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DESIGN GUIDE FOR OUTDOOR AC SUBSTATION EARTHING SYSTEMS, WITH SPECIFIC APPLICATION TO ESKOM BLOEMFONTEIN DISTRIBUTOR'S REQUIREMENTS

D J PIETERSE

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by

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EXTRACT

In modern high voltage substations, earthing has become one of the dominant problems of AC power system design. In order to understand the theoretical background and problems associated with earthing system design, various international guides were investigated and scrutinised.

This investigation of the theory led to the analysis of general methods and techniques used for earthing system design.

Due to the lack and short supply of human expertise in earthing system design, a computer program was developed on a Personal Computer, to help enhance and distribute the needed expertise.

The purpose of this thesis is to provide a complete, practical and scientific step-by-step guideline to design a safe and effective outdoor AC substation earthing system.

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UITTREKSEL

Beaarding van moderne hoogspanning wisselstroom-substasies, is 'n groot probleem in die ontwerp van hierdie substasies. Ten einde die teoretiese agtergrond en verwante probleme van aardstelselontwerp beter te verstaan, is verskeie internasionale gidse ondersoek en nagevors.

Hierdie ondersoek van die teorie het gelei tot die ontleding van die algemene metodes en tegnieke wat gebruik word vir aardstelselontwerp.

As gevolg van die tekort aan geskikte personeel om die aardstelselontwerp te behartig, is 'n rekenaarprogram ontwikkel op 'n persoonlike rekenaar om die nodige kennis te help versprei en te verbeter.

Die doel van hierdie skripsie is om 'n volledige, praktiese en wetenskaplike gids daar te stel vir die veilige en effektiewe ontwerp van aardstelsels.

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TABLE OF CONTENTS

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ANNEXURES

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ALPHABETICAL LIST OF SYMBOLS USED

α_o = thermal coefficient of resistivity at 0 °C

α_r = thermal coefficient of resistivity at 20 °C

°C = degrees Celsius

A = the area occupied by the ground grid in m^2

AC = Alternating Current

Acon = conductor cross section in mm^2

bf = equivalent radius of a foot in m

Cp = Current projection factor for future system growth

Cs = reduction factor for derating the nominal value of surface layer resistivity

d1 = diameter of grid conductors in m

d2 = diameter of ground rods in m

DC = Direct Current

Df = Decrement factor

dfeet = separation distance of the feet in m

Es = actual step voltage

Estep = maximum allowable step voltage

Etouch = maximum allowable touch voltage

GPR = Ground potential rise

$h^1 = \sqrt{d1h}$ for conductors buried at depth h, or 0,5d1 for conductors at h = 0 (on earth's surface)

H = thickness of the upper layer soil in m

Hz = Hertz (frequency)

h = depth of grid burial in m

hs = thickness of crushed rock surface layer in m

IA = current through the accidental circuit

IB = rms magnitude of the current through the body

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IBody = permissible body current

IG = maximum grid current

Ig = symmetrical ac grid current

Itcap = rms current carrying capacity of conductor in kA

K_1, K_2 = constants related to the geometry of the system

L = the total buried length of conductors (m)

l1 = total length of grid conductors in m

l2 = average length of a ground rod in m

mA = milli-amp

n = number of ground rods placed in area A

p1 = soil resistivity encountered by grid conductors buried at depth h in ohm.m

p2 = soil resistivity from depth H downward in ohm.m

p = earth resistivity in ohm.m

pa = apparent soil resistivity as seen by a ground rod in ohm.m

p_r = the resistivity of the ground conductor at 20 °C in m ohm/cm³

ps = crushed rock resistivity in ohm.m

R_1 = resistance of grid conductors

R_{12} = mutual resistance between the group of grid conductors and group of ground rods

R_2 = resistance of all ground rods (rodbed)

R2Fs = resistance of two feet in series

R2Fp = resistance of two feet in parallel

RA = total effective resistance of the accidental circuit

RB = body resistance

RMfoot = mutual resistance between the feet in ohm

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Rf = footing resistance (resistance of the ground just beneath the feet in ohm)

Rfault = fault resistance in ohm

Rfoot = self resistance of each foot to remote earth in ohm

Rg = substation ground resistance in ohm

SB = empirical constant related to the electric shock energy that can safely be tolerated by 99,5% of all persons without ventricular fibrillation

Sf = current division factor

TCAP = thermal capacity factor in $J/cm^3/°C$

Ta = equivalent system sub transient time constant in seconds

Tb = ambient temperature in °C

tf = fault duration in seconds

Tm = maximum allowable temperature in °C

ts = duration of the current exposure in seconds

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CHAPTER 1

1) INTRODUCTION

1.1) Problem definition

In modern high voltage AC substations, earthing has become one of the dominant problems of AC power system design. This is because earthing forms a significant factor in increasing the reliability of supply service. It helps to provide stability of voltage conditions, preventing excessive voltage leaks during disturbances and also a means of measuring the protection of a substation against lightning.

The Republic of South Africa and especially the Bloemfontein Distributor, has high earth resistivities, dry atmospheric conditions, high lightning densities and relatively high fault currents. All these conditions contribute to a potential disaster if they are not properly taken into the design of the earthing system. It is therefore essential to develop and apply suitable earthing system design procedures for protection of equipment and safety of personnel and the public against dangerous electrical shocks.

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1.2) Purpose of project

The voltage rise during power system faults need to be kept to low levels. It implies that earth resistance's in substations must be kept very low although a low earth resistance is no guarantee of a safe earthing system. There is no simple comparison between the resistance of the earthing system and the maximum shock current to which a person might be exposed. A substation of low earth resistance may be dangerous under some circumstances, while another with very high resistance may be safe or can be made safe by careful design.

Due to the lack and short supply of human expertise in earthing system design, a computer program can help enhance and distribute the needed expertise. The purpose of this paper is to provide a complete guide to design a safe and effective outdoor AC substation earthing system and to provide a computer program to assist with the design process.

1.3) Hypothesis

Currently the substation earthing systems in ESKOM - Bloemfontein Distributor are designed by using designer experience and know-how. A scientific approach to this problem can ensure that all future earthing systems will be able to perform according to Eskom's safety and technical standards. This approach and the computer program will also ensure

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that no earthing system will be over designed, resulting in an uneconomical system. It will also prevent an underdesigned system posing a safety hazard. Furthermore, all existing earthing systems can be evaluated by using the computer program, thus ensuring that the earthing system is within the safety standards. This will ensure that all substation earthing systems in the Bloemfontein Distributor will perform satisfactory under all fault conditions, and will not pose a safety hazard to personnel, the public or equipment.

1.4) <u>Demarcation of study field</u>

This guide will provide a practical and scientific step-by-step guideline to plan and design an outdoor earthing system with special reference to the following aspects:

* Electricity and the human body
* Typical shock situations
* Criteria of permissible potential difference
* Principal design considerations
* Field and physical data
* Calculation of touch, step and mesh voltages
* Design of an AC substation earthing system
* The use of computer analysis in earth mat design.

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1.5) Methods and Techniques

The methods and techniques used to accomplish the above, will mainly centre around the evaluation of existing design guides and standards used internationally. These guides will form the basis of a design procedure for ESKOM Bloemfontein Distributor, which will be adapted to suit our local conditions and requirements.

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CHAPTER 2

2) THEORETICAL BACKGROUND

2.1) Effect of electricity on the human body

To properly design an earthing system for an outdoor high voltage AC substation, it is important to understand the electrical characteristics of the most important part of the accidental ground circuit, the human body. Any definition of lethal exposure to electrical energy must consider the following factors:

- duration and magnitude of fault current and voltage
- frequency of shock current and
- resistance of the human body.

2.1.1) Duration and Magnitude of Fault Current and Voltage

According to the IEC Report (1984:21) the most common physiological effects of electric current passing through the body, stated in order of increasing current magnitude, are perception, muscular contraction, unconsciousness, fibrillation of the heart, respiratory nerve blockage, and burning.

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The magnitude of the electrical current passing through the human body at 50 Hz should be less than those currents that cause ventricular fibrillation.

Two types of shock currents will be considered:

- secondary shock current
- primary shock current

Gönen (1988:192) states that these shock currents can be either steady state or transient in nature. In AC power systems, steady state currents are sustained currents of 50 Hz or its harmonics. The transient currents are capacitive discharge currents whose magnitudes diminish rapidly with time.

- Secondary shock current

Current of >1 mA is generally recognised as the threshold of perception. This can be defined as the current magnitude at which a person is just able to detect a slight tingling sensation in his hands or fingertips caused by the passing current. The threshold of perception depends on several parameters, such as the area of the body in contact with an electrode (contact area), the conditions of contact (dry, wet, pressure, temperature), skin resistance and also on

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physiological characteristics of the involved individual.

Currents of between 1 mA - 6 mA are often termed let-go currents. Although unpleasant to sustain, these currents generally do not prevent the person holding an energised object, from releasing the object. Dalziel's experiment (1956:50) with 28 women and 134 men provides data indicating an average leg-go current of 10.5 mA for women and 15.87 mA for men, and 6 mA and 9 mA as the respective threshold values. The threshold of let-go depends on several parameters, such as the contact area, the shape and size of the electrodes and also on the physiological characteristics of the involved individual.

- Primary shock current

In a 9 mA - 25 mA range, currents may be painful and can make it hard or impossible to release energised objects clutched by the hand.

For still higher currents, muscular contractions could made breathing difficult. These effects are not permanent and disappear when the current is interrupted - unless the contraction is very severe and breathing is stopped. In the event of

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a severe exposure, such cases will often respond to resuscitation.

Current magnitudes in the range of 60 mA - 100 mA cause ventricular fibrillation, stoppage of the heart, or inhibition of respiration. These conditions might cause serious injury or possibly death. The threshold of ventricular fibrillation depends on physiological parameters (anatomy of the body, state of cardiac function etc.) as well as on electrical parameters (duration and pathway of current flow, kind of current, etc.)

The ANSI/IEEE Guide (1986:28) recommends that shock currents be kept below the fibrillation threshold by a carefully designed earthing system.

If shock currents can be kept below the primary shock current by careful earthing system design, injury or death may be avoided. Table 1 on page 84 lists the effect of electrical current on the human body.

The IEC report (1984:21) states that ventricular fibrillation is considered to be the main cause of death by electrical shock. There is also some evidence of death due to asphyxia or cardiac arrest. With currents of several amperes, heavy

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burns resulting in serious injury and even death are likely to occur.

Dalziel also found that the duration for which a 50 Hz current can be tolerated by most people is related to its magnitude by the following equation:

$$IB = k / \sqrt{ts} \qquad \text{(Eq 1)}$$

where

IB = rms magnitude of the current through the body

ts = duration of the current exposure in seconds

$k = \sqrt{SB}$

SB = empirical constant related to the electric shock energy that can safely be tolerated by 99,5% of all persons without ventricular fibrillation.

Dalziel found that fibrillation current is a function of individual body weight. The shock energy that can be survived by 99,5% of persons weighing approximately 50 kg results in a value of SB = 0.0135. More recent studies by Dalziel lead to a value of SB = 0.0246 for persons weighing 70 kg. The formula for the allowable body current becomes:

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$$IB = 0.116 / \sqrt{ts} \text{ for 50 kg body weight} \quad \text{(Eq 2)}$$

and

$$IB = 0.157 / \sqrt{ts} \text{ for 70 kg body weight} \quad \text{(Eq 3)}$$

Since the above equations are based on tests limited to a 0.03 - 3.0 second range, it obviously is not valid for very short or very long exposure times. Some values of current can be tolerated indefinitely. Graph 1 on page 87 shows the fibrillation current versus duration of current exposure for a 70 kg body weight based on the above equations.

The ANSI/IEEE Guide (1986:31) suggests *100 mA* as the fibrillation threshold if shock duration's are not specified. The value of 100 mA was derived from extensive experiments, on animals having body and heart weights comparable to man, for a maximum shock duration of 3.0 seconds.

Similar tests were made by Dalziel on men using direct current and 50 Hz sine wave alternating current to determine let-go potentials. Resistance's at the electrodes greatly affected the results. Only subjects with healthy skin were used. Variations in contact resistance were minimised and severe accident conditions were simulated by having the hands dripping wet or feet standing in salt water. The maximum safe

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let-go potential is established as the let-go potential of 99,5 % of a large group of people.

Current is the proper measure of electric shock intensity, and the hazard from the proposed reasonably safe potentials would be greatly increased if contact occurred at locations where the skin was torn or if local high current densities produced material breakdown of the skin. It was found that currents only slightly in excess of a person's let-go value are very painful, frightening, and hard to endure for even a short time. Failure to interrupt the current promptly is accompanied by a rapid decrease in muscular strength caused by pain and the fatigue associated with the severe involuntary muscular contractions. Prolonged exposure to currents only slightly in excess of a person's let-go limit may produce exhaustion, asphyxia, collapse, and unconsciousness followed by possible death.

2.1.2) Frequency of Shock Current

Humans are very vulnerable to the effects of electric current at frequencies of 50 Hz. Authorities generally agree that the human body can tolerate a slightly higher current at 25 Hz and approximately five times higher direct current according to the ANSI/IEEE Guide (1986:27). At frequencies of between 3000 Hz and

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10 000 Hz, even higher currents can be tolerated. In some cases the human body was able to tolerate very high currents from lightning surges; in the order of several hundred amperes.

2.1.3) Resistance of the Human Body

The IEC report (1984:9) states that the different parts of the human body - such as the skin, blood, muscles, other tissues and joints - present to the electric current a certain impedance composed of resistive and capacitive components. The values of these impedance's depend on a certain number of factors and, in particular; on the current path, on the touch voltage, the duration of current flow, the frequency, the degree of moisture of the skin, the surface area of contact, the pressure exerted and the temperature.

The ANSI/IEEE Guide (1986:35) suggest that the human body can be represented by a non inductive resistance for DC and AC at normal power frequency. The resistance is between extremities, that is, from one hand to both feet, or from one foot to the other one. The ANSI/IEEE Guide assumes the following:

- Hand and shoe contact resistance's will be assumed as equal to zero

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* A value of *1000 ohm* is selected as representing the resistance of a human body from hand to both feet and also from hand to hand, or from one foot to the other foot.

It should be remembered that the choice of 1000 ohm resistance value relates to paths such as those between the hand and one or both feet, where a major part of the current passes through parts of the body containing vital organs, including the heart. It is generally agreed that current flowing from one foot to the other is far less dangerous.

However, a voltage between the two feet, painful but not fatal, might result in a fall that could cause a current flow through the chest area. The degree of this danger would further depend on the fault duration and the possibility of another, successive fault - perhaps on reclosure.

Using the value of tolerable body current and the appropriate circuit constants, it is possible to determine the tolerable voltage between any two critical points of contact.

Let it be noted that for the accidental circuit equivalent, the following notation applies:

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IA = current through the accidental circuit

RA = total effective resistance of the accidental circuit

IBody = permissible body current

The ANSI/IEEE Guide (1986:36) states that:

IA < IBody is always required for safety.

Since the body resistance is assumed constant, to require IA smaller than IBody, is equivalent to saying that fibrillation may be prevented by keeping the total watts - seconds (Ws) of energy absorbed in the body during a shock below a certain value.

This value is 0.0135 Ws for k (50 kg) = 0.116 A, and 0.0246 Ws for k (70 kg) = 0.157 A, respectively. Thus, it can be seen that Dalziel's formula actually represents the relationship between shock current magnitude and duration for a constant shock energy.

Resistance of the accidental circuit RA is a function of the body resistance, RB and the footing resistance Rf (resistance of the ground just beneath the feet). The footing resistance may affect appreciably the value of RA, a fact that may be most helpful in some difficult situations. For the purposes of circuit

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analysis, the human foot is usually represented as a conducting metallic disk and the contact resistance of shoes and socks is neglected. The self and mutual resistance's for two metallic disks of radius b, separated by a distance df on the surface of a homogeneous earth of resistivity p, are:

$$Rfoot = p / 4bf \qquad \text{(Eq 4)}$$

and

$$Rmfoot = p / (2\pi dfeet) \qquad \text{(Eq 5)}$$

where

Rfoot = self resistance of each foot to remote earth in ohm

RMfoot = mutual resistance between the feet in ohm

bf = equivalent radius of a foot in m

dfeet = separation distance of the feet in m

The resistance's of the ground beneath the two feet in series and in parallel are:

$$R2Fs = 2(Rfoot - RMfoot) \qquad \text{(Eq 6)}$$

and

$$R2Fp = \tfrac{1}{2}(Rfoot + RMfoot) \qquad \text{(Eq 7)}$$

where, in addition to the symbols described before,

R2Fs = resistance of two feet in series

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R2Fp = resistance of two feet in parallel

Figure 1 on page 89 defines the circuit equivalent of a foot to foot contact. Here the potential U, shunted by the body, is the maximum potential difference between two accessible points on the ground surface, separated by the distance of one pace. The equivalent circuit resistance for the step potential circuit is given by the following equation:

$$Ra = Rb + 2(Rfoot - RMfoot) \qquad \text{(Eq 8)}$$

Next the equivalent circuit for a hand to two feet contact is illustrated in Figure 2 on page 89. The equivalent circuit resistance for the touch potential circuit is given by the following equation:

$$Ra = Rb + \tfrac{1}{2}(Rfoot + RMfoot) \qquad \text{(Eq 9)}$$

With only slight approximation, equations for the series and parallel resistance's of two feet can be obtained in numerical form and expressed in terms of p, as shown below:

$$R2Fs = 6(p) \qquad \text{(Eq 10)}$$

and

$$R2Fp = 1\tfrac{1}{2}(p) \qquad \text{(Eq 11)}$$

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The ANSI/IEEE Guide (1986:38) states that for all practical purposes, the resistance of a foot is equal to 3p. Equation 8 is used when computing the body current resulting from step voltages and equation 9 applies when calculating the body current produced by a mesh or touch potential with both feet buried at zero depth in the soil near the surface.

For example, if p = 2000 ohm.m, equations 10 and 11 yield 12 000 and 3 000 ohm for the series and parallel resistance's, respectively.

A more exact calculation of the self and mutual resistance's using 1 m separation yields R2Fs = 11863 ohm and R2Fp = 3284 ohm. Use of a value of dfoot = 1 m is conservative in calculating R2Fs. Though it might produce a slightly higher value of resistance than would a smaller separation between the feet, the resulting step voltage also is much higher with a larger separation than it would be with a smaller one, and that would be the dominant effect on body current.

The large separation is also conservative in computing R2Fp because it produces a lower resistance than a small separation would.

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The large separation is also conservative in computing R2Fp because it produces a lower resistance than a small separation would.

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2.2) <u>Typical shock situations</u>

When a fault current flows through an earth electrode, the potential of the electrode is raised with respect to remote earth. The earth surrounding the electrode is also raised to a potential which decreases exponentially with distance from the electrode.

The voltage rise of the electrode constitutes a danger to human life when these potential field lines are bridged by the extremities of the body. The manner in which this may be done is defined as follows: (Refer to Figure 3 on page 90).

2.2.1) Touch Potential

The potential difference between the ground rise and the surface potential at the point where a person is standing, while at the same time having his hands in contact with a grounded structure.

2.2.2) Step Potential

The difference in surface potential experienced by a person bridging a distance of 1 m with his feet without contacting any other grounded object.

2.2.3) Transfer Potential

A special case of the touch voltage where a voltage is transferred into or out of the

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substation. Typically, the case of transferred voltage occurs when a person standing within the station area touches a conductor grounded at a remote point or a person standing at a remote point touches a conductor connected to the substation grounding grid.

2.3) Criteria of permissible potential difference

Under normal conditions, the grounded electrical equipment operates at near zero ground potential, that is, the potential of a grounded neutral conductor is nearly identical to the potential of remote earth. During a ground fault, the portion of fault current that is conducted by a station grounding grid into the earth causes a rise of the grid potential with respect to remote earth. This voltage rise, is proportional to the magnitude of the grid current, and to the grid resistance.

The ANSI/IEEE Guide (1986:46) states that the safety of a person depends on preventing the critical amount of shock energy from being absorbed before the fault is cleared and the system de-energised. The maximum driving voltage of any accidental circuit should not exceed the limits defined below. For step voltage the limit is:

$$Estep = (RB + R2Fs)IB \qquad \text{(Eq 12)}$$

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The actual step voltage, Es, should be less than the maximum allowable step voltage, Estep, to ensure safety.

Similarly, the touch voltage limit is:

$$E_{touch} = (R_B + R_{2Fp})I_B \qquad \text{(Eq 13)}$$

With some modification to equations 12 and 13:

$$E_{step_n} = (1000 + 6C_s(h_s, K)\rho_s)n / \sqrt{t_s} \qquad \text{(Eq 14)}$$

and

$$E_{touch_n} = (1000 + 1.5C_s(h_s, K)\rho_s)n / \sqrt{t_s} \qquad \text{(Eq 15)}$$

where, in addition to the symbols described before,

E_{step_n} = step voltage for either 50 or 70 kg body weight

n = either 0.116 for 50 kg or 0.157 for 70 kg

E_{touch_n} = touch voltage for either 50 or 70 kg body weight

Cs = reduction factor for derating the nominal value of surface layer resistivity

and

$$K = (\rho - \rho_s) / (\rho + \rho_s) \qquad \text{(Eq 16)}$$

where

p = earth resistivity in ohm.m

ps = crushed rock resistivity in ohm.m

hs = thickness of crushed rock surface layer in m and

ts = duration of shock current in seconds.

