AN EARTHING DESIGN GUIDE FOR SINGLE WIRE EARTH RETURN (SWER) SYSTEMS IN THE NORTHERN CAPE REGION

CARL HEINRICH LOUIS SANDER

Dissertation submitted in fulfilment of the requirements for the Degree

MAGISTER TECHNOLOGIAE:

ENGINEERING: ELECTRICAL

in the

Faculty of Engineering

Department of Electrical Engineering

at the

Technikon Free State

Supervisor: Mr AC Britten, M.Eng.

Co-supervisor: Prof. GJ Prinsloo, Ph.D.(Eng.)

BLOEMFONTEIN

October 1997

DECLARATION OF INDEPENDENT WORK

I, CARL HEINRICH LOUIS SANDER, do hereby declare that this research project submitted for the degree MAGISTER TECHNOLOGIAE: ENGINEERING: ELECTRICAL, is my own independent work that has not been submitted before to any institution by me or anyone else as part of any qualification.

______________________________ ____________

SIGNATURE OF STUDENT DATE

ACKNOWLEDGEMENTS

This study would not have been possible without the help of several people from Eskom.

Firstly I would like to express my sincere gratitude and respect towards my supervisor, Mr Tony Britten, for his valued criticism and encouragement, making this goal in my life possible.

I am grateful towards Eskom Network Services, Bloemfontein, Mr Gys Human and Mr Kobus Barnard for the financial support received from them for this thesis and a special word of thanks to Mr Jan de Beer (Technology and Research Manager) of the Technology Research and Investigation Group for funding my journey to Australia.

A special word of thanks to my friend and colleague, Mr Philip Pieterse, for his endless support throughout this study.

I would also like to thank the Technikon Free State - especially Prof. G.J. Prinsloo - for the opportunity to complete this degree at your institution.

Thanks to Dr Henri Geldenhuys, Mr Darryl Chapman, Ms Sulé van der Walt and Ms Anèl Vorster for your assistance throughout this study.

Thank you to my parents for their encouragement during this study.

Finally a special word of thanks to my wife, Nakkie, and my children, Chandré, Simoné and Heinrich for their understanding, endless patience and continual support throughout this study.

SUMMARY

The success of the Reconstruction and Development Programme (RDP) with reference to the electrification of rural areas will be enhanced if cheaper technologies / techniques are applied than the three-phase and single-phase (2 wire) networks now in use.

Single-wire earth return (SWER) technology has been successfully implemented in other countries as part of their rural electrification plan, and already partially in Eskom.

The SWER technology consists of a single overhead high voltage (HV) conductor and the earth is used as the current return path. Savings are possible due to the fact that less material and labour are required to construct the network.

Existing SWER lines in Eskom indicated that savings were achieved. Further studies during this thesis, however, indicated that more savings and efficiency would have been possible if the earth electrodes installed had been designed according to the conditions on site (soil resistivities, soil type etc. were not previously rigorously taken into consideration).

The success and safe implementation of SWER as a technology by Eskom in the Northern Cape region to electrify rural areas, are mostly dependent on the design of the earth electrodes to be installed at the isolating and distribution transformers, as well as the costs involved.

Earthing of SWER systems is different from conventional earthing due to the continuous flow of current in the earth electrode compared with the conventional single-phase (2 wire) and three-phase networks where current will only flow in the earth electrode under fault conditions. This major difference highlights the importance of investigating the earthing practice related to the SWER technology in detail.

The completed study addresses the need for a SWER earthing guide for application in the Northern Cape region. Design factors such as earthing materials, costs, thermal resistivity of the soil, ground potential rise as well as the special conditions

related to the Northern Cape region, namely high soil resistivities, different soil types and seasonal variations, have for the first time been taken into consideration.

As previously mentioned, the feasibility of a SWER scheme is dependent on the earthing costs involved, and this is mainly determined by the previous ground potential rise (GPR) limit of 20V. The ground potential rise limit is a safety limit directly adopted from Australian SWER schemes.

SWER as a technology in the Northern Cape region with its special conditions is dependent on the possibility to increase the GPR limit of 20V. The feasibility of increasing the GPR limit formed the rationale behind this research. Studies indicate that the GPR limit can be increased from 20V to 35V in the Northern Cape region without sacrificing safety.

The studies include simulations done by using a specialised software package called CDEGS.

The success of this research is supported by the feasible, cost-effective safe earth electrodes designed and installed on the Rooiwal SWER scheme. Savings of 87% (R 167 352-00) were achieved by the installation of the SWER earth electrodes designed as part of this thesis. This excludes the additional savings of R 30 000-00 by not using conductive concrete such as mitronite as a standard on all SWER earth electrodes in the Northern Cape region.

