation 2.3 indicates that, in the region near the ground, the electric field is nearly constant. In the line under study Emax at the six foot level was only 9% greater than at ground level. The results in Table 1.1 indicate that Emax at the six foot level is more than six times larger than its corresponding value at ground level.

The above readings at the six foot level do not reflect the field values at this point but instead are a measure of the charging current through the line-to-probe capacitance. As it was pointed out previously, the probe isolated in space has no net charge and hence no electric field impinging on its surface. However, at any point in space, the probe is capacitively coupled to the line and ground as Figure 7.1 illustrates. In the case near the ground, the current flowing through the meter is determined primarily by the probe's coupling capacitance to the line and is given by equation 8.1. Even if the probe is grounded the current flow is still determined by this capacitance. As the probe's height is increased or decreased a corresponding increase or decrease in charging current will occur since the probe's coupling capacitance to the line is dependent upon height.

The above argument can be substantiated from Miller's readings. It was pointed out that a set of readings were taken at ground level by laying the probe on the ground and varying it from y=-2D to y=+2D. In this case the probe is at a reference potential and is not capacitively coupled to the ground. Therefore, an accurate measure of the electric field is expected. The readings obtained at ground level are in good agreement with the corresponding calculated values as shown in Table I.1. The ground capacitance of the probe would decrease significantly at the six foot level. In this case readings are expected that are proportinately higher than at ground. This is indeed the case for the readings at the six foot level, as shown in Table I.1. It can be concluded that the Miller probe can be used to measure the electric field or induced current in objects that are located at the reference potential and form part of the reference boundary. However, the probe cannot be used to measure low intensity fields under transmission lines as was stated. The probe can be used as was done in section 7.1, to measure the induced current or voltage gradient if its ground capacitance can be determined.

REFERENCES

l.	L.M. Olmstad - Design Survey Reveals Patterns of EHV Expansion- Electrical World - Nov. 15, 1965, p. 99-118.
2.	Ph. Sporn - The U.S. National Power Survey - Cigre - Vol. II - 1966 - Paper 313.
3.	Central Station Engineers - Westinghouse Transmission & Distribution Handbook - Book Fourth Edition - p. 796-798.
4.	G.A. Baril - Commissioning of the First Manicouagan - Montreal 735 KV Transmission Line - Cigre - Vol. III - 1966 - Paper 429.
5.	R. Keitley - Corona Power Loss and Radio Interference Measurements at 400 KV and 750 KV on the Leatherhead Experimental Line - Cigre - Vol. III - 1966 - Paper 419.
6.	R. Bartenstein - Corona Measurements on a Four Conductor Bundle for 700 KV-3 Phase Overhead Lines - Cigre - Vol. III - 1966 - Paper 426.
7.	B.P. Lebedev - EHV Transmission in U.S.S.R. Power Grid - IEEE Spectrum - Feb, 1967.
8.	H.P. Cooke - Design of above 400 KV Substations - IEE Publ. Conf. - 1965 - No. 15 p. 139-142.
9.	J.J. LaForest, M. Baretsky Jr., and D.D. MacCarthy - Corona Loss and Radio Interference of EHV Transmission Lines Based on Project EHV - IEEE Transactions on Power Apparatus and Systems - Vol. 85 - No. 12 - Dec. 1966, p. 1196-1230.
10.	E.H. Gehrig, A.C. Peterson, C.F. Clark and T.C. Rednour - BPA's 1100 KV D.C. Test Project - IEEE Transactions on Power Appar- atus and Systems - Vol. 86 - No. 3 - March, 1967 - p. 278
11.	Y. Saruyama, M. Yasui and S. Nagasaki - 500 KV Line Design 11 - IEEE Trans. on Power Apparatus and Systems - Vol 86- No. 9-Sept., 1967.
12.	V.I. Levitov - Operational Experience on 500 KV Networks in U.S.S.R Cigre - Vol. III - 1966 Paper 416.
13.	J.L. Blackburn - Voltage Induction in Parallel Transmission Lines - AIEE - Vol. 81 - 1962/63 - p. 921-6.
14.	W. Erbacker - Induction Effects of H.V. Lines - Cigre - Vol. III 1959 - paper 303.
15.	H.A. Erith - Some Aspects of Public Safety in the Vicinity of EHV Transmission Lines - CEA Meeting - Jan. 23, 1961.