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The actual touch voltage, mesh voltage, or transferred voltage should be less than the maximum allowable touch voltage, Etouch, to ensure safety.

2.4) Evaluation of ground resistance

According to the ANSI/IEEE Guide (1986:81) an ideal earthing system should provide a near zero resistance to remote earth. In practice, the ground potential rise (GPR) at the station site increases proportionally to the fault current; the higher the current, the lower value of a total system resistance thus has to be obtained. For most transmission and other large substations, the ground resistance should be about *1 ohm* or less. In smaller distribution substations the usually acceptable range is from *1 - 5 ohm*, depending on the local conditions.

2.4.1) Simplified Calculations

Estimation of the total resistance to remote ground is one of the first steps in determining the size and basic layout of a grounding system. At first glance this may appear difficult: the grounding system is not yet designed and so its resistance, depending on the design, is unknown. Fortunately, the station resistance depends primarily on the area to be occupied by the ground system, which is usually known in the early design stage.

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Thus, as a first approximation, a minimum value of the substation grounding resistance in uniform soil can be estimated by means of the formula of a circular metal plate at zero depth once the soil resistivity has been determined; so according to the ANSI/IEEE Guide (1986:81):

$$Rg = p / 4\sqrt{p / A} \qquad \text{(Eq 17)}$$

where

Rg = station ground resistance in ohm

p = average earth resistivity in ohm.m

A = the area occupied by the ground grid in m^2.

This equation should be used only when a value of substation resistance is desired for estimating the maximum fault current.

Next, an upper limit of the substation resistivity can be obtained by adding a second term to the above formula:

$$Rg = p / 4\sqrt{\pi / A} + p / L \qquad \text{(Eq 18)}$$

where L is the total buried length of conductors

The second term recognises the fact that the resistance of any actual grounding system that consists of a number of conductors is higher than

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that of a solid metallic plate, and that the difference will decrease with the increasing length of buried conductors, approaching 0 for infinite L, when the condition of a solid plate is reached.

Equations 17 and 18 can be used with reasonable accuracy for grid depths less than 0.25 m. For grid depths between 0.25 and 2.5 m, correction for the grid depth is required:

$$Rg = p\left[(1/L)+\left(1/\sqrt{20A}\right)*\left(1+\left(1/1+h\sqrt{20/A}\right)\right)\right] \qquad \text{(Eq 19)}$$

where h is the depth of the grid in m.

Equations 18 and 19 should be helpful in estimating the substation ground potential rise for a preliminary design evaluation, to determine the approximate length of buried conductors needed for control of the step and touch voltages.

2.4.2) Schwarz's Formula

The ANSI/IEEE Guide (1986:83) states that the total resistance of a system consisting of a combination of horizontal (grid) and vertical (rods) electrodes is lower than the resistance of either component alone, but still higher than

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that of their parallel combination. The total resistance is:

$$Rg = (R_1R_2 - R^2_{12}) / (R_1 + R_2 - 2R_{12}) \quad \text{(Eq 20)}$$

where

R_1 = resistance of grid conductors

R_2 = resistance of all ground rods (rodbed)

R_{12} = mutual resistance between the group of grid conductors and group of ground rods

This formula, developed by Schwarz gives a set of convenient formulas, defining the resistances in terms of the basic design parameters assuming multi layer soil conditions.

$$R_1 = \left(\frac{p1}{p l1}\right)\left(\ln\left(\frac{2l1}{h^1}\right) + K_1\left(\frac{l1}{\sqrt{A}}\right) - K_2\right) \quad \text{(Eq 21)}$$

$$R_2 = \left(\frac{pa}{2n\pi l2}\right)\left[\ln\left(\frac{8l2}{d2}\right) - 1 + 2K_1\left(\frac{l2}{\sqrt{A}}\right)\left(\sqrt{n} - 1\right)^2\right] \quad \text{(Eq 22)}$$

$$R_{12} = \left(\frac{pa}{\pi l1}\right)\left[\ln\left(\frac{2l1}{l2}\right) + K_1\left(\frac{l1}{\sqrt{A}}\right) - K_2 + 1\right] \quad \text{(Eq 23)}$$

where

p1 = soil resistivity encountered by grid conductors buried at depth h in ohm.m

pa = apparent soil resistivity as seen by a ground rod in ohm.m

H = thickness of the upper layer soil in m

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$p2$ = soil resistivity from depth H downward in ohm.m

$l1$ = total length of grid conductors in m

$l2$ = average length of a ground rod in m

h = depth of grid burial in m

$h^1 = \sqrt{d1h}$ for conductors buried at depth h, or $0,5d1$ for conductors at $h = 0$ (on earth's surface)

A = area covered by a grid of dimensions a x b in m^2

a = short side grid length in m

b = long side length in m

n = number of ground rods placed in area A

K_1, K_2 = constants related to the geometry of the system

$d1$ = diameter of grid conductor in m

$d2$ = diameter of ground rods in m

The preceding three equations are also valid for a two layer soil environment, with upper layer thickness H, in which ground rods penetrate the more conductive lower layer. In such a case, that is for $p1 > p2$, where the grid is buried in the upper layer of resistivity p1, but the ground rods are partly in p1, and partly in p2, R_2 and R_{12} are calculated with the use of an apparent soil resistivity seen by the ground rods, pa, defined as follows:

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$$p_a = l_2(p_1 p_2)(p_2 H + p_1(l_2 - H)) \qquad \text{(Eq 24)}$$

For the more usual case of the rod's top being in the same depth as the grid,

$$p_a = l_2(p_1 p_2) \,/\, (p_2(H - h) + p_1(l_2 + h - H)) \qquad \text{(Eq 25)}$$

For uniform soils, p2 = p1.

If the difference between p1 and p2 is not too great (preferably p2 not lower than 0.2 p1), and the first layer thickness H is at least 0.1 b, the resulting equations are reasonably accurate for most practical calculations and relatively easy to use. Moreover, the ability to work with separate expressions for a grid and a set of rods becomes advantageous in simplified calculations.

A slight problem with the application of these equations was that the factors (coefficients) K_1 and K_2 had been originally presented by Schwarz only in a graphical form.

However, given the near linear character of these curves, it is possible to use a linearised form of y = px + q to obtain K_1 and K_2 within the range of values shown in Figures 4 and 5 on page 91;

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or to linearly interpolate between several points taken from the original curve.

2.4.3) Resistance of grounding system

For the final design, more accurate estimates of the resistance may be desired, especially when ground rods are used to reach more conductive subsoil's. For this application, Equations 21, 22 and 23 on page 24 may be utilised to include the effects of two different soil resistivities in computing the grid resistance and the rodbed resistance. Computer analysis based on modelling the components of the grounding system in detail can compute the resistance with a high degree of accuracy, assuming the soil model is chosen correctly.

2.5) Principal design considerations

2.5.1) General Concept

Any grounding system should be installed in such a manner that it will limit the effect of ground potential gradients and assure continuity of service. The grounding system should limit the voltage and current levels so as not to endanger people or equipment under normal and fault conditions.

It is assumed that the system of ground electrodes has the form of a grid of horizontally

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buried conductors, supplemented by a number of vertical ground rods connected to the grid. (Refer to Figure 6 on page 92)

Some of the reasons for using the combined system of vertical rods and horizontal conductors are as follows:

- In substations a single electrode is, by itself, inadequate in providing a safe grounding system. In turn, when several electrodes, such as ground rods, are connected to each other and to all equipment neutrals, frames, and structures that are to be grounded, the result is, essentially a grid arrangement of ground electrodes, regardless of the original objective. If the connecting links happen to be buried in a soil of good conductivity, this network alone may represent an excellent grounding system. Partly for this reason, it is possible to depend on the use of a grid alone. However, ground rods are of a particular value, as explained next.

- If the magnitude of current dissipated into the earth is high, it seldom is possible to install a grid with resistance so low as to assure that the rise of a ground potential will not generate surface gradients unsafe for human

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contact. Then, the hazard can be eliminated only by control of local potentials through the entire area. A system that combines a horizontal grid and a number of vertical ground rods penetrating lower soils has the following advantages:

- While horizontal (grid) conductors are most effective in reducing the danger of high step and touch voltages on the earth's surface, provided that the grid is installed in a shallow depth usually 0.3 - 0.5 m below the surface, sufficiently long ground rods will stabilise the performance of such a combined system. For many installations this is important - because of freezing or drying out, the resistivity of upper soil layers could vary with seasons, while the resistivity of lower soil layers remains nearly constant.

- Rods penetrating the lower resistivity soil are far more effective in dissipating fault currents whenever a two- or multilayer soil is encountered and the upper soil layer has higher resistivity than the lower layers.

- If the rods are installed predominantly along the grid perimeter in high-to-low or uniform soil conditions, the rods will considerably

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moderate the steep increase of the surface gradient near the peripheral meshes.

2.5.2) Basic Aspects of Grid Design

The conceptual analysis of a earthing system usually starts with inspection of the station layout plan, showing all major equipment and structures. In order to establish the basic ideas and concepts, the ANSI/IEEE Guide suggests that the following points may serve as guidelines for starting a typical grounding grid design:

- A continuous conductor loop should surround the perimeter to enclose as much area as practical. This measure helps to avoid high current concentration and hence high gradients both in the grid area and near the projecting cable ends. Enclosing more area also reduces the resistance of the grounding grid.

- Within the loop, conductors should be laid in parallel lines and, where practical, along the structures or rows of equipment. This will ensure short and effective connections from the equipment structures to the grid.

- A typical grid system for a substation may include bare copper conductors buried 0.3 - 1.5 m below the surface, spaced 3 - 7 m apart, in a

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grid pattern. At cross-connections, the conductors would be securely bonded together by means of welded, bolted, brazed or pressure type joints. Ground rods may be installed at the grid corners and at each second junction point along the perimeter. Ground rods may also be installed at major equipment. In multilayer or very resistive soils, it might be useful to use longer rods.

- This grid system would be extended over the entire substation switchyard and often beyond the fence line (to avoid dangerous step and touch voltages developing when touching the fence from the outside of the substation). Multiple ground leads or larger sized conductors would be used where high concentrations of current may occur, such as at a neutral-to-ground connection of generators, capacitor banks, or transformers.

- The ratio of the sides of the mesh usually is from 1:1 to 1:3. Frequent cross-connections have a relatively small effect on lowering the resistance of a grid. Their primary role is to assure adequate control of the surface potentials. The cross-connections are also useful in securing multiple paths for the fault current, minimising the voltage drop in the

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grid itself, and providing a certain measure of redundancy in the case of a conductor failure.

2.5.3) Design in Difficult Conditions

In areas where the soil resistivity is rather high or the substation space is at a premium, it may not be possible to obtain a low impedance grounding system by spreading the grid electrodes over a large area, as is done in more favourable conditions.

This often makes the control of surface gradients difficult. Some of the suggested solutions include:

- Connection(s) of remote ground grid(s) and adjacent grounding facilities; a combined system utilising separate installations in buildings, underground pipework, etc. A predominant use of remote ground electrodes requires careful consideration of transferred potentials, surge arrester locations, and other critical points. A significant voltage drop may develop between the local and remote grounding facilities.

- Use of deep-driven ground rods and drilled ground wells, in combinations with a chemical treatment of soils, or use of bentonite clays

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for backfilling. The chemical treatment and the use of clay reduces the resistance of the soil.

- Use of counterpoise wire mats. In exposed areas, it is feasible to combine both an insulating material and fabricated mats made of wire mesh, expanded metal, or gratings; first to equalise the gradient field near the surface and then to reduce conductance from the surface to the underlying metal structures.

- Where feasible, controlled use of other available means to lower the overall resistance of a ground system, such a connecting static wires and neutrals to the ground. Typical is the use of metallic objects on the site that qualify for and can serve as auxiliary ground electrodes or as ground ties to other systems. Consequences of such applications, of course, have to be carefully evaluated.

- Wherever practical, a nearby deposit of low resistivity material of sufficient volume can be used to install an extra (satellite) grid. This satellite grid, when sufficiently connected to the main grid, will lower the overall resistance and, thus, the ground potential rise of the grounding grid. The

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nearby low resistivity material may be a clay deposit or it may be a part of some large structure, such as the concrete mass of a hydroelectric dam.

2.5.4) Connections to Grid

Conductors of adequate current carrying capacity and mechanical strength should be used for the connections between:

- All ground electrodes, such as grounding grids, rodbeds, ground wells, and where applicable, metal, water, or gas pipes, water well casings etc.

- All above-ground conductive metal parts that might accidentally become energised, such as metal structures, machine frames, metal housings of conventional or gas-insulated switch gear, transformer tanks, guards etc.

- All fault current sources such as surge arresters, capacitor banks or coupling capacitors, transformers and where appropriate, machine neutrals, secondary lighting, and power circuits.

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Copper cables or straps are usually employed for these ground connections. However, transformer tanks are sometimes used as part of a ground path for surge arresters mounted on the outside of the transformer. Similarly, most steel or aluminium structures may be used for the ground path if it can be established that their conductance, including that of any joints, is and can be maintained as equivalent to that of the conductor that would normally be installed.

All accessible ground leads should be inspected on a periodic basis. Exothermic weld, brazed, or pressure type connectors can be used for underground connections. Soldered connections shall be avoided because of the possibility of failure under high fault currents.

Open circuits, even in exposed locations, can escape detection and it obviously is impractical to inspect buried portions of the grounding network once it is installed. Those facilities that are most likely to supply or carry a high current, such as transformer and circuit breaker tanks, switch frames, and arrester pads, should always be connected to the grid with more than one earth lead. The leads should preferably be

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run in opposite directions to eliminate common mode failure.

One possible exception in grounding of the secondary is that of potential and current transformers. The grounding of such devices usually must be restricted to a single point to avoid any parallel path that could cause undesirable circulation of currents affecting the performance of relays and metering devices.

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CHAPTER 3

3) METHODS AND TECHNIQUES

3.1) Design Criteria

Unless proper precautions are taken in grounding system design, the maximum potential gradients along the earth surface may be of sufficient magnitude during ground fault conditions to endanger a person in the area. Dangerous potential differences may develop between structures or equipment frames that are grounded and the nearby earth.

The circumstances that make electric shock accidents possible are:

- Relatively high fault current to ground in relation to the area of ground system and its resistance to remote earth.

- Soil resistivity and distribution of ground currents such that high potential gradients may occur at points at the earth's surface.

- Presence of a person at such a point, time and position that the body is bringing two points of high potential difference.

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- Absence of sufficient contact resistance or other resistance to limit current through the body to a safe value under the above circumstances.

- Duration of the flow of current through a human body for a sufficient time to cause harm at the given current magnitude.

There are two main design goals to be achieved by any substation ground system under normal as well as fault conditions. These are (1) to provide means to dissipate electrical currents into the earth without exceeding any operating and equipment limits, and (2) to assure that a person in the vicinity of grounded facilities is not exposed to the danger of critical electric shock.

The design procedures described next are aimed at achieving safety from dangerous step and touch voltages within a substation. It should be remembered that it is possible for transferred potentials to exceed the ground potential rise (GPR) of the substation during fault conditions. The design procedure described here is based on assuring safety from dangerous step and touch voltages within, and immediately outside, the substation fenced area. Since the mesh voltage is the worst possible touch voltage, inside the substation (excluding transferred

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potentials), the mesh voltage will be used as the basis of this design procedure.

Step voltages are inherently less dangerous than mesh voltages. If, however, safety within the grounded area is achieved with the assistance of a high resistivity surface layer (crushed rock) which does not extend outside the fence, then step voltages may be dangerous. In any event, the computed step voltages should be compared with the permissible step voltage after a grid has been designed - to the satisfaction of the touch voltage criterion.

For equally or near equally spaced ground grids, the mesh voltage will increase along meshes from the centre to the corner of the grid. The rate of this increase will depend on the size of the grid, number and location of ground rods, spacing of parallel conductors, diameter and depth of the conductors and the resistivity profile of the soil.

The following site-dependent parameters have substantial impact on the grid design:

- maximum grid current
- fault duration
- shock duration
- earth resistivity
- high resistivity surface material
- and grid geometry.

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Several parameters define the geometry of the grid, but the area of the grounding system, the conductor spacing, and the depth of the ground grid have the most impact on the mesh voltage, while parameters such as the conductor diameter and the thickness of the surfacing material have less impact.

3.2) <u>Maximum Grid Current (IG)</u>

The evaluation of the maximum design value of ground fault current that flows through the substation grounding grid into the earth, should include the following considerations:

- the resistance of the ground grid
- division of the ground fault current between the alternate return paths and the grid
- the decrement factor (to allow for the effects of asymmetry of the fault current wave) and
- the possible future expansion of the power system.

The following steps are involved in determining the correct design value of maximum grid current for use in substation grounding calculations:

Step (a)

Assess the type and location of those ground faults that are likely to produce the greatest flow of current between the grounding grid and surrounding earth, and hence the greatest rise in grid potential

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with respect to remote earth (GPR) and largest local surface potential gradients in the substation area.

Step (b)

Determine, by computation, the fault current division factor Sf for each of the faults selected in Step (a) and establish the corresponding values of symmetrical grid current Ig.

Step (c)

For each fault, based on its duration time tf, determine the value of decrement factor, Df, to allow for the effects of asymmetry of the fault current wave.

Step (d)

Select the largest product Df.Ig, and hence the worst fault condition, and establish the value of a projection factor Cp to obtain the margin for the future system growth.

3.2.1) Worst Fault Type and Location - Step (a)

The worst fault type for a given grounding system is the one resulting in the highest value of the maximum grid current IG. Since this current is proportional to the zero-sequence current and the current division factor, and since the current division is almost independent of the fault type, the worst fault type can be defined as the one

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resulting in the highest zero-sequence current flow into the earth.

Many different types of faults may occur in the system. Unfortunately, it may be difficult to determine which fault type and location will result in the greatest flow of current between the ground grid and surrounding earth since no simple rule applies.

In determining the applicable fault types, consideration should be given to the probability of occurrence of the fault. Multiple simultaneous faults, even though they may result in higher ground current, should not be considered if their probability of occurrence is negligible. It is thus recommended, for practical reasons, that investigation be confined to single line to ground and line to line to ground faults.

The question of the fault location producing the maximum grid current IG, involves several considerations. The worst fault location may be either on the high voltage side or on the low voltage side, and in either case may be either inside the station or outside on a line, at a certain distance from the station. (A fault is classified as inside the station if it is related

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to a metallic structure that is electrically connected to the substation grounding grid via negligible impedance.) There are no universal rules for the determination of the worst fault location. The following discussion relates to some, but by no means all, possibilities.

For distribution substations with the transformer grounded only on the distribution side, the worst fault location for IG usually occurs on the high voltage side of the transformer. However, if the source of ground fault current on the high side is weak, or if a parallel operation of several transformers results in a strong ground fault current source on the low side, the worst fault location may be found somewhere on the distribution circuit.

For faults on the low voltage side of such a secondary grounded transformer, the transformer's contribution to the fault circulates in the station grid conductor with negligible leakage current into the earth and, thus, has no effect in the substation ground potential rise (GPR).

For faults outside the substation on a distribution feeder (far enough to be at remote earth with respect to the ground grid), a large portion of the fault current will return to its

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to a metallic structure that is electrically connected to the substation grounding grid via negligible impedance.) There are no universal rules for the determination of the worst fault location. The following discussion relates to some, but by no means all, possibilities.

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For faults on the low voltage side of such a secondary grounded transformer, the transformer's contribution to the fault circulates in the station grid conductor with negligible leakage current into the earth and, thus, has no effect in the substation ground potential rise (GPR).

For faults outside the substation on a distribution feeder (far enough to be at remote earth with respect to the ground grid), a large portion of the fault current will return to its

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source (that is, the transformer neutral) via the station grid, thus contributing to the substation GPR.

In transmission substations with three-winding transformers or auto transformers, the problem is more complex. The worst fault location for IG may occur on either the high or low voltage side of the transformer, both locations should be checked. In either case, it can be assumed that the worst fault location is at the terminals of the transformer inside the substation, if the system contribution to the fault current is larger than that of the transformers in the substation. Conversely, the worst fault location may be outside the substation on a transmission line, if the transformer contribution dominates.

Exceptions to the above generalities exist. Therefore, for a specific system, several candidates for the worst fault location should be considered. For each candidate, the applicable value of zero-sequence current Io should be established in this step.

3.2.2) Computation of Current Division - Step (b)

For the assumption of a sustained flow of the initial zero-sequence current the symmetrical grid current can be expressed as:

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$$I_g = S_f(3I_o) \quad \text{(Eq 26)}$$

where

S_f = Current division factor and

$3I_o$ = Symmetrical fault current in substation

To determine I_g, the current division factor S_f must be computed.