OPSOMMING

Die sukses van die Heropbou- en Ontwikkelingsprogram (HOP) met betrekking tot die elektrifisering van landelike gebiede sal slegs slaag indien daar na goedkoper tegnologië gekyk word in plaas van die huidige driefase- en enkelfase- (2 draad) netwerke.

Die "SWER"-tegnologie is suksesvol in ander lande geïnstalleer as deel van hulle landelike elektrifiseringsplan, asook gedeeltelik in Eskom.

Die "SWER"-tegnologie bestaan uit een oorhoofse hoogspanningsgeleier en die aarde om die stroombaan te voltooi. Koste word dus bespaar as gevolg van minder materiaal en arbeid verbonde aan die oprigting daarvan.

Bestaande "SWER"-lyne in Eskom het 'n kostebesparing getoon. Verdere ondersoeke gedurende hierdie studie toon egter dat groter besparings moontlik sou wees deur die installering van aardelektrodes vir die spesifieke toestande op terrein (Grondresistiwiteitstoetse en grondtipes ens. is byvoorbeeld voorheen nie in ag geneem nie).

Die sukses en veilige gebruik van "SWER" as 'n tegnologie deur Eskom in die landelike areas van die Noordkaap, is dus afhanklik van die ontwerp van die aardelektrodes wat geïnstalleer word by die isoleer- en distribusietransformators.

Die beaardingspraktyke rakende "SWER" verskil van bestaande standaarde in dié opsig dat daar 'n voortdurende lasstroom in die aardelektrode vloei en nie soos in konvensionele enkelfase- (2 draad) en driefasestelsels slegs onder fouttoestande nie.

Hierdie unieke verskil het daartoe bygedra dat die beaardingsfilosofie rakende "SWER" in detail ondersoek is. Die studie spreek die behoefte aan 'n "SWER"-beaardingshandleiding vir aanwending in die Noordkaap-omgewing, aan.

Ontwerpfaktore soos beaardingsmateriaal, koste, termiese resistiwiteit van verskillende grondtipes, spanningstyging sowel as die spesiale toestande verwant aan die Noordkaap-omgewing soos hoë grondresistiwiteit, verskillende grondtipes en seisoensveranderinge is vir die eerste keer in ag geneem.

Soos reeds genoem is die uitvoerbaarheid van 'n "SWER"-skema afhanklik van die beaardingskostes, en word grootliks bepaal deur die spanningstygingslimiet van 20V. Hierdie spanningstygingslimiet is daargestel uit 'n veiligheidsoogpunt en direk vanaf Australië geïmplementeer.

"SWER" as 'n tegnologie in die Noordkaap-omgewing met sy spesiale toestande, is dus afhanklik van die verhoging van die spanningstygingslimiet van 20V. Hierdie idee vorm die rasionaal agter hierdie navorsing. Studies het aangedui dat die spanningstygingslimiet in die Noordkaap-omgewing verhoog kan word vanaf 20V tot 35V sonder om die veiligheid van die stelsel te beïnvloed . Studies het simmulasies ingesluit wat uitgevoer is deur die gebruik van 'n spesiale sagtewarepakket met die naam "CDEGS".

Die sukses van hierdie navorsingsprojek word ondersteun deur die uitvoerbare, koste-effektiewe veilige aardelektrodes wat as deel van hierdie projek op die Rooiwal "SWER"-skema geïnstalleer is. Besparings van 87% (R 167 352-00) is teweeg gebring deur die installering van die aardelektrodes wat ontwerp is as deel van hierdie tesis. Hierdie besparings sluit nie die addisionele R 30 000-00 wat teweeg gebring is deur nie meer van geleidende beton as 'n standaard by alle SWER-aardelektrodes gebruik te maak nie.