- 16. H.C. Ross Electrostatic Induction Near EHV Transmission Lines -Ontario Hydro Research Report - No. 61-158 - May 18, 1961.
- 17. P.G. Buchan Electrostatic Induction Near EHV Transmission Lines as Related to the Hazards of Handling Gasoline - Ontario Hydro Research Report - No. 63-391 - Nov. 1, 1963.
- N.J. McMurtrie Guide to Height of Conductors Above Ground -Ontario Hydro - May 17, 1960.
- 19. G.J. Berg and F. Noakes Electric Potential and Gradients Below HV Lines - CEA Transactions, Engineering and Operating Division - Vol. 6 Part 4 - 1967.
- 20. R.P. Comsa An Air Model for the Study of Electrostatic Induction By Transmission Lines - IEEE Paper No. 31 - 1967 - p. 67-97.
- 21. C.J. Miller Measurements of Electric Fields in Live Line Working-IEEE Trans. on Power Apparatus and Systems - Vol. 86 - Nov. 4 -April 1967 - p. 493-497.
- 22. W.B. Kouwenhoven et. al. Medical Evaluation of Man Working in A.C. Electric Fields - IEEE Trans. on Power Apparatus and Systems -Vol. 86 - No. 4 - April 1967 - p. 506-511.
- 23. Canadian Standards Association Height of Conductors Above Ground CSA Specification C22.3 No. 1.5.
- 24. U.S. Bureau of Standards National Electrical Safety Codes.
- 25. A.F. Kip Electricity and Magnetism Book First Edition 1962 McGraw Hill p. 30.
- 26. W.B. Boast Principles of Electric and Magnetic Fields Book Second Edition - Harper and Bros. - 1956 - p. 138.
- 27. H.H. Skilling Electric Transmission Lines Book First Edition -1951 - McGraw Hill - p. 112, 118.
- 28. W.W. Lewis The Protection of Transmission Systems Against Lightning - Book - Dover Publication - 1951.
- 29. W.B. Kouwenhoven et. al. Body Currents in Live Line Working -IEEE Trans. on Power Apparatus and Systems - Vol. 85 - No. 4 -April, 1966 - p. 403.
- 30. J.A. Stratton Electromagnetic Theory Book McGraw Hill 1951 p. 52, 56, 48, 195.
- 31. C.R. Wylie Advanced Engineering Math Book McGraw Hill p. 79.
- 32. Standard Mathematical Tables C.R.C. Book 12th Edition p. 288-9, 403.
- 33. E.F. DuBois and D. DuBois A Formula to Estimate Surface Area if Height and Weight be known - Arch. Interin Med. - Vol. 17 -1916 - p. 863.

- 34. Biological Data Book Federation of American Societies for Experimental Biology.
- 35. Saunders Handbook of Biological Data National Academy of Sciences N.R.C.
- 36. M.G. Poland, M.W. Belsher and A.A. Osipouich BPA's llOOKV DC Test Project I: Measurements and Instrumentation - IEEE Trans. on Power Apparatus and Systems - Vol. 86-No. 3 - March 1967 - p. 268.
- 37. H.C. Barnes, A.J. McElroy and J.H. Charrow Rational Analysis of Electric Fields in Live Line Working - IEEE Trans. on Power Apparatus and Systems - Vol. 86 - No. 4. - April, 1967 - p. 482.
- 38. C.J. Miller The Measurements of Electric Fields in Live Line Working - IEEE Trans. on Power Apparatus and Systems - Vol. 86 - No. 4 - April 1967 - P. 493.
- 39. R. Plonsey and E. Collin Principles and Applications of Electromagnetic Fields - Book First Edition - 1961 - McGraw Hill - p. 68.