The process of computing consists of deriving an equivalent representation of the overhead ground wires, neutrals, etc., connected to the grid and then solving the equivalent to determine what fraction of the total fault current flows between the grid and earth, and what fraction flows through the ground wires or neutrals. S_f is dependent on many parameters, some of which are:

- Location of the fault
- Magnitude of station ground grid resistance
- Buried pipes and cables in the vicinity of or directly connected to, or both, the station ground system
- Overhead ground wires, neutrals, or other ground return paths

Because of S_f, the symmetrical grid current I_g, and therefore also I_G, are closely related to the location of the fault. If the additional ground

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paths of the last two items above are neglected, the current division ratio can be computed using traditional symmetrical components. However, the current Ig computed using such a method may be overly pessimistic, even if the future system expansion is taken into consideration.

Since overhead transmission lines are present at most substations, the remaining discussion refers only to overhead ground wires and neutral conductors, although the principles involved also apply to buried pipes, cables or any other conduction path connected to the grid.

High voltage transmission lines are commonly provided with overhead static wires, either throughout their length or for short distances from each substation as discussed in the SABS Code 0199-1985 (1985:79). They may be grounded at each tower along the line or they may be insulated from the towers.

Where transmission line overhead ground wires or neutral conductors are connected to the station ground, they divert a substantial portion of the ground currents away from the station ground grid. Where this situation exists, the overhead ground wires or neutral conductors can be taken

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into consideration in the design of the ground grid.

It should be realised that connecting the station ground to overhead ground wires or neutral conductors, or both, and through them to transmission line towers, will usually have the overall effect of increasing the hazard at tower bases, while lessening it at the substation. This is due to the fact that each of the nearby towers will share in each voltage rise of the substation ground mat whatever the cause, instead of being affected only by a local insulation failure or flashover at one of the towers. Conversely, when such a tower fault does occur, the effect of the connected station ground system should decrease the magnitude of gradients near the tower bases.

3.2.3) Effect of Asymmetry - Step (c)

The maximum grid current, IG, is the maximum asymmetrical ac current that will flow between the grounding grid and surrounding earth. This asymmetrical current, includes the symmetrical ac current, Ig, as well as a correction for a dc component. The dc component decays exponentially and is known as the dc offset current. Since the design of a grounding grid must consider the asymmetrical current, a *decrement factor, Df,*

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will be derived to take into account the effect of dc current offset.

The decrement factor Df is determined by the following:

$$Df = \sqrt{1 + Ta / tf\left(1 - e^{-tf/Ta}\right)} \qquad \text{(Eq 27)}$$

where

tf = fault duration in s

Ta = equivalent system sub transient time constant in seconds.

For relatively long fault duration's, the effect of the dc offset current can be assumed to be more than compensated by the decay of the sub transient component of ac current. A decrement factor of 1.0 is, therefore, conservative for fault duration's of 30 cycles or more.

For closely spaced successive shocks (possibly from reclosures), the preceding discussion of the symmetrical fault current decrement factor suggests that the use of the shortest fault duration in conjunction with the longest shock duration, or sum of the shock duration's, may result in an over-designed grounding system. This is especially true for faults of intermediate duration (that is, 6 - 30 cycles),

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where the decrement factor is relatively large and the ac component of current is assumed to remain at its sub transient value.

3.2.4) Effect of Future Changes - Step (d)

It is a common experience for maximum fault currents at a given location to increase as system capacity is added or new connections are made to the grid. While an increase in system capacity will increase the maximum expected fault current, new connections may increase or decrease the maximum grid current IG. One case in which the grid current may decrease with new connections is when new transmission lines are added with ground or neutral wires, or both. In general, if no margin for increase in IG is included in the original ground system design, the design may become unsafe. Also, subsequent additions will usually be much less convenient and more expensive to install. Allowance for an increase in IG can be made by decreasing the value of system impedance used in the calculations; or simply by multiplying the value of calculated fault current by an appropriate factor, Cp (current projection factor for future system growth); Cp > 1. It has been a widely accepted practice to assume the total fault current, between the grid and surrounding earth (that is, ignoring any current division) in an

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attempt to allow for system growth. While this assumption would be overly pessimistic for present year conditions, it may not exceed the current IG computed considering current division and system growth. If the system growth is taken into account and current division is ignored, the resulting grid will be over designed. An estimate of the future system conditions could then be obtained by including all system additions forecasted.

Caution should be exercised when future changes involve such design changes as disconnection of overhead ground wires coming into the substations. Such changes may have an effect on ground fault currents, resulting in an inadequate grounding system. However, future changes such as additions of incoming overhead ground wires may decrease the current division ratio, resulting in the existing ground system being, in effect, over designed.

3.2.5) Effect of Substation Ground Resistance

In the great majority of cases it is sufficient to derive the maximum grid current IG, by neglecting the system resistance, the station ground resistance, and the resistance at the fault. The error thus introduced is usually small, and is always on the side of safety.

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However, there may be unusual cases where the predicted station ground resistance is so large, in relation to system reactance, that it is worthwhile to take the resistance into account. This poses a problem since the station ground system is not yet designed and its resistance is not known. However, the resistance can be estimated by the use of the approximate formulas. (Refer to Equations 17 to 20 on page 22,23 and 24). This estimated resistance generally gives sufficient accuracy for determining the current Ig and hence IG.

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3.2.6) Effect of Fault Resistance

If the fault is an insulation breakdown within the local station, the only safe assumption is that the resistance of the fault be assumed zero.

In the case of a fault outside of the local station area, on a line connected to the station bus, it is permissible, if a conservative minimum value of fault resistance, Rfault, can be assigned, to use this in the ground fault current calculations. If, however, the actual fault resistance does not maintain a value at least as great as the value of Rfault used in the calculations, then the fault resistance should be

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neglected. Any error from neglecting Rfault will, of course, be on the side of safety.

3.3) <u>**Fault Duration (tf) and Shock Duration (ts)**</u>

The fault duration and shock duration are normally assumed equal, unless the fault duration is the sum of successive shocks, such as from reclosures. The selection of tf should reflect fast clearing time for transmission substations and slow clearing times for distribution and industrial substations. The choices tf and ts should result in the most pessimistic combination of fault current decrement factor and allowable body current. Typical values for tf and ts range from 0.25 - 2.0s.

3.3.1) Importance of High-Speed Fault Clearing

Considering the significance of fault duration (tf) as an accident-exposure factor, high speed clearing of ground faults are advantageous for two reasons:

- The probability of electric shock is greatly reduced by fast fault clearing time, in contrast to situations in which fault currents could persist for several minutes or possibly hours.

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- Both tests and experience show that the chance of severe injury or death is greatly reduced if the duration of a current flow through the body is very brief; the allowed current value may therefore be based on the clearing time of primary protective devices, or that of the back-up protection.

A good case could be made for the use of primary protection devices because of the low combined probability that relay malfunctions will coincide with all other adverse factors necessary for an accident as described in paragraph 3.1 on page 37.

If the probabilistic aspects are neglected, choice of the backup relay clearing times are more conservative since it assures greater safety margins.

An additional incentive to use switching times less than 0.5 seconds results from the evidence that a human heart becomes increasingly susceptible to ventricular fibrillation when the time of exposure to current is approaching the heartbeat period, but that the danger is much smaller if the time of exposure to current is in the region of 0.06 - 0.3 seconds.

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In reality, high ground gradients from faults are usually infrequent, and shocks from this cause still more so. Furthermore, both events are often of very short duration. Thus, it would not be practical to design against shocks that are merely painful and cause no serious injury, that is, for currents below the fibrillation threshold.

3.3.2) Reclosing

Reclosure after a ground fault is common in modern operating practice. In such circumstances, a person might be subjected to the first shock, which would not permanently injure him, but would upset and disturb him temporarily. Next, a single fast automatic reclosure could result in a second shock, initiated within less than 0.5 seconds from the start of the first. It is this second shock, occurring after a relatively short interval of time before the person has recovered, that might cause a serious accident. With manual reclosure, the possibility of exposure to a second shock is reduced since the reclosing time interval may be substantially greater.

The cumulative effect of two or more closely spaced shocks has not been thoroughly evaluated, but a reasonable allowance can be made by using

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the sum of individual shock duration's as the time of a single exposure.

3.4) <u>Soil Resistivity</u>

The grid resistance and the voltage gradients within a substation are directly dependent on the soil resistivity. Since in reality soil resistivity will vary horizontally as well as vertically, sufficient data must be gathered for a substation yard. Various techniques are described in the literature. Some of the more commonly used techniques, as described by Tagg (1964:22 & 42), are: the Wenner and Schlumberger sounding curve techniques to measure the soil resistivity. The Schlumberger array is the method favoured by the European geophysicists while the Wenner array is used in English speaking countries. The Schlumberger method has been derived theoretically whereas the Wenner method has been based on empirical formulae.

3.4.1) Investigation of Soil Structure

Field investigation of a substation site is most essential for determining both the general soil composition and obtaining some basic ideas as to its homogeneity. Usually, excavations and other civil engineering work are already in progress at or near the site where the earth system will be located. The boring of test samples and other geological investigations often provide useful

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information on the presence of various layers and the nature of soil material, leading at least to some ideas as to its resistivity and the range of values at the site.

3.4.2) Classification of Soils and Ranges of Resistivity

A number of tables exist in the literature, showing the ranges of resistivity for various soils and rocks. Table 2 on page 85 shows various ranges of resistivity for some soils and rocks.

3.4.3) Resistivity Measurements

Estimates based on soil classification yield only a rough approximation of the resistivity. Actual resistivity tests therefore are imperative. These should be made at a number of places within the site. Station sites where the soil may possess uniform resistivity throughout the entire area and to a considerable depth are seldom found. Typically, there are several layers, each having a different resistivity. Most often lateral changes also occur, but in comparison to the vertical ones, these changes usually are more gradual. Soil resistivity tests should be made to determine any important variation of resistivity with depth.

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If the resistivity varies appreciably with depth, it is often desirable to use an increased range of probe spacing. The idea is that a fairly accurate estimate for still greater spacing can be determined by extrapolation. This is possible because as the probe spacing is increased, the test source current penetrates more and more distant areas, in both vertical and horizontal directions, regardless of how much the current path is distorted due to the varying soil conditions.

As the soil resistivity varies greatly with seasons, the resistivity measurement records should include temperature , time, date, season and information on the moisture condition of the soil at the time of measurement. All data available on buried conductors already known or suspected to be in the area studied should also be recorded.

Buried bare conductors in contact with the soil can invalidate readings if they are close enough to alter the test current flow pattern. For this reason, the soil resistivity measurements are of little value in an area where grid conductors have already been installed, except, perhaps, for shallow depth measurements in or near the centre of a very large mesh rectangle. In such cases, a

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few approximate readings might be taken in a short distance outside the grid, with the probes so placed as to minimise the effect of the grid on the current flow pattern. Though not conclusive as to conditions inside the grid, such readings may be used for approximation, especially if there is reason to believe that the soil in the entire area is reasonably homogeneous.

3.4.4) Uniform Soil Assumption

The derivation of most equations for soil measurements is based on the assumption that the soil resistivity is uniform. This requires that the soil resistivity is constant both laterally and with depth to infinity. Obviously, this is never the case. However, this assumption can be made without significant error if the soil is essentially uniform (both horizontally and vertically) to a distance (measured from the edge of the grid) of approximately 3 - 5 times the diagonal dimension of the grid. The uniform soil assumption can be used with less accuracy when the resistivity varies slightly with depth by using the apparent resistivity, pa.

3.4.5) Non uniform Soil Assumptions

More exact theoretical approaches to situations where resistivity varies markedly with depth can

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be used. For example, it is often possible, from field readings taken with a wide range of probe spacing, to deduce a stratification of the earth into two or more layers of appropriate thickness that will account for the actual test variations.

3.4.6) Two-Layer Soil Model

Remarks below are limited to the assumption of the simplest soil stratification, that is, it is anticipated that a two-layer model is reasonably valid for the actual soil conditions and the range of resistivity variations found on the site. In practice, it is often possible to satisfy these requirements without risking a serious calculation error.

In principal, as shown in the ANSI/IEEE Guide (1986:77):

- A earthing system in a two-layer soil environment behaves differently in comparison with the same system in uniform soil. Generally, for a earthing system in uniform soil or in two-layer soil with p1 less than p2 (upper layer soil resistivity less than lower layer resistivity), the current density is higher in the conductors at the outer edges of the earthing grid. In two-layer soil with p1 greater than p2 (the soil in the upper layer is more resistive than the lower layer soil), the

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current density is more uniform over all the conductors of the earthing system. This is caused by the tendency of the leakage current to go downward into the layer of lower resistivity, rather than up and outward to the more resistive upper layer.

- The equations that govern the performance of a earthing system buried in multilayer soil can be obtained by solving La Place's equations for a point current source, or by the method of images, which gives identical results. The use of either method in determining the earth potential caused by a point current source results in an infinite series of terms representing the contributions of each consequent image of the point current source.

The abrupt changes in resistivity at the boundaries of each soil layer can be described by means of the reflection factor, K, as defined by equation 16 on page 20.

While the most accurate representation of a earthing system should certainly be based on the actual variations of soil resistivity present at the substation site, it will rarely be economically justifiable or technically feasible to model all these variations. However, in most

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cases, the representation of a earth electrode based on an equivalent two-layer earth model is sufficient for designing a safe earthing system.

3.4.7) Comparison of Uniform and Two-Layer Soil Model

The two-layer model approach has been found to be much more accurate than the uniform soil model. Some of the reasons are:

- Variations in soil resistivity have considerable influence on the performance of most earthing systems, affecting both the value of earth resistance and earth potential rise, and the step and touch surface voltages. In general, for negative values of K (upper layer more resistive than lower layer), the resistance is less than that of the same earthing system in uniform soil with resistivity p1. In contrast, for positive values of K, the resistance is generally higher than that in uniform soil with resistivity p1. Also, for positive values of K, the step and touch voltages are generally higher than in uniform soil.

- Other parameters, such as the surface layer height H, also affect the differences in the performance of earth electrodes in a two-layer

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environment and in uniform soil conditions. The general rule is that when the upper layer height H becomes significantly larger than the electrode's own dimensions, the performance of the electrode approaches the performance of the same electrode in uniform soil of resistivity p1.

- Also, it must be recognised that the above characteristics are based on the premise of a constant fault current source. The actual currents in the earthing system will change from case to case as a function of p1 and p2, reflecting the local changes relative to all other earth fault current paths predetermined by the fault location. Therefore, in certain cases some of the assumptions given above may not always hold true.

Since the use of two-layer or multilayer models necessitates the application of powerful computers having large memory space available, it is impractical to insist on the use of multilayer models for all earthing studies. For design applications involving relatively simple earthing arrangements of electrodes buried in a reasonably uniform soil, the approximate methods will be suitable for obtaining a realistic design with adequate safety margins. However, for designs

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involving a large earthed area, odd shaped grids, etc., or where the resistivity of soil is clearly very non uniform, the engineer responsible for the design should decide which method to use and whether or not a multilayer model is warranted, based on all the information available.

3.5) <u>Resistivity of Surface Layer (ps)</u>

A thin surface layer of crushed rock helps in limiting the body current by adding resistance to the equivalent body resistance. Values from 1000 - 5000 ohm.m have been used for ps.

The crushed rock layer also improves the surface for the movement of equipment and vehicles in the substation. The area covered by this crushed rock layer is generally of sufficient size to validate the assumption of the feet being in contact with a area of uniform resistivity in the lateral direction. However, the relatively shallow depth (usually about 100 mm) of the crushed rock as compared to the equivalent radius of the foot precludes the assumption of uniform resistivity in the vertical direction when computing the self and mutual resistance's of the feet. (Refer to Eq. 4 and 5 on page 15).

If the underlying soil has a lower resistivity than the crushed rock, only some grid current will go

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upward into the thin upper layer of crushed rock, and the surface voltage will be very nearly the same as that without the rock layer. The current through the body will be lowered considerably with the addition of the crushed rock surface because of the greater contact resistance between the earth and the feet. However, this resistance may be considerably less than that of a crushed rock layer of great thickness (that is, thick enough to assume uniform resistivity in all directions).

The converse of the derating principle is also true. If the underlying soil has a higher resistivity than the crushed rock, a substantial portion of the grid current will go upward into the thin layer of crushed rock. However, unlike the case described above, the surface potentials will be altered substantially, due to this concentration of current near the surface. The effective resistivity of the crushed rock should not be upgraded without taking into account this change in surface potential. This problem can best be solved by using multilayer soil analysis as described in paragraph 3.4.6. on page 59.

3.6) <u>Grid Geometry</u>

In general, the limitation on the physical parameters of a earth grid are based on economics and the physical limitations of the installation of the grid. The economic limitation is obvious: it is

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impractical to install a copper plate earthing system.

Some of the limitations encountered in the installation of a grid includes the digging of the trenches into which the conductor material is laid is limited by a conductor spacing of approximately 2 m or more. Typical conductor spacing range from 3 - 15 m, while typical grid depths range from 0.5 - 1.5m.

For the typical conductors, the conductor diameter has negligible effect on the mesh voltage. The area of the earthing system is the single most important geometrical factor in determining the resistance's of the grid. The larger the area earthed, the lower the grid resistance and, thus, the lower the GPR and mesh voltage.

3.7) <u>Conductor data</u>

3.7.1) Basic Requirements

In assessing which conductor material and what conductor size or what maximum allowable temperature limit need to be applied in individual design situations, the final choice should always reflect the following basic considerations:

Each element of a earthing system, including grid conductors, joints, connecting leads, and all

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primary earthing electrodes, should be so designed that for the expected design life of the installation, the element will:

- Have sufficient conductivity, so that it will not contribute substantially to local voltage differences

- Resist fusing and mechanical deterioration under the most adverse combination of a fault current magnitude and duration

- Be mechanically reliable and rugged to a high degree, especially on locations exposed to corrosion or physical abuse

The first requirement for selecting a conductor with sufficient conductivity is usually fulfilled when the other two requirements for current-carrying ability and mechanical strength are satisfied.

3.7.2) Conductor Size

A quantitative determination of the short time temperature rise in a earth conductor can be calculated. The following equation [ANSI/IEEE Guide (1986:65)] evaluates the current carrying capacity of any conductor for which the material constants are known, or can be determined by

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calculation. Material constants of the commonly used earthing materials are listed in Table 3 on page 86.

$$Itcap = Acon\sqrt{\left(TCAP.10^{-4} / t_t\alpha_r p_r\right) \ln(Ko + Tm / Ko + Tb)} \quad \text{(Eq 28)}$$

where

Itcap = rms current carrying capacity in kA

Acon = conductor cross section in mm²

Tm = maximum allowable temperature in °C

Tb = ambient temperature in °C

Ko = $1/\alpha_o$, or Ko = $(1/\alpha_r) - Tr$

α_o = thermal coefficient of resistivity at 0 °C

α_r = thermal coefficient of resistivity at 20 °C

p_r = the resistivity of the earth conductor at 20 °C in μ ohm/cm³

t_t = time of current flow in s

TCAP = thermal capacity factor from Table 3 on page 86, in J/cm³/°C

Equation 28 (which defines TCAP), reflect two basic assumptions:

- all heat will be retained in the conductor, and
- the product of specific heat (SH) and specific weight (SW), TCAP, is approximately constant since SH increases and SW decreases at about the same rate. For most metals, these premises are applicable over a reasonably wide

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temperature range, as long as the fault duration is within a few seconds. The error is always on the conservative side.

3.7.3) Additional Sizing Factors

As a rule, the designer should take precautions to ensure that the temperature of any conductor will not exceed the maximum allowable temperature of the lowest rated component, or some other limitation, such as:

- Low temperature due to special circumstances. Typically, conductors near flammable materials could be subjected to more stringent limitations.

- Environmental factors. A possible exposure to a corrosive environment should be carefully examined. If a gradual degradation of the earthing system could occur during the planned design life, extra allowances should be made in this respect.

The down leads to the grid conductor may be subjected to the total fault current into the grid, while the grid conductor subdivides this current so that each conductor segment in the grid is only subjected to some fraction of the total grid current. Thus, the down leads may be

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required to be larger than the grid conductor in order to have sufficient current carrying capacity for this total grid current.

Conductors that are used as earth leads conducting the lightning current seldom require further consideration. The size of a conductor, which is selected according to its fault current duty, usually is also adequate for carrying short-time surges caused by lightning.

3.7.4) Final Choice of Conductor Size

In practice, the requirements on mechanical reliability will set a minimum conductor size.

While it might seem proper for the designer to establish minimum sizes in light of local conditions, the need for conservatism deserves consideration. Some of the specific reasons are:

- Relay malfunctions and human errors can result in fault duration in excess of primary clearing times. The back-up clearing time is usually adequate for sizing the conductor. For small substations, this may approach 3 seconds or longer. However, since large substations usually have complex or redundant protection schemes, the fault will generally be cleared in 1 second or less.

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- The ultimate value of current used to determine the conductor size should take into account the possibility of future growth. It is less costly to include an adequate margin in conductor size during the initial design than to try and reinforce a number of earth leads at a later date.

3.7.5) Conductor Material

Copper is by far the most common material used for earthing. Copper conductors, in addition to their high conductivity, have the advantage of being resistant to underearth corrosion since copper is cathodic with respect to the metals that are likely to be buried in the vicinity. The use of copper therefore assures that the integrity of an underearth network will be maintained for years, so long as the conductors are of adequate size and not damaged.