TABLE OF CONTENTS

CHAPTER THREE

REVIEW OF SWER ELECTRICITY DISTRIBUTION IN AUSTRALIA AND ELSEWHERE

CHAPTER FOUR

REVIEW OF EXISTING SWER ELECTRICITY DISTRIBUTION IN ESKOM AND PARTICULARLY IN THE NORTHERN CAPE REGION

CHAPTER FIVE

EARTHING GUIDE FOR SWER IN THE NORTHERN CAPE REGION

CHAPTER SIX

DISCUSSION AND CONCLUSIONS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

A	-	ampère
ACSR	-	Aluminium Core Steel Reinforced
BIL	-	Basic Insulation Level
°C	-	degree Celsius
dia.	-	diameter
GPR	-	Ground Potential Rise
HOP	-	Heropbou- en Ontwikkelingsprogram
HV	-	high voltage
K	-	kelvin
kg	-	kilogramme
km	-	kilometre
kV	-	kilovolt
kVA	-	kilovolt-ampere
LV	-	low voltage
m	-	metre
ME	-	Main Earth Electrode
MOV	-	maximum over voltage
mm	-	millimetre
MV	-	medium voltage
O/C	-	over current
PVC	-	Polyvinylchloride
R	-	resistance
RDP	-	Reconstruction and Development Programme
RE	-	Rural Electrification
rms	-	root mean square
SABS	-	South African Bureau of Standards
SCAC	-	Steel Core Aluminum Class
sec.	-	seconds
SEF	-	sensitive earth fault
SWER	-	Single-wire Earth Return
TE	-	Transformer Earths

T/R	-	Thermal Resistivity (K.m/W)
TRI	-	Technology Research & Investigation Group of Eskom
TRFR	-	Transformer
UV	-	ultraviolet
V	-	volt

LIST OF SYMBOLS

Ω	-	ohm
λ	-	thermal conductivity (W/K.m)
$\varnothing$	-	temperature rise (°C)
$\wp$	-	Resistivity (ohm metre)

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

During 1991 Eskom started with its electrification programme. This programme was focused on the unelectrified townships and informal settlements that surround towns and cities. The electrification of townships in the close proximity to existing electrical infrastructure is now being completed and Eskom is now moving towards the electrification of the vast unelectrified rural areas such as the former Homelands (Bophuthatswana, Qwa-Qwa, Transkei, Lebowa and Ciskei) and remote farming communities. The provision of electricity to rural households will lead to a significant improvement in the quality of life, and will result in the social upliftment of these peoples [31].

It is also in line with South Africa's Reconstruction and Development Programme (RDP). To meet the objectives of the RDP, 2.5 million households need to be electrified by the year 2000. This includes the electrification of existing schools (approximately 19 000) and clinics (approximately 2 200) as soon as possible [31].

Although South Africa has sophisticated electrical infrastructures with the state of art technology, almost 50 % of the dwellings are unelectrified. The situation is particularly grave in the rural areas where up to 80 % of the dwellings are unelectrified.

Eskom's commitment towards the RDP is to electrify 1,75 million households by the year 1999 (250 000 in 1994 and thereafter 300 000 per year).

The average cost per connection in urban areas is ± R2 000,00/stand compared to ± R6 000,00/stand in rural areas.

The revenue generated by the small distribution loads in the sparsely populated areas due to the extreme poverty found in these areas, does not justify the establishment of existing technologies such as three-phase or single-phase networks, and initiated the need to investigate alternatives for cheap and economic supplies of electricity.

This led to the renewed interest in Single-wire Earth Return (SWER) systems as a technology to reduce the capital layout to provide such an electrical infrastructure. The system comprises of a single high voltage (HV) overhead conductor with the earth as the ground return path. The system has lower design, material, construction and maintenance costs than a single-phase (2 wire) network, and has been successfully implemented in Australia and other countries as part of their Rural Electrification (RE) plan in sparsely populated areas.

1.2 DIFFICULTIES IN THE IMPLEMENTATION OF THE SWER TECHNOLOGY

The successful implementation of SWER as a technology to reduce electrification costs in sparsely populated areas is dependent on the earth electrode design and installation costs involved at the isolating and distribution transformers. The absence of a SWER Earthing Guide in Eskom, indicating the earth electrode to be installed for the specific conditions on site and the costs involved, makes it impossible for the Network planners to investigate and motivate the electrification of a sparsely populated area with a SWER scheme instead of the existing single-phase systems in use.

Earth electrodes installed on existing SWER lines in the Northern Cape region are designed to the Australian GPR limit of 20V. This resulted in the design of large and very expensive earth electrodes because of the difference in soil types and much higher soil resistivities related to the Northern Cape region.

The above-mentioned difficulty can be resolved by the compilation of SWER Earthing Guide indicating the most economic earth electrode configuration to be installed by taking the soil resistivities, soil types, seasonal variations etc. of the Northern Cape region into consideration.

1.3 HYPOTHESIS

SWER earth electrodes can be technically optimised, cost-effectively designed and implemented in the Northern Cape region by considering the thermal resistivity of the soil, the soil type itself, the soil resistivities found on site and a safe-ground potential rise (GPR), thereby making SWER a technology to reduce electrification costs in rural areas.