3.8) Selection of Joints

3.8.1) General Considerations

All joints that connect various parts of the earthing network into an electrically continuous system of apparatus, conductors, and earth electrodes should be evaluated in terms of conductivity, thermal capacity, mechanical strength, and reliability.

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An obvious consideration is to ensure that the connection will withstand expected mechanical stresses without any significant deterioration due to corrosion, metal fatigue, and electromagnetic forces for the life span of the substation (this could be from 30 - 50 years).

Electromagnetic forces produced by a high fault current can be severe; copper cables were observed to stretch in staged fault tests when temperatures approached the fusing limit of the tested conductor. Also, where overhead earth wires are installed in tension, some reduction in strength (due to annealing) should be anticipated.

3.8.2) Type of joints

The most common methods of making earth connections utilise exothermic welds, brazed joints, and pressure type connectors. Provided these connectors are properly designed and installed, some of the guidelines of their applications are:

- If, for mechanical reasons, annealing of a conductor is a consideration, it may be prudent not to exceed 250 °C regardless of the type of connection used.

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- The temperature limit of 450 °C is a reasonable value for brazed connections, considering that in practice many copper-based eutectic brazing alloys will start to melt at temperatures less than 600 °C.

- Exothermic welded joints will intimately join the cable with a connector or material that has about the same fusing temperature, so that the entire connection can be viewed and rated as being an integral part of one homogeneous conductor.

- Pressure type connectors exist in a variety of types and makes. The bolted, wedge, and compression types are most common. In general, pressure type connectors operate at lower temperatures than the conductor. Due to a heat-sink effect caused by the presence of a relatively large connector, the conductor may fuse before the joint fails.

- If there is uncertainty or a lack of test data, it is reasonably conservative to design for temperatures within a 250 - 350 °C range.

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CHAPTER 4

4) RESULTS

4.1) Worked Example

The basic problem in the design of an earthing system for a substation will be discussed with the aid of a worked example. The following example from ANSI/IEEE Guide (1986:181) will be used as reference to prove the procedures and use of the computer program. Refer to Annexure B for an example of a practical design. The basic layout of the example ANSI/IEEE substation is shown in figure 7 on page 92. The following design parameters will be used:

3Io = 3180 A

Sf = 0.6

Soil resistivity = 400 ohm.m

Crushed rock resistivity = 2500 ohm.m

Depth of grid burial = 0.5 m

Fault and shock duration = 0.5 seconds

4.1.1) Field and soil resistivity data

The design of a earthing system should start with the inspection of the general arrangement plan of the substation. This plan will provide a good estimate of the area to be earthed. A soil resistivity test will determine the soil resistivity profile of the area and also give an indication of the soil model that will be used

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(single or multi layer). A typical soil resistivity profile is shown in graph 2 on page 87. This profile can be used to determine the resistivity of the soil.

4.1.2) Conductor and joint data

The conductor size is determined by the maximum fault current and mechanical factors prevailing in the substation and surrounding area.

4.1.3) Fault Current and fault duration data

The maximum expected three phase fault current in the substation is determined by either calculation or obtained from system information documents which list these fault currents. The fault duration is determined by the primary protection or backup protection times.

4.2) Detail design using computer program

The computer program, "GRID.EXE", will be used to analyse the proposed earthing system. Annexure A lists the flow diagram and the Turbo Pascal source code for the program. The design procedure for the earthing system will proceed in an iterative fashion. The designer must assume a certain preliminary design and then perform an analysis of the design. The analysis determines whether the design criteria and safety standards are met.

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4.2.1) Data input

The input data is included on the enclosed disk as 'EXAMPLE1'.

- Grid geometry

  The example earthing grid consists of a rectangular mesh of conductors, spaced 7 m apart. The length and width of the grid is 70 m respectively. The number of X- and Y-direction conductors are 110 each. The data can be interactively entered into the computer or, noting the format of the '*.DIM' files on the enclosed disk, be entered via any text editor. This data is stored automatically on disk for future use.

- Conductor and joint data

  The ESKOM standard copper conductors of 10 mm diameter will be used for the grid and ground rods. The conductors will be brazed together at crossings and joints.

- Soil and yard surface data

  A uniform soil model will be used with a resistivity of 400 ohm.m. A crushed rock surface layer of resistivity 2500 ohm.m with a thickness of 100 mm will be spread over the entire surface of the substation yard.

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- Fault current data

  The highest fault current in the substation is 3180 A. A current division factor (Sf) of 0.6 is used and no load growth will be taken into account. The fault (tf) and shock (ts) duration's will be assumed equal at 0.5 seconds.

4.2.2) Calculations

Once all the input data is entered into the computer the calculations can be performed. It is advisable to perform the safety check first and once the safety criteria are within limits, the mesh voltage calculations can be performed.

4.2.3) Output data

The program calculates the total area of the grounding grid, the total length of the grid conductors and ground rods and the total grid resistance. The touch and step voltage criteria and the maximum ground potential rise is calculated, and expressed in volts. The program then performs a preliminary safety check with the calculated data.

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4.3) **Evaluation of calculated results**

If the design criteria are met, no further analysis is necessary. Only additional conductors required to provide access to equipment grounds is necessary.

Because the calculated ground potential rise of Example 1 exceeds the maximum safe tolerable touch voltage, the design should be revised. These revisions may include the following possible remedies, and should be studied and applied where appropriate.

- Decrease in total grid resistance will decrease the maximum ground grid potential rise and hence the maximum transferred potential. The most effective way to decrease ground grid resistance is by increasing the area occupied by the grid. Deep driven rods or wells may be used if the available area is limited. Decrease in station resistance may or may not decrease appreciably the local gradients, depending on the method used.

- Improvements of gradient control. By employing closer spacing of grid conductors, the condition of the continuous plate can be approached more closely. Dangerous potentials within the station can thus be eliminated at a cost. The problem at the perimeter may be more difficult, especially at a small station where earth resistivity is high. However, it is

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usually possible, by burying the grid perimeter ground conductor outside the fence line, to ensure that the steeper gradients immediately outside this grid perimeter do not contribute to the more dangerous touch contacts. Another effective and economical way to control perimeter gradients is to increase the density of ground rods at the perimeter. This density may be decreased towards the centre of the grid. Another approach to controlling perimeter gradients and step potentials is to bury two or more parallel conductors around the perimeter at successively greater depth as distance from the station is increased.

- Diverting a greater part of the fault current to other paths, for example, by connecting overhead ground wires of transmission lines or by decreasing the tower footing resistance's in the vicinity of the substation. In connection with the latter, however, the effect on fault gradients near tower footings should be weighed.

- Limiting of short-circuit currents flowing in the earth mat to lower values. If feasible, this will, of course, decrease the total rise in earth mat voltage and all gradients in proportion. Other factors, however, will usually make this impractical. Moreover, if accomplished at the expense of greater

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fault clearing time, the danger may be increased rather than diminished.

- Barring of access to limited areas where it may be impractical to eliminate possibility of excessive potential differences during a fault.

By using one or more of the above methods where necessary, the design can be completed for construction purposes. These should be reasonably liberal, as grounding facilities can usually be installed more cheaply if all go in as part of the general construction job, without the necessity of making additions later.

4.4) Mesh voltage calculations

The program can calculate and plot a voltage profile along a user defined Y - direction on the surface of the grid. The "combined integration / matrix method" as described by Meliopoulos (1988:143) is used to calculate the mesh voltages in the grid. This method involves the integration along the length of a finite segment and the utilisation of basic equations to determine the relationship between the voltage of these segments and the electric current emanating from the surface of these segments. The size of the involved matrix is equal to the number of selected segments and this has a direct influence on the computer calculation time.

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The "combined integration / matrix method" involves the relationships between the total electric current emanating the surface of a finite length of conductor and the voltage at a given point in earth. The voltage at any point, or the "transferred" voltage to another conductor or the voltage of the conductor itself is proportional to the total electric current emanating the conductor, and is given by the following equation:

$$GPR = Rt \, . I \qquad \text{(Eq 29)}$$

where

I = total electric current emanating the surface of the conductor under consideration,

Rt = a function depending on the geometry of the system and the conductivity of the soil (it will be referred to as the VDF) and

GPR = ground potential rise of the earthing system

To limit the possible geometric arrangements for the conductors, only earth-embedded conductors along the three co-ordinate axes (x, y and z) will be considered. Refer to Annexure C for the expressions for the VDF.

Refer to Annexure D for the printout of the mesh voltage profile of Example 1.

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4.5) Advantages of the program

The computer program, GRID, offers the following advantages:

- It is easy to use
- The program offers a dialogue type input / output format
- The program offers file handling capabilities for easy data storage and file retrieval
- The program facilitates an iterative design procedure
- An automatic safety assessment is done with the aid of the program.

4.6) Conclusion

Although the use of computer analysis in grounding grid design is frequently used, this guide and computer program attempts to provide quick, but sufficiently accurate analysis of earthing grids. The program is justified by the inability of the simplified methods of the ANSI/IEEE Guide to analyse complex grounding grids. This program can evaluate unsymmetrical earthing grids, uneven grid conductor or ground rod spacing and single or two layer soil models. Like the simplified methods, the computer program's performance is limited by the quality of the input data.

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CHAPTER 5

5) SUMMARY

The basic criteria in the design of the substation earthing system are:

- assuring the safety of personnel operating in and about the substation and
- minimisation of the earth potential rise.

In general the earthing system must be designed to:

- Limit the earth potential rise to an acceptable level and
- Limit the resulting touch, step, and transfer voltages in and around the substation to acceptable safety standards.

As was shown, the two objectives are interrelated. The touch, step and transfer voltages are proportional to the earth potential rise. This depend on the design of the earthing system.

Basically the design of the earthing system address the following problems:

- Determination of soil resistivities
- Computation of the maximum earth potential rise
- Computation of the touch, step and transfer voltages and

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- A safety assessment of the proposed design.

As was shown, the earthing system should be designed to ensure the lowest possible and most economical resistance to earth mass for the expected fault currents flowing to earth, and to ensure that the potential difference induced by these fault currents into the earth mat, is kept within internationally accepted safety margins.

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Table 1

Effect of Electrical Current on the Human Body

50 Hz Current	Effect
Secondary Shock Currents	
0 - 1 mA	No sensation (not felt)
0 - 3 mA	Perceptible, mild
3 - 5 mA	Annoyance, pain, or surprise
5 - 10 mA	Painful shock
Primary Shock Currents	
10 - 15 mA	Local muscle contractions, sufficient to cause "freezing" to circuit for 2.5 % of population
15 - 3- mA	Local muscle contractions, sufficient to cause "freezing" to circuit for 50 % of population
30 - 50 mA	Breathing difficult, can cause unconsciousness
50 - 100 mA	Possible ventricular fibrillation of heart
100 - 200 mA	Certain ventricular fibrillation of heart
Over 200 mA	Severe burns and muscular contractions; heart more apt to stop than fibrillate
Over a few amperes	Irreparable damage to body tissue

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Table 2

Ranges of Resistivity for various Soils and Rocks
ANSI/IEEE Guide (1986:76)

Type of Soil/Rock	**Resistivity in ohm.m**
Loams, gardens soils, etc.	5 - 50
Clays	8 - 50
Clay, sand and gravel mixtures	40 - 250
Sand and gravel	60 - 100
Slates, shale, sandstone, etc.	10 - 500
Crystalline rocks	200 - 10000

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Table 3

Material Constants
ANSI/IEEE Guide (1986:66)

Description	**Material Conductivity (%)**	**αr Factor @ 20 °C**	**K (1/α0) @ 0°C**	**Fusing Temp. (°C)**	**pr @ 20°C (μΩ/cm)**	**TCAP Factor (J/cm³/°C)**
Standard Annealed Soft Copper Wire	100	0.00393	234	1083	1.7241	3.422
Commercial Hard Drawn Copper Wire	97	0.00381	242	1084	1.7774	3.422
Copper-Clad Steel Core Wire	40	0.00378	245	1084/ 1300	4.397	3.846
Copper-Clad Steel Core Wire	30	0.00378	245	1084/ 1300	5.862	3.846
Commercial EC Aluminium Wire	61	0.00403	228	657	2.862	2.556
Aluminium Alloy Wire 5005	53.5	0.00353	263	660	3.2226	2.598
Aluminium Alloy Wire 6201	52.5	0.00347	268	660	3.2840	2.598
Aluminium-Clad Steel Core Wire	20.3	0.00360	258	660/ 1300	8.4805	2.670
Zinc-Coated Steel Core Wire	8.5	0.00320	293	419/ 1300	20.1	3.931
Stainless Steel No 304	2.4	0.00130	749	1400	72.0	4.032

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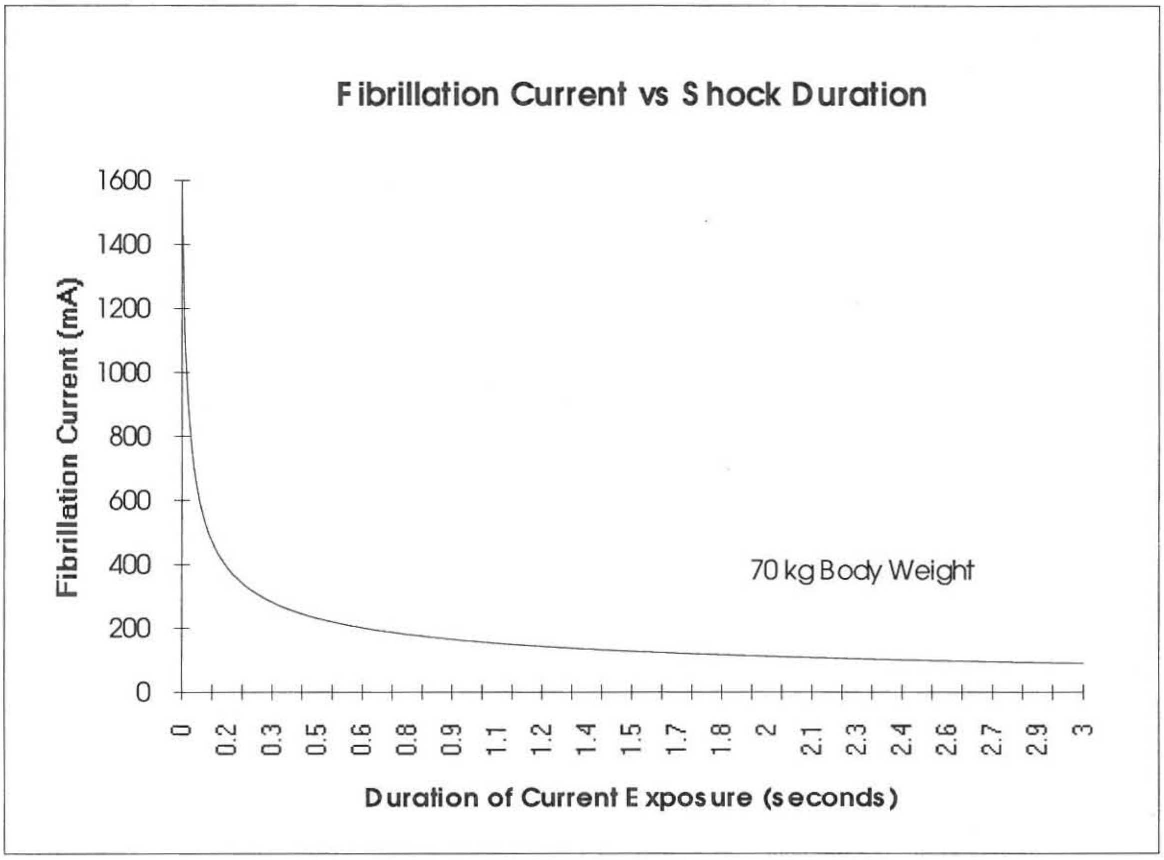
Graph 1:



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Graph 2:

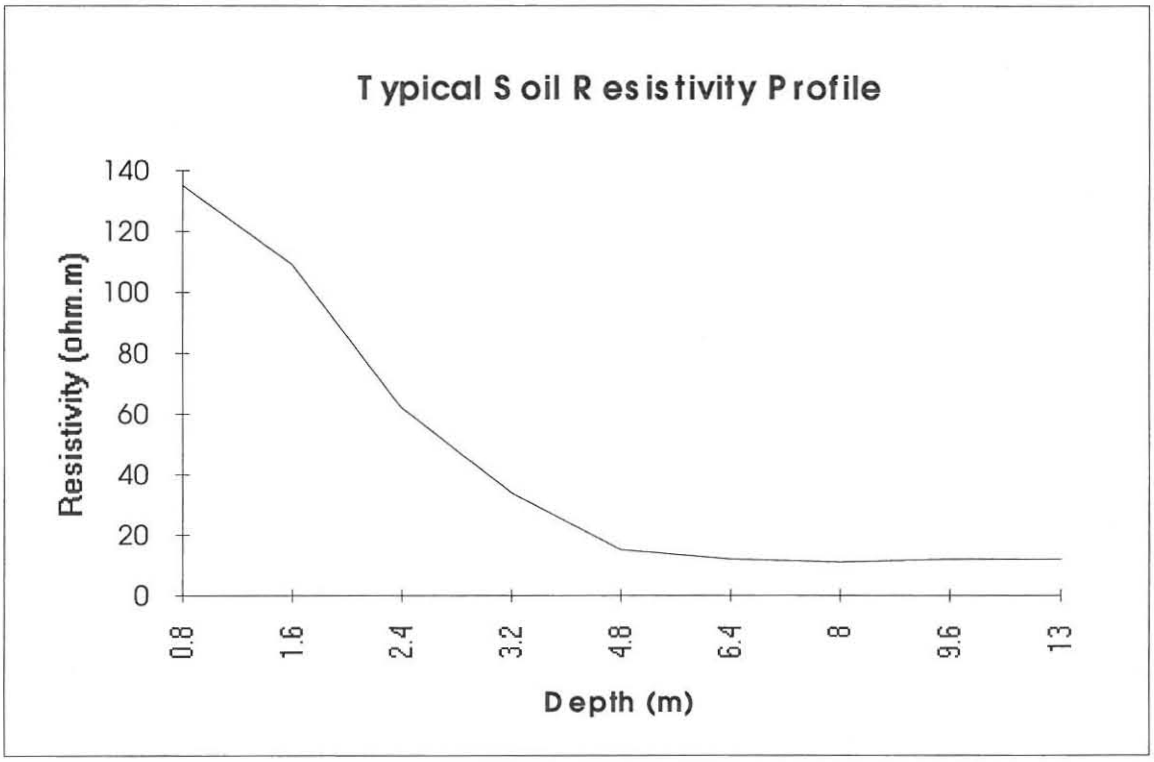

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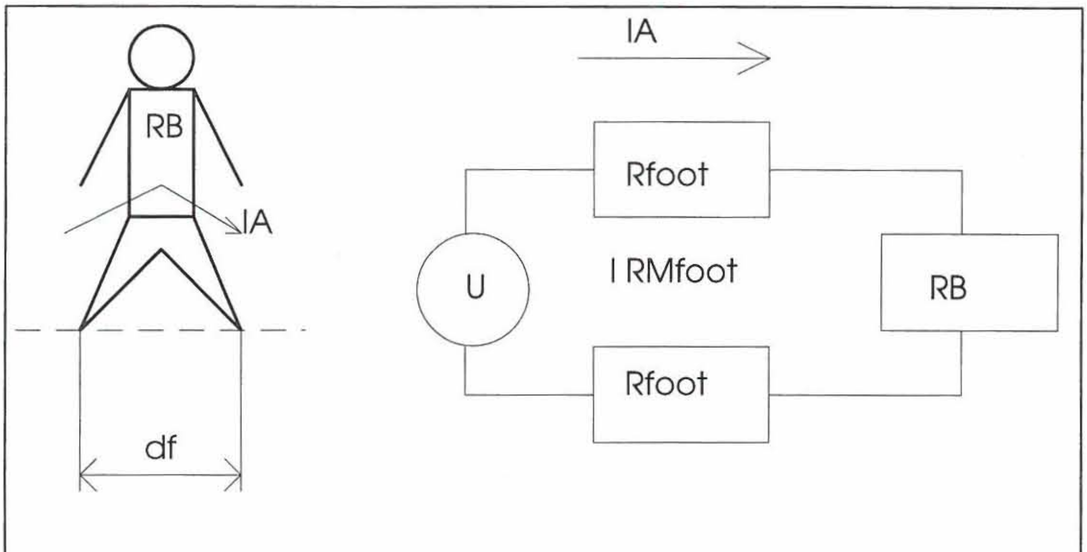
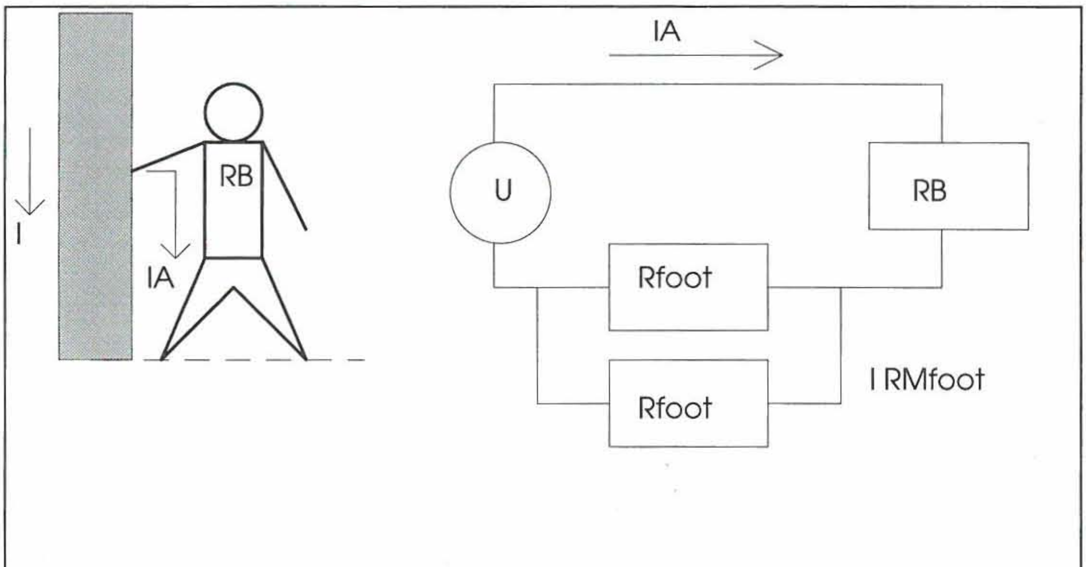
Figure 1:



Circuit Equivalent of a foot to foot contact.

Figure 2:



Circuit Equivalent for a hand to two feet contact.

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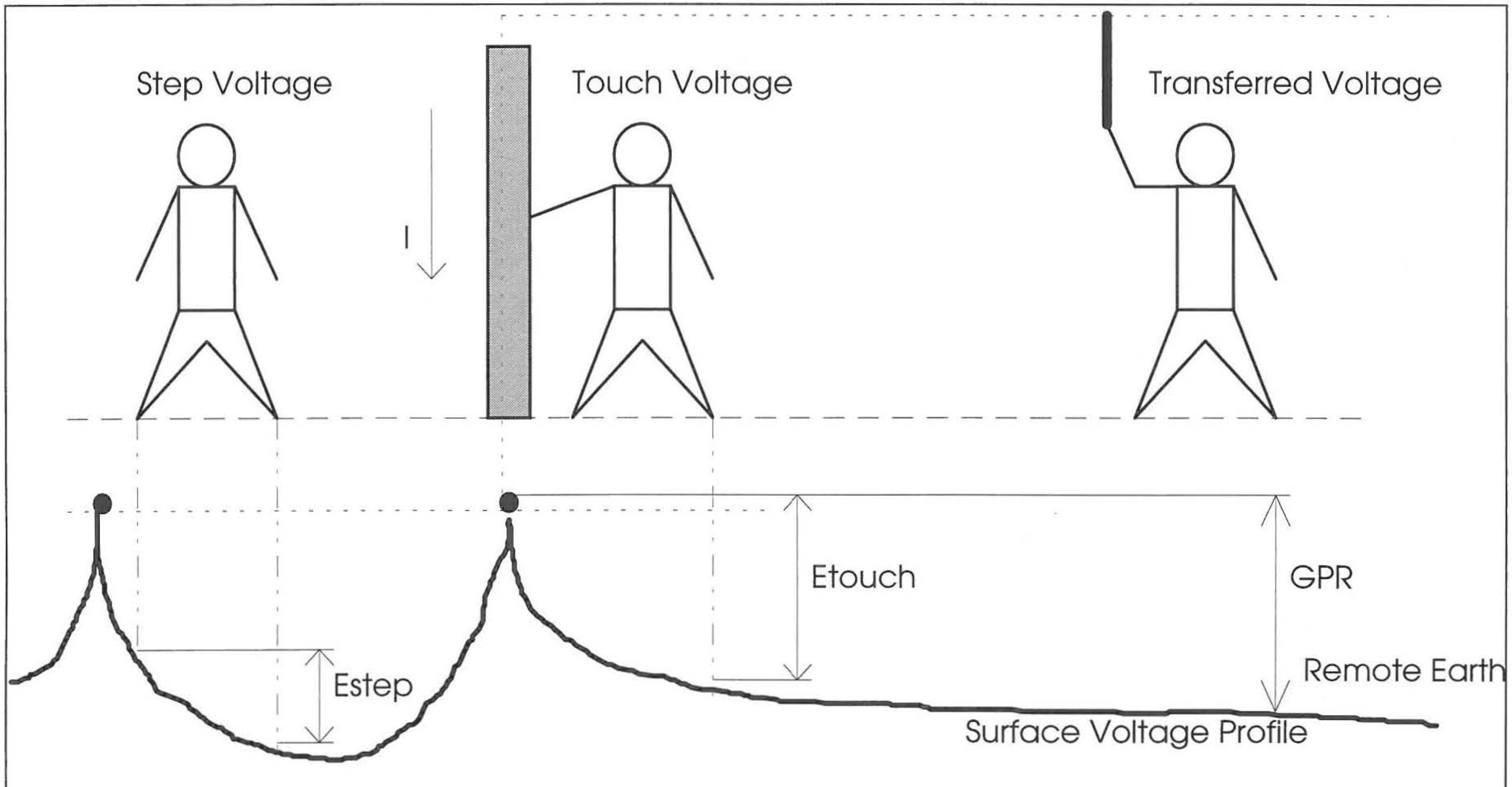
Figure 3:



Basic Shock Situations.

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Figure 4:

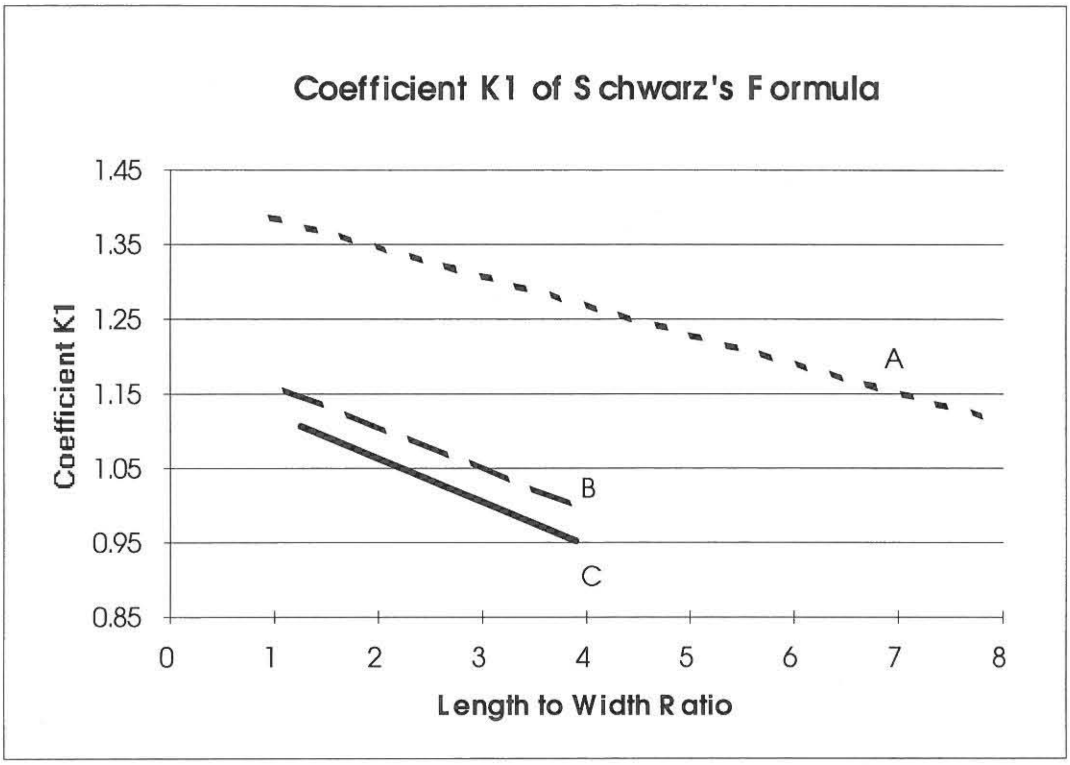

Figure 5:

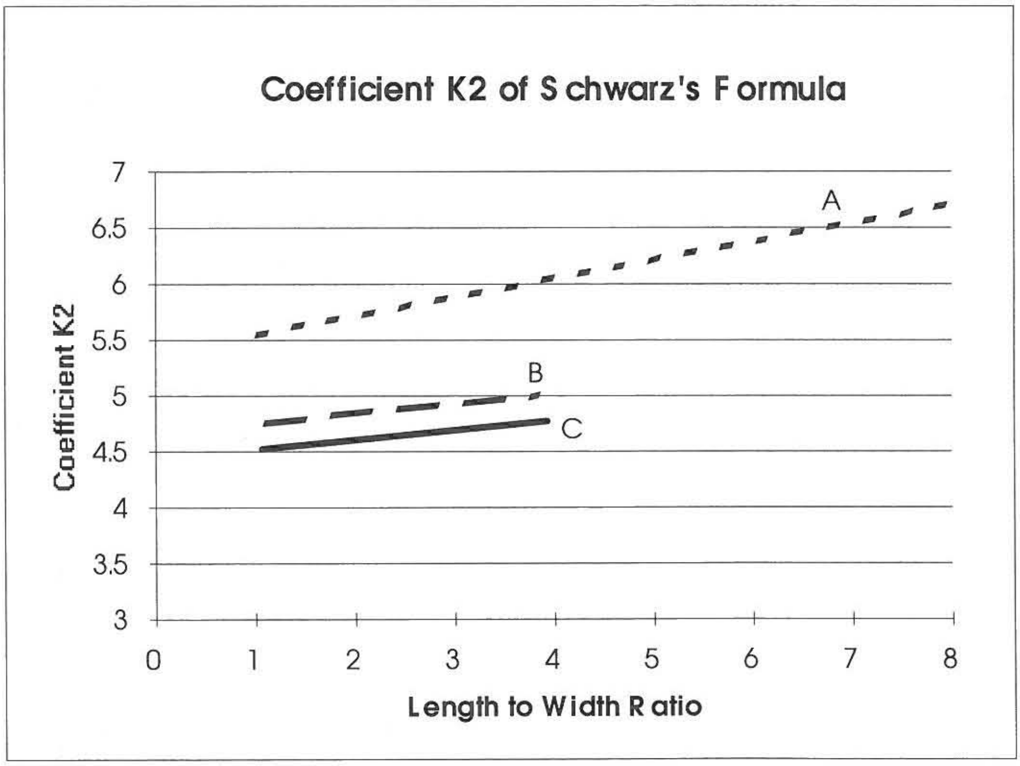

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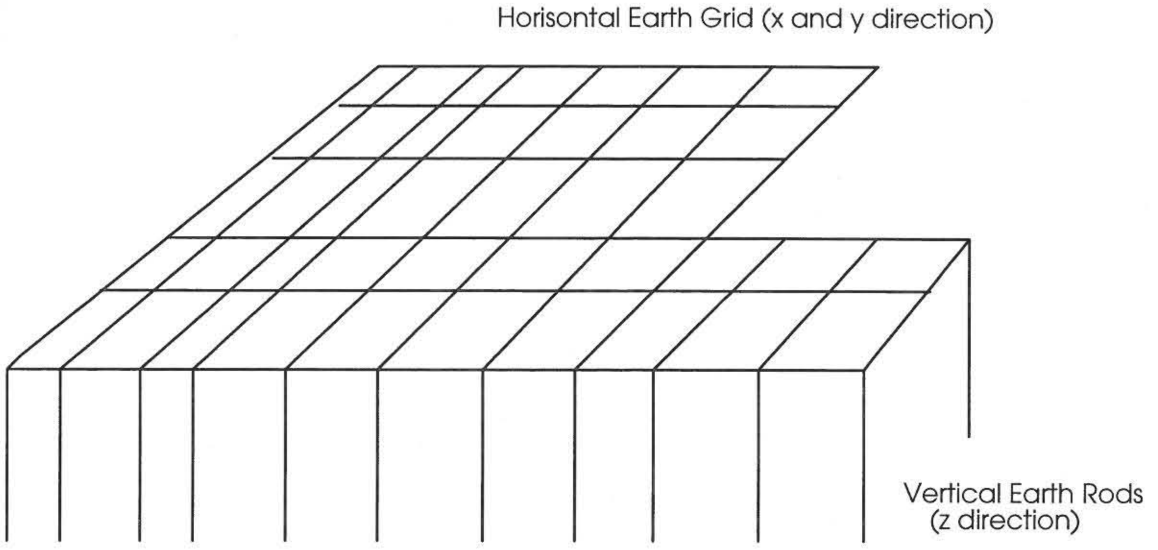
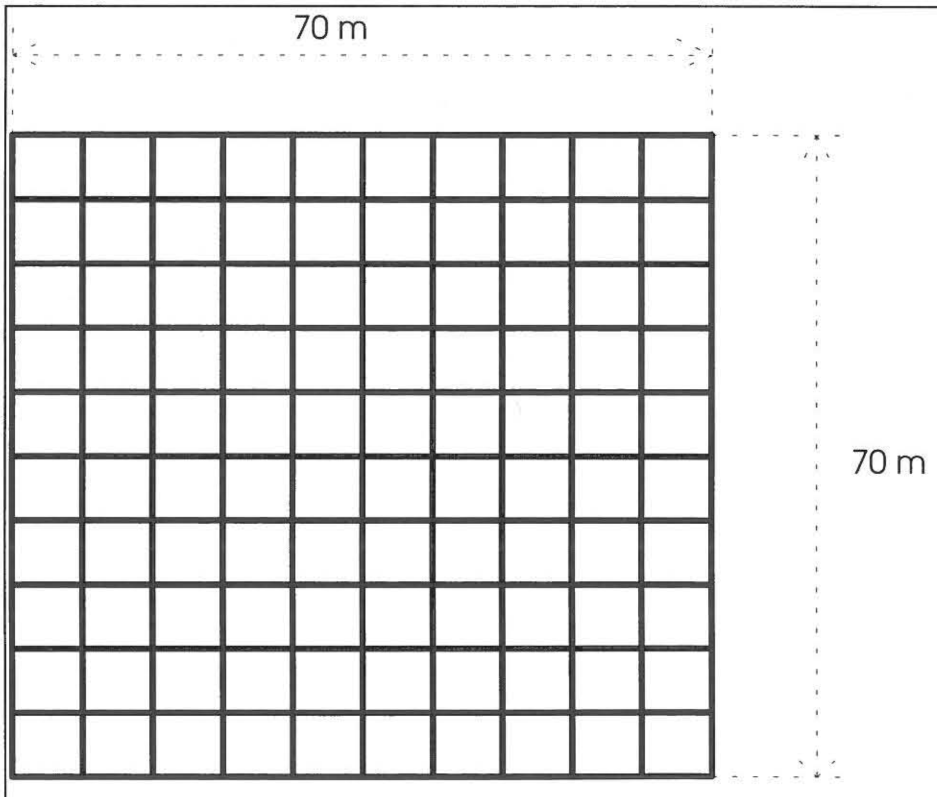
Figure 6:



Typical Earthing Grid and Earth Rods

Figure 7:



Basic layout of Example 1

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ANNEXURE A

Flow Chart for program GRID.EXE:

Step 1: **Enter field data;** grid dimensions, grid burial depth, grid/rod conductor diameter, conductor joint types, soil and yard surface data, fault current, current division factor, load growth factor and fault duration data.

Step 2: **Perform calculations;** total area of grid, total length of buried conductors and grid resistance.

Step 3: **Perform safety check;** Calculate Touch and Step voltage criteria and ground potential rise.

Step 4: **If the safety check is satisfactory,** the design is complete and the mesh voltages can be calculated if necessary.

Step 5: **If the safety criteria is not met,** the design should be revised and steps 1 to 4 should be repeated.

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Source Code for program GRID.EXE

```
{$N+,E+}
program grid;                          {Ver 2.0   -   11-4-1994}

uses                                   {Declare units}
graph,dos,crt,graphics;

const                                  {Declare constants}
pi=3.142857142857;
n=100;                                 {Iterations}

type
matrixelement = record
                 value: file of real;
                 nextt:pointer;
                end;

var                                    {Declare variables}

mx1              : double;
my1              : double;
rods             : double;
background       : integer;
lines            : integer;
i                : integer;
j                : integer;
xdir             : integer;
ydir             : integer;
rodnum           : integer;
count            : integer;
gd,gm            : integer;
iter             : real;
Rg               : real;
R1               : real;
R2               : real;
R12              : real;
pa               : real;
x                : real;
h10              : real;
h6               : real;
k1               : real;
k2               : real;
hh               : real;
Length           : real;
area             : real;
Ta               : real;
rodlength        : real;
maksxdir         : real;
maksydir         : real;
d                : real;
h                : real;
```

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```
p1              : real;
p2              : real;
h1              : real;
ps              : real;
hs              : real;
kfact           : real;
Fault           : real;
GroundPR        : real;
Sf              : real;
Ig              : real;
Imax            : real;
Cp              : real;
Df              : real;
tf              : real;
ts              : real;
Cs              : real;
Estep70         : real;
Etouch70        : real;
Estep50         : real;
Etouch50        : real;
Tmax            : real;
lxtotal         : real;
lytotal         : real;
lrodtotal       : real;
lrodavg         : real;
y               : real;
oux1            : real;
xdir_from_xco   : array[1..500] of real;
ydir_from_xco   : array[1..500] of real;
xdir_from_yco   : array[1..500] of real;
ydir_from_yco   : array[1..500] of real;
xdir_to_xco     : array[1..500] of real;
ydir_to_xco     : array[1..500] of real;
xdir_to_yco     : array[1..500] of real;
ydir_to_yco     : array[1..500] of real;
rodxco          : array[1..50]  of real;
rodyco          : array[1..50]  of real;
lenrod          : array[1..50]  of real;
lx              : array[1..500] of real;
ly              : array[1..500] of real;
xv,yv,zv        : array[1..250] of double;
v,vp            : array[1..250] of real;
day             : word;
month           : word;
year            : word;
dow             : word;
uur             : word;
uur1            : word;
min             : word;
min1            : word;
sek             : word;
sek1            : word;
sek100          : word;
b               : char;
```

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```
joint          : char;
soilmodel      : char;
loadgrowth     : char;
gridtype       : char;
inputt         : char;
option         : char;
opsie          : char;
waarde         : char;
option1        : char;
ans            : char;
loop1          : boolean;
loop2          : boolean;
loop3          : boolean;
filexist       : boolean;
s              : string;
filename       : string;
name           : string;
alpha          : text;

procedure setupscreen;  forward;

procedure intro;                   {G R I D  screen}
begin
  clrscr;
  gd:=detect;
  initgraph(gd,gm,'');
     setcolor(yellow);
     settextstyle(1,horizdir,10);
     outtextxy(90,130,'G R I D');
     delay(2000);
  closegraph;
  clrscr;
  textattr:=white;
  if keypressed then begin
    b:=readkey;
    if b=#0 then b:=readkey;
  end;
end;



procedure entree;                   {Intro/begin screen}
begin
getdate(year,month,day,dow);
gotoxy(1,1);
writeln('ÉÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍ
ÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍ»');
gotoxy(1,2);
writeln('º                                           E S K O M
º');
gotoxy(1,3);
writeln('º                   B L O E M F O N T E I N   D I S
T R I B U T O R              º');
gotoxy(1,4);
```

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```
writeln('ÇÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄ
ÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄ¶');
gotoxy(1,5);
writeln('º                    SUBSTATION GROUNDING GRID
DESIGN PROGRAM                  º');
gotoxy(1,6);
writeln('ÌÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍ
ÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍ¹');
gotoxy(1,7);
writeln('ºThis program, written in Pascal, by D.J.
Pieterse (Eskom BFN Dist.), uses     º');
gotoxy(1,8);
writeln('ºthe IEEE Std 80 method to evaluate AC
substation grounding grids.  The programº');
gotoxy(1,9);
writeln('ºcalculates the physical dimensions  (area &
total length of conductor),   stepº');
gotoxy(1,10);
writeln('ºand touch  voltage  criteria,  resistance  of
grounding  grid to earth and theº');
gotoxy(1,11);
writeln('ºmaximum  ground  potential  rise.   A prelimary
design check is done to ensureº');
gotoxy(1,12);
writeln('ºthat the designer  is  not  wasting
unnecessary  time and effort on an unsafeº');
gotoxy(1,13);
writeln('ºgrid design.   After the  prelimary  design
check,  the program calculates a º');
gotoxy(1,14);
writeln('ºmesh voltage profile along a user defined plane
on the grid.
º');
gotoxy(1,15);
writeln('º
º');
gotoxy(1,16);
writeln('º
º');
gotoxy(1,17);
writeln('º
º');
gotoxy(1,18);
writeln('º
º');
gotoxy(1,19);
writeln('º
º');
gotoxy(1,20);
writeln('º
º');
gotoxy(1,21);
writeln('º
º');
```

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```
gotoxy(1,22);
writeln('º
º');
gotoxy(1,23);
writeln('ÈÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍ
ÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍ Version 2.0 Í¼');
gotoxy(3,23);
write(' ',day:0,'-',month:0,'-',year:0,' ');
gotoxy(10,21);
write('Press any key to continue...');
b := readkey;
end;



procedure file_info(colour:integer);
begin
  textcolor(colour);
  gotoxy(53,7);
  write('File: ' + name);
end;



procedure border;                        {Draw border and add
Headings}
begin
clrscr;
gotoxy(1,1);
writeln('ÉÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍ
ÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍ»');
gotoxy(1,2);
writeln('º                                   E S K O M
º');
gotoxy(1,3);
writeln('º               B L O E M F O N T E I N   D I S
T R I B U T O R          º');
gotoxy(1,4);
writeln('ÇÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄ
ÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄ¶');
gotoxy(1,5);
writeln('º                  SUBSTATION GROUNDING GRID
DESIGN PROGRAM               º');
gotoxy(1,6);
writeln('ÌÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍ
ÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍ¹');
gotoxy(1,7);
writeln('º
º');
gotoxy(1,8);
writeln('ÌÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍ
ÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍ¹');
gotoxy(1,9);
```

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```
writeln('º
º');
gotoxy(1,10);
writeln('º
º');
gotoxy(1,11);
writeln('º
º');
gotoxy(1,12);
writeln('º
º');
gotoxy(1,13);
writeln('º
º');
gotoxy(1,14);
writeln('º
º');
gotoxy(1,15);
writeln('º
º');
gotoxy(1,16);
writeln('º
º');
gotoxy(1,17);
writeln('º
º');
gotoxy(1,18);
writeln('º
º');
gotoxy(1,19);
writeln('º
º');
gotoxy(1,20);
writeln('º
º');
gotoxy(1,21);
writeln('ÇÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄ
ÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄ¶');
gotoxy(1,22);
writeln('º
º');
gotoxy(1,23);
writeln('ÈÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍ
ÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍ Version 1.0 Í¼');
gotoxy(3,23);
write(' ',day:0,'-',month:0,'-',year:0,' ');
file_info(15);
end;


procedure cleanup;                          {Clear all vars}
begin
```

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```
mx1              := 0;
my1              := 0;
rods             := 0;
xdir             := 0;
ydir             := 0;
rodnum           := 0;
count            := 0;
Rg               := 0;
R1               := 0;
R2               := 0;
R12              := 0;
pa               := 0;
x                := 0;
h10              := 0;
h6               := 0;
k1               := 0;
k2               := 0;
hh               := 0;
Length           := 0;
area             := 0;
Ta               := 0;
rodlength        := 0;
maksxdir         := 0;
maksydir         := 0;
d                := 0;
h                := 0;
p1               := 0;
p2               := 0;
h1               := 0;
ps               := 0;
hs               := 0;
kfact            := 0;
Fault            := 0;
GroundPR         := 0;
Sf               := 0;
Ig               := 0;
Imax             := 0;
Cp               := 0;
Df               := 0;
tf               := 0;
ts               := 0;
Cs               := 0;
Estep70          := 0;
Etouch70         := 0;
Estep50          := 0;
Etouch50         := 0;
Tmax             := 0;
lxtotal          := 0;
lytotal          := 0;
lrodtotal        := 0;
lrodavg          := 0;
y                := 0;

for i := 1 to 500 do
```

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```
  begin
   xdir_from_xco[i]     := 0;
   ydir_from_xco[i]     := 0;
   xdir_from_yco[i]     := 0;
   ydir_from_yco[i]     := 0;
   xdir_to_xco[i]       := 0;
   ydir_to_xco[i]       := 0;
   xdir_to_yco[i]       := 0;
   ydir_to_yco[i]       := 0;
   rodxco[i]            := 0;
   rodyco[i]            := 0;
   lenrod[i]            := 0;
   lx[i]                := 0;
   ly[i]                := 0;
   xv[i]                := 0;
   yv[i]                := 0;
   zv[i]                := 0;
   v[i]                 := 0;
 end;
end;

procedure griddim;                   {Input procedure for
grid dimensions}
begin
gotoxy(1,1);
writeln('ÉÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍ
ÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍ»');
gotoxy(1,2);
writeln('º                                        E S K O M
º');
gotoxy(1,3);
writeln('º                    B L O E M F O N T E I N   D I S
T R I B U T O R               º');
gotoxy(1,4);
writeln('ÇÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄ
ÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄÄ¶');
gotoxy(1,5);
writeln('º                    INPUT PROCEDURE FOR GROUNDING
GRID DESIGN PROGRAM              º');
gotoxy(1,6);
writeln('ÌÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍ
ÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍ¹');
gotoxy(1,7);
writeln('º The grid dimension data will be entered
interactively via the keyboard.      º');
gotoxy(1,8);
writeln('º The earth conductors can only be orientaded
along the three coordinates,     º');
gotoxy(1,9);
writeln('º x, y and z.  The corner of the grid must be
positioned at (x;y;z) = (0;0;0). º');
gotoxy(1,10);
writeln('º All ground rods will be on the z-axis
(vertically downwards) and the grid    º');
```

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```
gotoxy(1,11);
writeln('º on the x and y-axis (horisontally).  Refer to
Figure 6  of the thesis        º');
gotoxy(1,12);
writeln('º for an example layout of the grid and rods
along the x, y and z axes.        º');
gotoxy(1,13);
writeln('º
º');
gotoxy(1,14);
writeln('º Hint : Count and number all the conductors the
in x, y and z directions.     º');
gotoxy(1,15);
writeln('º        This will avoid confusion and will ease
the input process.           º');
gotoxy(1,16);
writeln('º
º');
gotoxy(1,17);
writeln('º
º');
gotoxy(1,18);
writeln('º
º');
gotoxy(1,19);
writeln('º
º');
gotoxy(1,20);
writeln('º
º');
gotoxy(1,21);
writeln('º
º');
gotoxy(1,22);
writeln('º
º');
gotoxy(1,23);
writeln('ÈÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍ
ÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍÍ Version 1.0 Í¼');
gotoxy(10,21);
write('Press any key to continue...');
b := readkey;
border;
gotoxy(2,7);
write('INPUT : Grid dimensions and geometry');
gotoxy(2,9);
write('Enter the number of X - direction conductor
segments: ');
readln(xdir);
gotoxy(2,11);
write('Enter the number of Y - direction conductor
segments: ');
readln(ydir);
gotoxy(2,13);
```

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```
write('Enter the number of Z - direction ground rods: ');
readln(rodnum);

 if xdir > 0 then
  maksxdir := 0;
  begin
  for i := 1 to xdir do
   begin
   border;
   gotoxy(2,7);
   write('INPUT : Grid dimensions and geometry');
   gotoxy(2,9);
   writeln('X - direction conductor segment
coordinates:');
   gotoxy(2,11);
   write('
');
   gotoxy(2,11);
   write ('Conductor segment : (X-',i,')  FROM - X
coordinate: ');
   readln (xdir_from_xco[i]);
   gotoxy(2,12);
   write('
');
   gotoxy(2,12);
   write ('                              Y
coordinate: ');
   readln (xdir_from_yco[i]);
   gotoxy(2,14);
   write('
');
   gotoxy(2,14);
   write ('                           TO  -  X
coordinate: ');
   readln (xdir_to_xco[i]);
   gotoxy(2,15);
   write('
');
   gotoxy(2,15);
   write ('                              Y
coordinate: ');
   readln (xdir_to_yco[i]);
   lx[i] := xdir_to_xco[i] - xdir_from_xco[i];

   {determine maksxdir}
   if xdir_to_xco[i] > maksxdir then
   maksxdir := xdir_to_xco[i];

   {calc total length of x direction segments}
   lxtotal := lxtotal + lx[i];
  end;
 end;

 if ydir > 0 then
```

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```
  maksydir := 0;
  begin
  for i := 1 to ydir do
   begin
   border;
   gotoxy(2,7);
   write('INPUT : Grid dimensions and geometry');
   gotoxy(2,9);
   writeln('Y - direction conductor segment
coordinates:');
   gotoxy(2,11);
   write('
');
   gotoxy(2,11);
   write ('Conductor segment : (Y-',i,')  FROM - X
coordinate: ');
   readln (ydir_from_xco[i]);
   gotoxy(2,12);
   write('
');
   gotoxy(2,12);
   write ('                                 Y
coordinate: ');
   readln (ydir_from_yco[i]);
   gotoxy(2,14);
   write('
');
   gotoxy(2,14);
   write ('                             TO  -  X
coordinate: ');
   readln (ydir_to_xco[i]);
   gotoxy(2,15);
   write('
');
   gotoxy(2,15);
   write ('                                 Y
coordinate: ');
   readln (ydir_to_yco[i]);
   ly[i] := ydir_to_yco[i] - ydir_from_yco[i];

   {determine maksydir}
   if ydir_to_yco[i] > maksydir then
   maksydir := ydir_to_yco[i];

   {calc total length of y direction segments}
   lytotal := lytotal + ly[i];
  end;
 end;

if rodnum > 0 then
begin
for i := 1 to rodnum do
 begin
  border;
```

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```
  gotoxy(2,7);
  write('INPUT : Grid dimensions and geometry');
  gotoxy(2,9);
  writeln('Z - direction ground rod coordinates:');
  gotoxy(2,11);
  write('
');
  gotoxy(2,11);
  write ('Ground rod: ',i,' - X coordinate: ');
  readln (rodxco[i]);
  gotoxy(2,13);
  write('
');
  gotoxy(2,13);
  write ('                 Y coordinate: ');
  readln (rodyco[i]);
  gotoxy(2,15);
  write('
');
  gotoxy(2,15);
  write ('                   Length (m): ');
  readln (lenrod[i]);
  lrodtotal := lrodtotal + lenrod[i];               {calc
total len of rods}
 end;
lrodavg := lrodtotal/rodnum;                        {calc
avg len of rods}
end;

 if xdir or ydir > 0 then
 begin
  border;
  gotoxy(2,7);
  writeln('INPUT : Grounding grid burial depth');
  gotoxy(2,9);
  write('Enter grid burial depth (m): ');
  readln(h);
 end;

{calc length + area of grid and rods}
length := (lxtotal + lytotal + lrodtotal);
area   := (maksxdir * maksydir);
end;

procedure getch(default:char);      {Read a caracter from
keyboard - given }
var  x,y        :integer;           { a default value.}
     ch         :char;
begin
  x:=wherex;
  y:=wherey;
  ch:=readkey;
  if ch=chr(13) then waarde:=default else begin
    while ch<>chr(13) do begin
```

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```
        if ch=#0 then ch:=readkey;
        if ch=chr(8) then begin
          gotoxy(x,y);  write('     ');  gotoxy(x,y);
          ch:=' ';
          waarde:=default;
        end else begin
          write(ch);
          waarde:=ch;
        end;
        ch:=readkey;
      end;
    end;
end;


function getvalue(min,max,vall : real) : real;    { This
function reads a    }
var  inlimit : boolean;                           { number
from the keyboard }
     value    : real;                             { and
accepts <ENTER> for  }
     x,x1,y   : integer;                          { the
default value.       }
     i,code   : integer;                          { Min
and max values are   }
     ch       : char;                             {
predetermined. No value  }
     valle    : string;                           {
outside these minimum or }
     vale     : array[1..15] of char;             {
maximum values will be   }
     test     : double;                           {
accepted!                }
begin
  inlimit:=false;
  test:=1;
  x:=wherex;  y:=wherey;
  gotoxy(2,22);
  write(' Default : ',vall:11:3,'          Min :
',min:5:3,'         Max : ',max:11:3);
  repeat
    gotoxy(x,y);
    write('            ');
    gotoxy(x,y);
    for i:=1 to 15 do
      vale[i]:=' ';
    for i:=1 to 15 do begin
      ch:=readkey;
      x1:=wherex;
      if ch=#0 then ch:=readkey;
      if (ch=chr(13)) and (i=1) then begin
        test:=0;
        i:=15;
        inlimit:=true;
```

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```
        end else begin
          if ch=chr(13) then begin
            vale[i]:='.';
            i:=15;
          end else
          if ch=chr(8) then begin
            vale[i]:=' ';
            if i<2 then i:=1
            else begin
              if x1<>x then x1:=x1-1;
              gotoxy(x1,y); write(' '); gotoxy(x1,y);
              i:=i-2;
            end;
          end else begin
            vale[i]:=ch;
            write(ch);
          end;
        end;
      end;
      if test=1 then begin
        valle:='';
        for i:=1 to 15 do
          valle:=concat(valle,vale[i]);
        while pos(' ',valle)>0 do
          valle[pos(' ',valle)]:='0';
        j:=0;
        for i:=1 to 15 do
          if valle[i]='.' then begin
            j:=j+1;
            if j>1 then valle[i]:='0';
          end;
        val(valle,value,code);
        if (value>=min) and (value<=max) then inlimit:=true
        else begin
          sound(320);
          delay(520);
          nosound;
        end;
      end;
    until inlimit;
    if test=0 then getvalue:=vall else
      getvalue:=value;
end;

procedure conductor;                    {Input conductor
data}
begin
 border;
 gotoxy(2,7);
 writeln('INPUT : Grid/rod conductor size and joint
data');
 gotoxy(2,9);
 write('Conductor diameter (mm): ');
 d := getvalue(0,1000,d*1000);
```

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```
 d := d*0.001;          {convert to meter}
 gotoxy(2,11);
 write('Choose conductor joint type:  (A) - Bolted
(250øC),');
 gotoxy(32,12);
 write('(B) - Brazed (450øC) or');
 gotoxy(32,13);
 write('(C) - Welded (1084øC).');
 gotoxy(2,22);
 write(' defaut : ',joint,'
');
 gotoxy(32,15);
 write('Select : ');
 getch(joint);
 joint:=waarde;
 joint := UpCase(joint);
 case joint of
   'A' : Tmax := 250;
   'B' : Tmax := 450;
   'C' : Tmax := 1084;
 else
  gotoxy(57,15);
  write('   ');
  gotoxy(59,15);
  sound(320);
  delay(500);
  nosound;
  conductor;
 end;
end;


procedure surface;
begin
  clrscr;
  border;
  gotoxy(2,7);
  writeln('INPUT : Surface data');
  gotoxy(2,9);
  write('Resitivity of surface layer (ê.m): ');
  ps := getvalue(0,10000,ps);
  if ps > 0 then begin
   gotoxy(2,11);
   write('Depth of surface layer (m): ');
   hs := getvalue(0,10,hs);
  end;
end;



procedure uniform;
begin
 border;
 gotoxy(2,7);
```

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```
 writeln('INPUT : Soil data for UNIFORM layer
assumption');
 gotoxy(2,9);
 write('Resitivity of uniform soil layer (ê.m): ');
 p1 := getvalue(0,10000,p1);
 p2 := p1;
 h1 := 10000;
 surface;
 if (ps <= 0) or (ps = p1) then begin
  Cs := 1;
 end else
  Cs := 1-0.106*((1-(p1/ps))/(2*hs+0.106));
end;


procedure multi;
begin
 border;
 gotoxy(2,7);
 writeln('INPUT : Soil data for MULTI layer assumption
');
 gotoxy(2,9);
 write('  Resitivity of first soil layer (ê.m): ');
 p1 := getvalue(0,10000,p1);
 gotoxy(2,10);
 write('          Depth of first soil layer (m): ');
 h1 := getvalue(0,1000,h1);
 gotoxy(2,11);
 write(' Resitivity of second soil layer (ê.m): ');
 p2 := getvalue(0,10000,p2);
 surface;
 if (ps <= 0) or (ps = p1) then begin
  Cs := 1;
 end else
  Cs := 1-0.106*((1-(p1/ps))/(2*hs+0.106));
end;


procedure soil;
begin
 clrscr;
 border;
 gotoxy(2,7);
 writeln('INPUT : Soil Data');
 gotoxy(2,9);
 write('Choose soil model: (A) - Uniform (single) laye
or');
 gotoxy(21,11);
 write('(B) - Multi (two) layer soil model.');
 gotoxy(2,22);
 write(' defaut : ',soilmodel,'
');
 gotoxy(21,13);
 write('Select : ');
```

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```
 getch(soilmodel);
 soilmodel:=waarde;
 soilmodel := upcase(soilmodel);
  case soilmodel of
   'A' : uniform;
   'B' : multi;
  else
   gotoxy(42,13);
   sound(320);
   delay(500);
   nosound;
   soil;
  end;
end;


procedure usercp;
begin
 gotoxy(2,21);
 write('Enter a load growth factor for the substation, Cp
= ');
 cp := getvalue(0,3,cp);
end;


procedure current;
begin
 clrscr;
 border;
 gotoxy(2,7);
 writeln('INPUT : Fault Current data');
 gotoxy(2,9);
 write('Enter the highest fault current in substation
(Amps): ');
 fault := getvalue(0,100000,fault);
 gotoxy(2,10);
 write('          Enter the current division factor
(0<Sf<1): ');
 sf := getvalue(0,1,sf);
 gotoxy(2,12);
 write('Choose a load growth scenario for the
substation:');
 gotoxy(20,13);
 write('(A) - High growth                       (Cp =
2.0),');
 gotoxy(20,14);
 write('(B) - Meduim growth                     (Cp =
1.6),');
 gotoxy(20,15);
 write('(C) - Low growth                        (Cp =
1.3),');
 gotoxy(20,16);
```

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```
 write('(D) - No load growth                    (Cp = 1.0)
or');
 gotoxy(20,17);
 write('(E) - User defined load growth factor  (Cp =
?).');
 gotoxy(2,22);
 write(' defaut : ',loadgrowth,'
');
 gotoxy(20,19);
 write('Select : ');
 getch(loadgrowth);
 loadgrowth:=waarde;
 loadgrowth := upcase(loadgrowth);
 case loadgrowth of
  'A' : Cp := 2.0;
  'B' : Cp := 1.6;
  'C' : Cp := 1.3;
  'D' : Cp := 1.0;
  'E' : usercp;
 else
   gotoxy(55,22);
   sound(320);
   delay(500);
   nosound;
   current;
  end;
 clrscr;
 border;
 gotoxy(2,7);
 write('INPUT : Fault current data');
 gotoxy(2,9);
 write('Maximum fault current clearing time [tf]
(seconds): ');
 tf := getvalue(0,100,tf);
 gotoxy(2,11);
 write('Maximum shock duration time [ts] (seconds): ');
 ts := getvalue(0,100,ts);
end;


procedure max_current;
var
Condarea,minarea,dmin  : real;
begin
  Ta := 20/(100*pi);
  Df := sqrt(1+(Ta/tf)*(1-exp(-tf/Ta)));
  Imax := Cp*Df*sf*fault;
  minarea := d*1000*d*1000*pi/4;
  condarea := 11.9 * Imax/1000;
  dmin := sqrt(condarea*4)/pi;
  if Condarea > minarea then begin
   loop2:=false;
   clrscr;
   border;
```

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```
    gotoxy(2,7);
    writeln('Conductor diameter check');
    gotoxy(2,9);
    writeln('Minimum diameter of conductor required =
',dmin:5:3,' mm.');
    gotoxy(2,11);
    writeln('Total diameter of conductor installed =
',d*1000:5:3,' mm.');
    gotoxy(2,13);
    writeln('Increase the conductor diameter and re-run
the program.');
    gotoxy(2,22);
    write('Press any key to continue...');
    b := readkey;
  end;
end;


procedure touchstep;
begin
 Estep50  := (1000+(6*Cs*ps))*0.116/(sqrt(ts));
 Estep70  := (1000+(6*Cs*ps))*0.157/(sqrt(ts));
 Etouch50 := (1000+(1.5*Cs*ps))*0.116/(sqrt(ts));
 Etouch70 := (1000+(1.5*Cs*ps))*0.157/(sqrt(ts));
end;


procedure gridR;
begin
  if rodnum=0 then

Rg:=p1*((1/(lxtotal+lytotal)+1/sqrt(20*area))*(1+1/(1+h*s
qrt(20/area))))
  else begin
    h10 := 1/10*sqrt(area);
    h6  := 1/6*sqrt(area);
    if lxtotal/lytotal < 1 then
         x := lytotal/lxtotal
    else x := lxtotal/lytotal;
    if h=0 then begin
      hh :=  0.5 * d;
      k1 := -0.04 * x + 1.41;
      k2 :=  0.15 * x + 5.50;
      pa := lrodavg*p1*p2*(p2*h1+p1*(lrodavg-h1));
    end else
     if (h<h6) and (h>0) then begin
      hh :=  sqrt(d * h);
      k1 := -0.05 * x + 1.20;
      k2 :=  0.10 * x + 4.68;
      pa := lrodavg*p1*p2/(p2*(h1-h)+p1*(lrodavg+h-h1));
     end else
     begin
      hh := sqrt(d * h);
      k1 := -0.05 * x + 1.13;
```

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```
      k2 := -0.05 * x + 4.40;
      pa := lrodavg*p1*p2/(p2*(h1-h)+p1*(lrodavg+h-h1));
     end;

    R1 := p1/(pi*lxtotal+lytotal) *                  {R of
Conductors}
              (Ln(2*lxtotal+lytotal/hh) +
              K1*(lxtotal+lytotal/sqrt(area)) - K2);

    R2 := pa/(2*rodnum*pi*lrodavg) *                 {R of
rods}
              (ln(8*lrodavg/d) -1 +
              2*K1*(lrodavg/sqrt(area))*
              sqr(sqrt(rodnum)-1));

    R12 := pa/(PI*(lxtotal+lytotal)) *
{Mutual R - grid and rods}
               (ln(2*(lxtotal+lytotal)/lrodavg) +
               k1*((lxtotal+lytotal)/sqrt(area)) - k2+1);

    Rg := abs((R1*R2-sqr(R12))/(R1+R2-2*R12));
  end;
end;


procedure Rise;
begin
 GroundPR := Rg*Imax;
end;


procedure y_axis(biggest:real);
var i          : integer;
    max_value : double;
    s          : string;
begin
  if biggest<=10 then
    max_value:=round(biggest)+1
  else
  if (biggest>10) and (biggest<=100) then
    max_value:=round(biggest)+10
  else
  if (biggest>100) and (biggest<=1000) then
    max_value:=round(biggest)+10
  else
  if (biggest>1000) and (biggest<=10000) then
    max_value:=round(biggest)+100
  else
  if (biggest>10000) then
    max_value:=round(biggest)+100;
  for i:=1 to 10 do begin
    textcolor(white);
    str((i*max_value/10):9:2,s);
```

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```
    outtextxy(25,getmaxy-
round((i*max_value/10)/max_value*(getmaxy-100))-53,s);
    moveto(100,getmaxy-
round((i*max_value/10)/max_value*(getmaxy-100))-50);
    lineto(110,getmaxy-
round((i*max_value/10)/max_value*(getmaxy-100))-50);
  end;
  SETLINESTYLE(DottedLn,0,NormWidth);
  lineto(getmaxx-100,getmaxy-
round((10*max_value/10)/max_value*(getmaxy-100))-50);
  SetLineStyle(SolidLn,0,NormWidth);
end;



function f1(t,a,b,c,d : real) : real;     {Function F1}
begin
  f1:=ln(t+sqrt(t*t + sqr(sqrt(sqr(a-b)+sqr(c+d)))));
end;


function f2(t,a,b,c,d : real) : real;     {Function F2}
var test  : real;
begin
  test:= t+sqrt(t*t + sqr(sqrt(sqr(a-b)+sqr(c+d))));
  if test=0 then f2:=0 else
    f2:=t*ln(test)-sqrt(sqr(a-b)+sqr(c+d));
end;


function f3(t,u,w : real) : real;         {Function F3}
var  test1,test2,test3  : real;
begin
  test1:=t+sqrt(t*t+u*u+w*w);
  test2:=u+sqrt(t*t+u*u+w*w);
  if w=0 then test3:=0 else
test3:=2*w*arctan((t+u+sqrt(t*t+u*u+w*w))/w);
  if (test1=0) and (test2=0) then
    f3:=-u + test3
  else if test1=0 then
    f3:=-u+ t*ln(test2) + test3
  else if test2=0 then
    f3:=-u+ u*ln(test1) + test3
  else
  f3:=-u+ u*ln(test1) + t*ln(test2) + test3;
end;


function f4(t,u : real) : real;          {Function F4}
var  test1  : real;
begin
  test1:=t+sqrt(t*t+u*u);
  f4:=t*ln(test1)-sqrt(t*t+u*u);
end;
```

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```
procedure MESH1;
var
  i,j,count1,k,m                              : integer;
  x_inc,oux                                   : double;
  x,z,x1,y1,z1,L,vdr,xvdr,yvdr,zvdr           : real;
  L2,x2,y2,z2,oux1,a1,biggest                 : real;
  s                                           : string;

begin
 count:=1;
 oux:=100;
 gd:=detect;
 initgraph(gd,gm,'');                      {Set up screen for
graphics output}
 z:=  0;
{ n:=round(iter);}
 z1:= -h;
 L:=lx[1]/(2*n);
 x1:=xdir_from_xco[1]+L;
 y1:=xdir_from_yco[1];
 L2:=lx[1]/(2*n);
 x2:=xdir_from_xco[1]+L2;
 y2:=xdir_from_yco[1];
 z2:=z1;
 a1:=(d/2);
 x_inc:=(getmaxx-200)/100;
 x:=xdir_from_xco[1]-2;

 outtextxy(0,0,'Calculating...Please Wait');

  for count:=1 to 100 do begin                  {Number of
points on plot}
     count1:=0;
     xvdr:=0;
     yvdr:=0;
     zvdr:=0;
     for i:=1 to xdir do begin
       for j:=1 to n do begin
         vdr:=f1(x-x1+L,y,y1,z,-z1);
         vdr:=vdr-f1(x-x1-L,y,y1,z,-z1);
         vdr:=vdr+f1(x-x1+L,y,y1,z,z1);
         vdr:=vdr-f1(x-x1-L,y,y1,z,z1);
         vdr:=vdr*(1/(8*L*pi*p1));
         xvdr:=xvdr+vdr;
         x1:=x1+2*L;
       end;
       L:=lx[i]/(2*n);
       x1:=xdir_from_xco[i]+L;
       if xdir_from_yco[i]>y1 then y1:=xdir_from_yco[i];
       count1:=count1+1;
     end;
     count1:=0;
```

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```
      L:=ly[1]/(2*n);
      x1:=ydir_from_xco[1];
      y1:=ydir_from_yco[1]+L;
      for i:=1 to ydir do begin
        for j:=1 to n do begin
          vdr:=f1(y-y1+L,x,x1,z,-z1);
          vdr:=vdr-f1(y-y1-L,x,x1,z,-z1);
          vdr:=vdr+f1(y-y1+L,x,x1,z,z1);
          vdr:=vdr-f1(y-y1-L,x,x1,z,z1);
          vdr:=vdr*(1/(8*L*pi*p1));
          yvdr:=yvdr+vdr;
          y1:=y1+2*L;
        end;
        L:=ly[i]/(2*n);
        y1:=ydir_from_yco[i]+L;
        if ydir_from_xco[i]>x1 then x1:=ydir_from_xco[i];
        count1:=count1+1;
      end;
      count1:=0;
      z1:=-h-L;
      for i:=1 to rodnum do begin
        L:=lenrod[i]/(2*n);
        x1:=rodxco[i];
        y1:=rodyco[i];
        vdr:=f1(z-z1+L,x,x1,y,-y1);
        vdr:=vdr-f1(y-y1-L,x,x1,y,-y1);
        vdr:=vdr+f1(z-z1+L,x,x1,y,-y1);
        vdr:=vdr-f1(z-z1-L,x,x1,y,-y1);
        vdr:=vdr*(1/(8*L*pi*p1));
        zvdr:=zvdr+vdr;
        z1:=z1-2*L;
        count1:=count1+1;
      end;
     xv[count]:=xvdr;
     yv[count]:=yvdr;
     zv[count]:=zvdr;

vp[count]:=(xv[count]+yv[count]+zv[count])*imax/(n*(xdir+
ydir+rodnum));
     x:=x+(maksxdir+4)/100;
  end;

   oux:=100;
   biggest:=0;
   for count:=1 to 100 do if vp[count]>biggest then
biggest:=vp[count];
   setupscreen;
   y_axis(biggest);
   for count:=1 to 100 do begin
     if count=1 then else if count=2 then
moveto(round(oux),getmaxy-50-
round(vp[count]/biggest*(getmaxy-100))) else
        lineto(round(oux),getmaxy-50-
round(vp[count]/biggest*(getmaxy-100)));
```

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```
    oux:=100+(count+1)*x_inc;
  end;
  str(groundpr:9:2,s);
  setcolor(black);
  outtextxy(0,0,'Calculating...Please Wait');
  setcolor(lightgray);
  outtextxy(getmaxx-420,0,'Ground Potential Rise (V): ');
  outtextxy(getmaxx-200,0,s);
  outtextxy(0,0,'Press <ENTER> to exit');
  readln(b);
  closegraph;
  writeln(alpha,count);
  for i:=1 to count do begin
    writeln(alpha,xv[i]);
    writeln(alpha,yv[i]);
    writeln(alpha,zv[i]);
  end;
end;


procedure algprint;
begin
 clrscr;
 border;
 gotoxy(2,7);
 writeln('OUTPUT : Area, Length and Grid Resistance');
 gotoxy(2,9);
 writeln('Total AREA of grounding grid = ',area:5:2,'
mý.');
 gotoxy(2,11);
 writeln('Total LENGTH of buried conductor =
',Length:5:2,' m.');
 gotoxy(2,13);
 writeln('Grid RESISTANCE = ',Rg:3:2,' ê.');
 gotoxy(2,22);
 write('Press any key to continue...');
 b := readkey;
end;


procedure stgprint;
begin
 clrscr;
 border;
 gotoxy(2,7);
 writeln('OUTPUT : Touch and step voltage criteria and
maximum ground potential rise');
 gotoxy(2,9);
 writeln('TOUCH Voltage (70 kg) = ',Etouch70:5:2,' V');
 gotoxy(2,11);
 writeln('STEP Voltage (70 kg) = ',Estep70:5:2,' V');
 gotoxy(2,13);
 writeln('Maximum Ground Potential Rise =
',GroundPR:5:2,' V');
```

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```
 gotoxy(3,16);
 write('In order to attain a safe grounding grid, the GPR
must be');
 gotoxy(3,17);
 write('below the tolerable TOUCH voltage. ');
 gotoxy(2,22);
 write('Press any key to continue...');
 b := readkey;
end;


procedure vcheck;
begin
 clrscr;
 border;
 gotoxy(2,7);
 write('OUTPUT : Prelimary Design Check');
 groundpr := trunc(groundpr);
 etouch70 := trunc(etouch70);
 if groundpr > etouch70 then
  begin
   gotoxy(2,9);
   write('Calculations based on the prelimary design
indicate that dangerous potentials');
   gotoxy(2,10);
   write('can exist within the substation yard.  This is
unacceptable and the design ');
   gotoxy(2,11);
   write('must be revised.  The following remedies should
be applied where appropriate:');
   gotoxy(2,13);
   write('- Decrease the grid resistance by increasing
the area occupied by the grid.');
   gotoxy(2,14);
   write('- Improve the gradient control by closer
conductor spacing.');
   gotoxy(2,15);
   write('- Divert a greater part of the fault current to
other parts in the grid.');
   gotoxy(2,16);
   write('- Limit short-circuit currents flowing in the
ground mat to lower values.');
   gotoxy(2,17);
   write('- Prohibit access to dangerous areas.');
   gotoxy(2,19);
   write('By using one or more of the above methods the
design can be made safe.');
   gotoxy(2,20);
   write('Review the design, make the neseccary changes,
and re-run the program.');
   gotoxy(2,22);
   write('Press any key to continue...');
   b := readkey;
```

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```
  end else
  begin
   gotoxy(2,9);
   write('Calculations based on the prelimary design
indicate that no dangerous ');
   gotoxy(2,10);
   write('potentials exists within the substation yard.
This is acceptable and the');
   gotoxy(2,11);
   write('design only need refinements to be completed.
This can include the');
   gotoxy(2,12);
   write('provision of access to equipment by additional
conductors.');
   gotoxy(2,15);
   write('The prelimary design check is satisfactory.');
   gotoxy(10,22);
   write('Press any key to continue...');
   b := readkey;
  end;
end;


procedure write_dimension_data;
begin
  write(alpha,xdir);  write(alpha,' ');
  write(alpha,ydir);  write(alpha,' ');
  write(alpha,rodnum);  write(alpha,' ');
  writeln(alpha,h);
  writeln(alpha,'');
  for i:= 1 to xdir do begin
    write(alpha,xdir_from_xco[i]);
    write(alpha,' ');
    write(alpha,xdir_from_yco[i]);
    write(alpha,'     ');
    write(alpha,xdir_to_xco[i]);
    write(alpha,' ');
    writeln(alpha,xdir_to_yco[i]);
  end;
  writeln(alpha,'');
  for i:= 1 to ydir do begin
    write(alpha,ydir_from_xco[i]);
    write(alpha,' ');
    write(alpha,ydir_from_yco[i]);
    write(alpha,'     ');
    write(alpha,ydir_to_xco[i]);
    write(alpha,' ');
    writeln(alpha,ydir_to_yco[i]);
  end;
  writeln(alpha,'');
  for i:= 1 to rodnum do begin
    write(alpha,rodxco[i]);
    write(alpha,' ');
    write(alpha,rodyco[i]);
```

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```
    write(alpha,'  ');
    writeln(alpha,lenrod[i]);
  end;
end;


procedure write_conductor_data;
begin
  writeln(alpha,d);
  writeln(alpha,tmax);
  writeln(alpha,joint);
end;


procedure write_soil_data;
begin
  writeln(alpha,p1);
  writeln(alpha,ps);
  writeln(alpha,hs);
  writeln(alpha,h1);
  writeln(alpha,p2);
  writeln(alpha,cs);
  writeln(alpha,soilmodel);
end;


procedure write_current_data;
begin
  writeln(alpha,cp);
  writeln(alpha,fault);
  writeln(alpha,sf);
  writeln(alpha,tf);
  writeln(alpha,ts);
  writeln(alpha,loadgrowth);
end;


procedure read_dimension_data;
begin
  read(alpha,xdir);
  read(alpha,ydir);
  read(alpha,rodnum);
  readln(alpha,h);
  for i:= 1 to xdir do begin
    read(alpha,xdir_from_xco[i]);
    read(alpha,xdir_from_yco[i]);
    read(alpha,xdir_to_xco[i]);
    readln(alpha,xdir_to_yco[i]);
  end;
  lxtotal:=0;
```

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```
  maksxdir:=0;
  for i:=1 to xdir do begin
    lx[i]:=xdir_to_xco[i]-xdir_from_xco[i];
    lxtotal:=lxtotal+lx[i];
    if xdir_to_xco[i]>maksxdir then
maksxdir:=xdir_to_xco[i];
  end;
  for i:= 1 to ydir do begin
    read(alpha,ydir_from_xco[i]);
    read(alpha,ydir_from_yco[i]);
    read(alpha,ydir_to_xco[i]);
    readln(alpha,ydir_to_yco[i]);
  end;
  lytotal:=0;
  maksydir:=0;
  for i:=1 to ydir do begin
    ly[i]:=ydir_to_yco[i]-ydir_from_yco[i];
    lytotal:=lytotal+ly[i];
    if ydir_to_yco[i]>maksydir then
maksydir:=ydir_to_yco[i];
  end;
  for i:= 1 to rodnum do begin
    read(alpha,rodxco[i]);
    read(alpha,rodyco[i]);
    readln(alpha,lenrod[i]);
  end;
  lrodtotal:=0;
  for i:=1 to rodnum do
    lrodtotal:=lrodtotal+lenrod[i];
  lrodavg:=lrodtotal/rodnum;
  length:=lxtotal+lytotal+lrodtotal;
  area:=maksxdir*maksydir;
end;


procedure read_conductor_data;
begin
  readln(alpha,d);
  readln(alpha,tmax);
  readln(alpha,joint);
end;


procedure read_soil_data;
begin
  readln(alpha,p1);
  readln(alpha,ps);
  readln(alpha,hs);
  readln(alpha,h1);
  readln(alpha,p2);
  readln(alpha,cs);
  readln(alpha,soilmodel);
```

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```
end;


procedure read_current_data;
begin
  readln(alpha,cp);
  readln(alpha,fault);
  readln(alpha,sf);
  readln(alpha,tf);
  readln(alpha,ts);
  readln(alpha,loadgrowth);
end;


procedure init;                  {Default values}
begin
  d:=0.01;                       {Conductor diameter}
  joint:='B';                    {Joint type}
  p1:=0;                         {Resistivity p1}
  p2:=0;                         {Resistivity p2}
  ps:=3000;                      {Surface resistivity}
  h1:=0.1;                       {Depth of surface layer}
  cp:=0;                         {Load Growth Factor}
  fault:=0;                      {Fault current}
  sf:=1;                         {Current Division Factor}
  tf:=0.5;                       {Fault Time}
  ts:=0.5;                       {Shock Time}
  loadgrowth:='D';               {Default loadgrowth}
  soilmodel:='A';                {Default soilmodel}
  iter:=100;                     {Default number of
Iterations}
end;


procedure numbers;
begin
  str(i,s);
  outtextxy(96+(i+2)*round((getmaxx-
200)/(maksxdir+4)),getmaxy-40,s);
  moveto(100+(i+2)*round((getmaxx-
200)/(maksxdir+4)),getmaxy-50);
  lineto(100+(i+2)*round((getmaxx-
200)/(maksxdir+4)),getmaxy-55);
end;


procedure setupscreen;
begin
  settextstyle(defaultfont,vertdir,1);
  outtextxy(50,round(getmaxy/3),'Voltage (p.u.)');
  settextstyle(defaultfont,horizdir,1);
  outtextxy(round(getmaxx/3),getmaxy-20,'X Coordinate
(m)');
```

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```
  line(100,40,100,getmaxy-50);
  line(100,getmaxy-50,getmaxx-90,getmaxy-50);
  setlinestyle(solidln,0,normwidth);
  for i:=-2 to round(xdir_to_xco[xdir]+2) do begin
    if xdir_to_xco[xdir]<=10 then numbers else
    if (xdir_to_xco[xdir]>10) and (xdir_to_xco[xdir]<=50)
then begin
      if (i mod 5)=0 then numbers;
    end else
    if (i mod 10)=0 then numbers;
  end;
end;



{M A I N   P R O G R A M}
var  x_inc   : double;
     oux     : double;
     biggest : real;

begin
  background:=lightgray;
  lines:=blue;
  name:='NONE';
  DetectGraph(gd,gm);
  registreer_grafika(gd);
  clrscr;
  intro;                   {G R I D  screen}
  entree;                  {Begin screen}
  cleanup;                 {Clear output arrays}

loop1:=True;
while loop1 do begin
    clrscr;
    border;
    gotoxy(2,7);
    write('File management');
    gotoxy(2,9);
    write('Do you want to: ');
    gotoxy(2,11);
    write('(R) ead case data from an existing file, ');
    gotoxy(2,12);
    write('(C) reate a new case file or              ');
    gotoxy(2,13);
    write('(E) xit from program.                     ');
    gotoxy(2,15);
    write('Select : ');
    readln(inputt);
    inputt:=upcase(inputt);

    if inputt='R' then begin      {Read data from
existing file}
      loop2:=true;
      repeat
```

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```
        repeat
          if pos('.',name)>0 then begin
            gotoxy(2,22);  write('USE OF EXTENSIONS NOT
ALLOWED!   RE-ENTER FILE NAME.');
          end;
          gotoxy(2,17);
          write('File name for data : ');
          write('                            ');
gotoxy(23,17);
          readln(name);
        until pos('.',name)=0;
        filename:=concat(name,'.dim');
        assign(alpha,filename);
        {$I-}  reset(alpha);  close(alpha);  {$I+}
        filexist:=(ioresult=0) and (filename<>'');
{**toets of die le^r bestaan}
        if (not filexist) then begin
          gotoxy(2,22);  write('FILE NOT FOUND!   RE-
ENTER FILE NAME');
        end;
      until filexist;
      file_info(10+blink);
      assign(alpha,filename);
      reset(alpha);
      read_dimension_data;
      close(alpha);
      file_info(15);
      filename:=concat(name,'.con');
      file_info(10+blink);
      assign(alpha,filename);
      reset(alpha);
      read_conductor_data;
      close(alpha);
      file_info(15);
      filename:=concat(name,'.sol');
      file_info(10+blink);
      assign(alpha,filename);
      reset(alpha);
      read_soil_data;
      close(alpha);
      file_info(15);
      filename:=concat(name,'.cur');
      file_info(10+blink);
      assign(alpha,filename);
      reset(alpha);
      read_current_data;
      close(alpha);
      file_info(15);
    end else

    if inputt='C' then begin        {Create a new data
file}
      loop2:=true;
      init;
```

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```
      repeat
        if pos('.',name)>0 then begin
          gotoxy(2,22);  write('USE OF EXTENSIONS NOT
ALLOWED!  RE-ENTER FILE NAME');
        end;
        gotoxy(2,17);
        write('File name for data : ');       {input file
name}
        write('                             ');
gotoxy(23,17);
        readln(name);
      until pos('.',name)=0;
      filename:=concat(name,'.dim');
      griddim;                                {input
dimension data}
      file_info(12+blink);
      assign(alpha,filename);
      rewrite(alpha);
      write_dimension_data;
      close(alpha);
      file_info(15);
      filename:=concat(name,'.con');
      conductor;                              {input
conductor data}
      file_info(12+blink);
      assign(alpha,filename);
      rewrite(alpha);
      write_conductor_data;
      close(alpha);
      file_info(15);
      filename:=concat(name,'.sol');
      soil;                                   {input soil
data}
      file_info(12+blink);
      assign(alpha,filename);
      rewrite(alpha);
      write_soil_data;
      close(alpha);
      file_info(15);
      filename:=concat(name,'.cur');
      current;                                {input
current data}
      file_info(12+blink);
      assign(alpha,filename);
      rewrite(alpha);
      write_current_data;
      close(alpha);
      file_info(15);
    end else
    if inputt='E' then begin
      loop1:=false;
      loop2:=false;
      clrscr;
      intro;
```

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```
    end;

  while loop2 do begin
    clrscr;
    border;
    gotoxy(2,7);
    write('Select option');
    gotoxy(2,9);
    write('Do you want to: ');
    gotoxy(2,11);
    write('(C) hange the existing case data,');
    gotoxy(2,12);
    write('(S) tart the calculations or ');
    gotoxy(2,13);
    write('(E) xit to start of program. ');
    gotoxy(2,15);
    write('Select : ');
    readln(inputt);
    inputt:=upcase(inputt);

    if inputt='C' then begin                      {Change data}
      clrscr;
      border;
      gotoxy(2,7);
      write('Change existing data');
      gotoxy(2,9);
      write('Do you want to: ');
      gotoxy(2,11);
      write('Change (G) rid dimension data <restart>,');
      gotoxy(2,12);
      write('       (C) onductor data,');
      gotoxy(2,13);
      write('       (S) oil data,');
      gotoxy(2,14);
      write('       (F) ault current data or    ');
      gotoxy(2,15);
      write('       (E) xit to previous menu.    ');
      gotoxy(2,17);
      write('Select : ');
      readln(option);
      option:=upcase(option);
      if option='G' then loop2:=false
      else
      if option='C' then begin
        filename:=concat(name,'.con');
        conductor;
        file_info(12+blink);
        assign(alpha,filename);
        rewrite(alpha);
        write_conductor_data;
        close(alpha);
        file_info(15);
      end else
      if option='S' then begin
```

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```
          filename:=concat(name,'.sol');
          soil;
          file_info(12+blink);
          assign(alpha,filename);
          rewrite(alpha);
          write_soil_data;
          close(alpha);
          file_info(15);
        end else
        if option='F' then begin
          filename:=concat(name,'.cur');
          current;
          file_info(12+blink);
          assign(alpha,filename);
          rewrite(alpha);
          write_current_data;
          close(alpha);
          file_info(15);
        end else
        if option='E' then begin
         loop1:=false;
        end;
      end else

      if inputt='S' then begin                          {Start
calculations}
         max_current;                                   {Calc Max
current}
         touchstep;                                     {Calc Touch
and Step voltage criteria}
         gridR;                                         {Calc Area
and Rg}
         Rise;                                          {Calc Ground
Potential Rise (GPR)}
        loop3:=true;
        while loop3 do begin
          clrscr;
          border;
          file_info(15);
          gotoxy(2,7);  write('Results');
          gotoxy(2,9);  write('(S) afety check');
          gotoxy(2,10); write('(M) esh voltage
calculations');
          gotoxy(2,11); write('(E) xit to previous menu');
          gotoxy(2,13); write('Select : ');
readln(optionl);
          optionl:=upcase(optionl);
          if optionl='S' then begin
            loop3:=false;
            algprint;               {Print area, length and
grid resistance}
            stgprint;               {Print step, touch and
ground potential rise}
            vcheck;                 {Check design}
```

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```
        end else
        if option1='M' then begin
          loop3:=false;
          filename:=concat(name,'.mes');
          assign(alpha,filename);
          {$I-}  reset(alpha);  close(alpha);  {$I+}
          filexist:=(ioresult=0) and (filename<>'');
{Test for File}
          ans:='C';
          if filexist then begin
            gotoxy(2,15);  write('Use existing data in
(F)ile or (C)ompute new mesh data : ');
            read(ans); ans:=upcase(ans);
            if ans='F' then begin
              file_info(10+blink);
              assign(alpha,filename);
              reset(alpha);
              readln(alpha,count);
              for i:=1 to count do begin
                readln(alpha,xv[i]);
                readln(alpha,yv[i]);
                readln(alpha,zv[i]);
              end;
              close(alpha);
              file_info(15);
              gd:=detect;
              initgraph(gd,gm,'');
              for i:=1 to count do begin

vp[i]:=(xv[i]+yv[i]+zv[i])*imax/(n*(xdir+ydir+rodnum));
              end;

              x_inc:=(getmaxx-200)/100;
              oux:=100;
              biggest:=0;
              for count:=1 to 100 do if vp[count]>biggest
then biggest:=vp[count];
              setupscreen;
              y_axis(biggest);
              for count:=1 to 100 do begin
                if count=1 then else if count=2 then
moveto(round(oux),getmaxy-50-
round(vp[count]/biggest*(getmaxy-100))) else
                  lineto(round(oux),getmaxy-50-
round(vp[count]/biggest*(getmaxy-100)));
                oux:=100+(count+1)*x_inc;
              end;
              str(groundpr:9:2,s);
              setcolor(black);
              outtextxy(0,0,'Calculating...Please Wait');
              setcolor(lightgray);
              outtextxy(getmaxx-420,0,'Ground Potential
Rise (V): ');
              outtextxy(getmaxx-200,0,s);
```

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```
                outtextxy(0,0,'Press <ENTER> to exit');
                readln(b);
                closegraph;
              end;
          end;
            if ans='C' then begin
              gotoxy(2,15);
              write('Enter the Y-direction distance (m)
from the origin for profile : ');
              y:=0.0;
              y := getvalue(xdir_from_yco[1]-
1,xdir_to_yco[ydir]+1,y);
              filename:=concat(name,'.mes');
              assign(alpha,filename);  rewrite(alpha);
              file_info(12+blink);
              gettime(uur,min,sek,sek100);
              mesh1;
              close(alpha);
              file_info(15);
            end;
            clrscr;
          end else
          if optionl='E' then loop3:=false;
        end;
      end else
      if inputt='E' then loop2:=false;
    end;
  end;
  clrscr;
  end.
```

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Annexure B

Example 2 : 'KSV SHAFT 132/6.6 kV' Substation

The data for Example 2 is stored on the disk as "EXAMPLE2".

Field Data: The earth mat at KSV Shaft consists of a horizontal grid with *40 x-direction* conductors and *42 y-direction* conductors. The grid also has *48 z-direction* earth rods, of 2 meter length. The diameter of the conductors are 10 mm and all joints are brazed. The grid is buried in multi-layer soil, and therefore a two-layer soil model will be used. The resistivity of the first layer is 60 ohm.m with a depth of 8 m. The resistivity of the second layer is 20 ohm.m and that of the 100 mm deep surface layer is 3000 ohm.m. The maximum 3Io fault current in the substation is 6000 Amp with a current distribution factor of 0.5. The future load growth factor will be taken as 1. The fault and shock duration will be assumed equal at 0.5 seconds.

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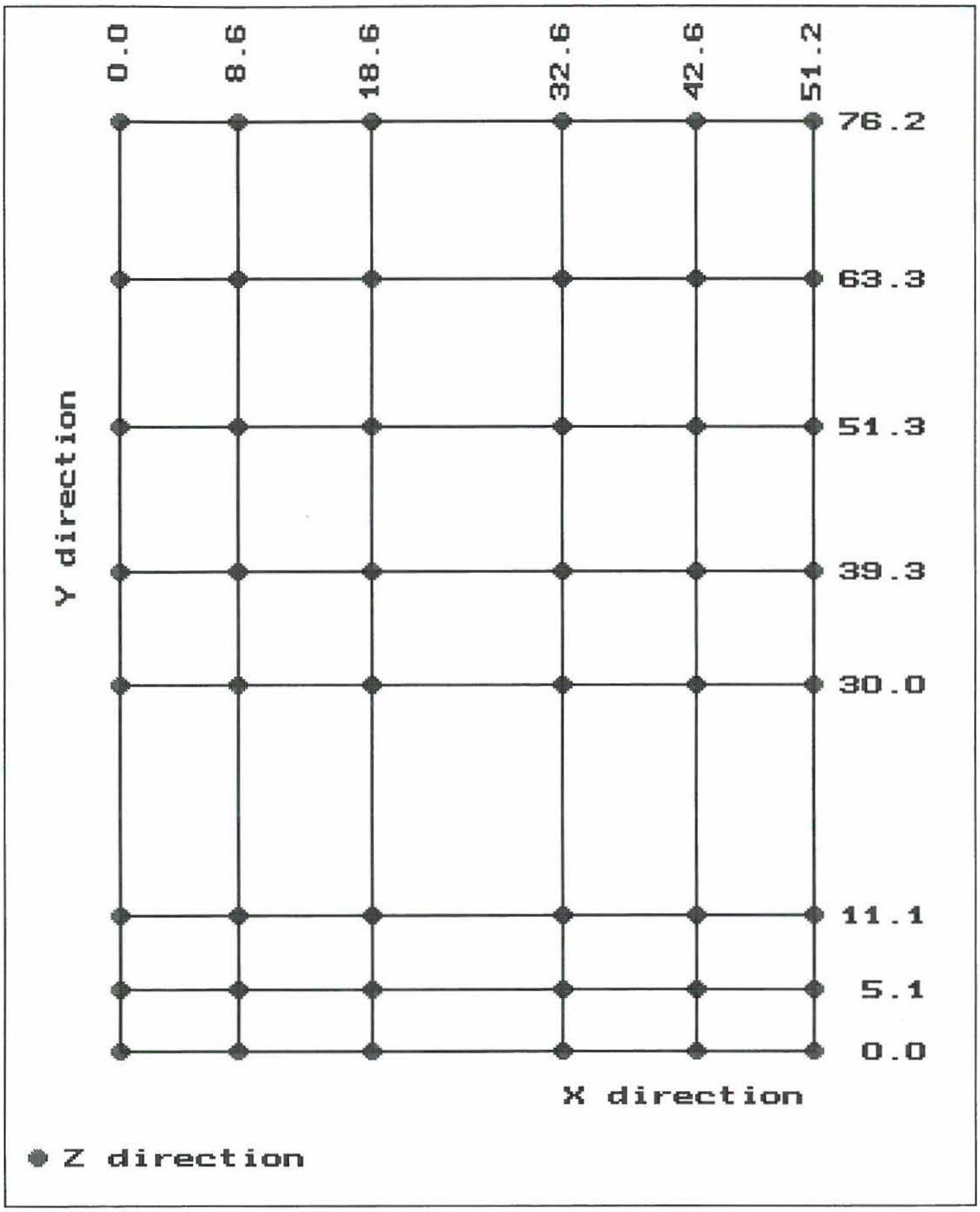

Diagram of Example 2 Earth Mat Layout.

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Annexure C

Equations for Voltage Distribution Factors.

Equations for Voltage Distribution Factors between a Conductor Segment and a Point (Transfer Resistance)

Direction of conductor segment [a,b]	Voltage distribution factors [c]
x-directed	
$\frac{1}{8L\pi\sigma}\left[F_1(x-x_1+L,A_x^-)-F_1(x-x_1-L,A_x^-)+F_1(x-x_1+L,A_x^+)-F_1(x-x_1-L,A_x^+)\right]$	
y-directed	
$\frac{1}{8L\pi\sigma}\left[F_1(y-y_1+L,A_y^-)-F_1(y-y_1-L,A_y^-)+F_1(y-y_1+L,A_y^+)-F_1(y-y_1-L,A_y^+)\right]$	
z-directed	
$\frac{1}{8L\pi\sigma}\left[F_1(z-z_1+L,A_z^-)-F_1(z-z_1-L,A_z^-)+F_1(z-z_1+L,A_z^+)-F_1(z-z_1-L,A_z^+)\right]$	

[a]Conductor segment length is 2L.
[b]Conductor segment is centered at (x_1, y_z, z_1).
[c]$F_1(t,u) = \ell n[t + (t^2 + u^2)^{0.5}]$; $A_x^{\pm} = [y - y_1)^2 + (z \pm z_1)^2]^{0.5;}$ $A_y^{\pm} = [(x - x_1)^2 + (x \pm z_1)^2]^{0.5}$; $A_z^{-} = [(x - x_1)^2 + (y - y_1)^2]^{0.5}$.

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Equations for Voltage Distribution Factors between Two Conductor Segments (Mutual Resistance)

Conductor direction[a,b]		
Segment 1	Segment 2	Voltage distribution factors[c,d]
x-directed	x-directed	$\frac{1}{16L_1L_2\pi\sigma}$ $[F_2(x_2-x_1+L_1+L_2,B_x^- - F_2(x_2-x_1+L_1-L_2,B_x^-)$ $- F_2(x_2-x_1-L_1+L_2,B_x^-)+F_2(x_2-x_1-L_1-L_2,B_x^-)$ $+ F_2(x_2-x_1+L_1+L_2,B_x^+)-F_2(x_2-x_1+L_1-L_2,B_x^+)$ $- F_2(x_2-x_1-L_1+L_2,B_x^+)+F_2(x_2-x_1-L_1-L_2,B_x^+)]$
y-directed	y-directed	$\frac{1}{16L_1L_2\pi\sigma}$ $[F_2(y_2-y_1+L_1+L_2,B_y^- - F_2(y_2-y_1+L_1-L_2,B_y^-)$ $- F_2(y_2-y_1-L_1+L_2,B_y^-)+F_2(y_2-y_1-L_1-L_2,B_y^-)$ $+ F_2(y_2-y_1+L_1+L_2,B_y^+)-F_2(y_2-y_1+L_1-L_2,B_y^+)$ $- F_2(y_2-y_1-L_1+L_2,B_y^+)+F_2(y_2-y_1-L_1-L_2,B_y^+)]$
z-directed	z-directed	$\frac{1}{16L_1L_2\pi\sigma}$ $[F_2(z_2-z_1+L_1+L_2,B_z^- - F_2(z_2-z_1+L_1-L_2,B_z^-)$ $- F_2(z_2-z_1-L_1+L_2,B_z^-)+F_2(z_2-z_1-L_1-L_2,B_z^-)$ $+ F_2(z_2+z_1+L_1+L_2,B_z^-)-F_2(z_2+z_1+L_1-L_2,B_z^-)$ $- F_2(z_2+z_1-L_1+L_2,B_z^-)+F_2(z_2+z_1-L_1-L_2,B_z^-)]$
x-directed	y-directed	$\frac{1}{16L_1L_2\pi\sigma}$ $[F_3(x_2-x_1+L_1,y_2-y_1+L_2,z_2-z_1)-F_3(x_2-x_1+L_1,y_2$ $-y_1-L_2,z_2-z_1)-F_3(x_2-x_1-L_1,y_2-y_1+L_2,z_2-z_1)$ $+F_3(x_2-x_1-L_1,y_2-y_1-L_2,z_2-z_1)+F_3(x_2-x_1+L_1,y_2$ $-y_1+L_2,z_2+z_1)-F_3(x_2-x_1+L_1,y_2-y_1-L_2,z_2+z_1)$ $-F_3(x_2-x_1-L_1,y_2-y_1+L_2,z_2+z_1)+F_3(x_2-x_1-L_1,y_2$ $-y_1-L_2,z_2+z_1)]$

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x-directed z-directed

$$\frac{1}{16L_1L_2\pi\sigma}$$
$$\begin{aligned}&[F_3(x_2-x_1+L_1,z_2-z_1+L_2,y_2-y_1)-F_3(x_2-x_1+L_1,z_2\\&-z_1-L_2,y_2-y_1)-F_3(x_2-x_1-L_1,z_2-z_1+L_2,y_2-y_1)\\&+F_3(x_2-x_1-L_1,z_2-z_1-L_2,y_2-y_1)+F_3(x_2-x_1+L_1,z_2\\&+z_1+L_2,y_2-y_1)-F_3(x_2-x_1+L_1,z_2+z_1-L_2,y_2-y_1)\\&-F_3(x_2-x_1-L_1,z_2+z_1+L_2,y_2-y_1)+F_3(x_2-x_1-L_1,z_2\\&+z_1-L_2,y_2-y_1)]\end{aligned}$$

y-directed z-directed

$$\frac{1}{16L_1L_2\pi\sigma}$$
$$\begin{aligned}&[F_3(y_2-y_1+L_1,z_2-z_1+L_2,x_2-x_1)-F_3(y_2-y_1+L_1,z_2\\&-z_1-L_2,x_2-x_1)-F_3(y_2-y_1-L_1,z_2-z_1+L_2,x_2-x_1)\\&+F_3(y_2-y_1-L_1,z_2-z_1-L_2,x_2-x_1)+F_3(y_2-y_1+L_1,z_2\\&+z_1+L_2,x_2-x_1)-F_3(y_2-y_1+L_1,z_2+z_1-L_2,x_2-x_1)\\&-F_3(y_2-y_1-L_1,z_2+z_1+L_2,x_2-x_1)+F_3(y_2-y_1-L_1,z_2\\&+z_1-L_2,x_2-x_1)]\end{aligned}$$

---

[a]Segment 1 length is $2L_1$. Segment 2 length is $2L_2$.
[b]Segment 1 is centered at (x_1, y_1, z_1). Segment 2 is centered t (x_2, y_2, z_2).
[c]$B\frac{\pm}{x} = [(y_2 - y_1)^2 + (z_2 \pm a_1)^2]^{0.5}$, $B\frac{\pm}{y} = [x_2 - x_1)^2 + (z_2 \pm z_1)^2]^{0.5}$, $B\frac{-}{z} = [(x_2 - x_1)^2 + (y_2 - y_1)^2]^{0.5}$.
[d]The functions F_2 and F_3 are defined in the text.

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Equations for Self-Voltage Distribution Factors ("Self-Resistance")

Direction of conductor segment[a,b]	Self-voltage distribution factors[c]
x-directed	$\frac{1}{16L^2\pi\sigma}$ $[F_2(2L,a) + F_2(-2L,a) - 2a + F_2(2L,\|z_1\|\sqrt{2}) + F_2(-2L,\|z_1\|\sqrt{2}) - 2\|z_1\|\sqrt{2}]$
y-directed	$\frac{1}{16L^2\pi\sigma}$ $[F_2(2L,a) + F_2(-2L,a) - 2a + F_2(2L,\|z_1\|\sqrt{2}) + F_2(-2L,\|z_1\|\sqrt{2}) - 2\|z_1\|\sqrt{2}]$
z-directed	$\frac{1}{16L^2\pi\sigma}$ $[F_2(2L,a) + F_2(-2L,a) - 2a + F_2(2\|z_1\| + 2L,a) + F_2(2\|z_1\| - 2L,a) - 2F_2(2\|z_1\|,a)]$

[a]Conductor segment length is 2L.
[b]Conductor segment is centered at (x_1, y_1, z_1).
[c]$F_2(t,u) = t \ln[t + (t^2 + u^2)0.5] - (t^2 + u^2)^{0.5}$.

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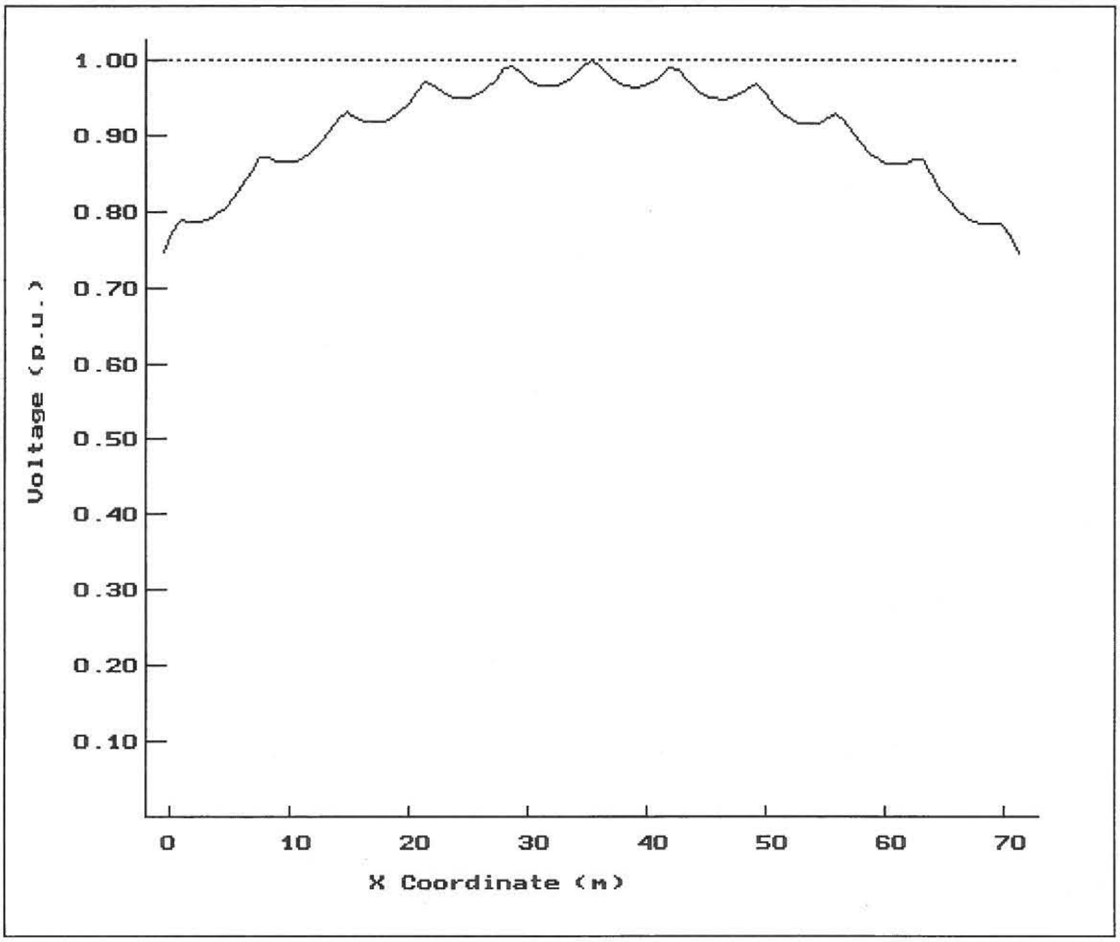
Annexure D

Mesh Voltage profile - Example 1



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