1.4 SCOPE AND OBJECTIVES OF THIS THESIS

The scope of this study is the cost-effective application of SWER in the Northern Cape region of Eskom with special emphasis on the design of the earth electrodes to be installed in the Northern Cape region.

The main objective of this thesis is to compile a SWER Earth Electrode Design Guide that can be used by the Eskom network planners, designers, contractors and maintenance personnel in the Northern Cape region.

The following needs will be addressed in the earthing guide by taking the South African, and especially the Northern Cape region conditions, into consideration.

⇒ The optimum design of earth electrodes to be installed at the isolating and distribution transformers.

⇒ The safety aspects for humans and animals regarding SWER earth electrodes (specifically the maximum ground potential rise limit to ensure safe step and touch voltages, transfer potentials etc. during normal operating conditions).

⇒ Maintenance of SWER earth electrodes.

⇒ Soil corrosiveness and its effects on the earthing materials used.

⇒ The effect of seasonal variations on the earth electrode resistance.

⇒ Soil resistivity and earth electrode resistance measurements.

⇒ Security of the earth electrodes.

⇒ Soil types and their influence on the earth electrode configuration to be installed.

⇒ Earthing materials to be used.

⇒ Earthing of the following:

- Transformer tank
- Surge arresters (separate earthing of the surge arresters or not)
- Earthing of the isolating transformer
- Earthing of the distribution transformer
- Earthing on the low-voltage (LV) side of the distribution transformer
- Earthing of transformers in villages

The earth electrode designs in this study can be adopted into Eskom via Distribution Technology as a National Standard.

1.5 IMPORTANCE OF THIS STUDY

High construction and material costs and a low return on investment owing to relatively small loads make the electrification of remote rural communities in the Northern Cape region uneconomical compared with conventional three-phase and single-phase rural lines.

A wooden pole, three-phase rural line costs an average of R50 000/km to erect, and a single-phase line approximately R29 000/km. These costs depend on construction configuration, span length, conductor type, etc.

A similar economic dilemma was faced by power authorities in countries such as Australia, New Zealand, Brazil, Canada and India. SWER technology has been implemented successfully by these countries and it is therefore very important to investigate the SWER technology with special emphasis on economic earth electrode designs for implementation by Eskom, thereby ensuring Eskom's electrification targets are within acceptable costs.

1.6 UNIQUENESS OF THIS STUDY

The SWER earth electrode is a continuous current carrying electrode making it different from conventional three-phase and single-phase (2 wire) systems where current will only flow in the earth electrode for the duration of a fault. Due to the continuous current flowing in the earth electrode, a safe GPR to ensure safe step, touch and transferred potentials will for the first time be introduced in designing SWER earth electrodes for installation in the Northen Cape region. The earth electrodes designed will also take the soil type and soil resistivities at different depths into consideration.

This study is also unique from those being conducted elsewhere due to the following special conditions related to the Northern Cape region:

⇒ High soil resistivities

⇒ High temperatures

⇒ Low rainfall statistic levels

⇒ Different soil types (varies from clay to sand and rock)

⇒ Low consumer density

⇒ Long distances from existing three-phase or single-phase (2 wire) networks

After the completion of this study, it will be possible for the network planners to do an accurate cost comparison between SWER and other single-phase systems to ensure the installation of the most cost-effective technology to electrify a sparsely populated area.

1.7 BASIC APPROACH TAKEN

The literature study indicated that the SWER technology was developed by New Zealand and adopted by other countries such as South Africa, India and Australia, of which Australia today, is by far the greatest user of SWER. In fact, most of the papers available on SWER are of Australian origin and those available from India refer to the Australian SWER practice. It thus appears as if the Australians are the leaders in this field, and it was therefore decided to extend the Australian's design principles as a bench mark for designs in Eskom. Their similar environmental conditions to South Africa and their forty years of experience on the SWER technology further supported the above decision.

The fact that there is no real handbook covering SWER in detail, but rather a variety of papers and presentations floating around, necessitate the requirement to combine most of their information in a guide. This will provide the reader with a good background on the function of SWER as a technology as well as the rationale behind certain decisions taken on SWER. This background is most definitely required to understand the earthing practices required because of the continuous ground return current flowing in the earth electrode.

It is also the author's opinion that, due to a lack of experience, research and available information, both previous attempts on earth electrode designs by Eskom have failed.

Earthing costs involved due to the direct adoption of Australian's maximum earth electrode resistance readings to ensure a GPR of 20V led to the installation of large earth electrodes with huge costs involved (see paragraph 5.4). This is because soil resistivities in South Africa and particularly in the Northern Cape region where SWER is needed is much higher than in Australia. The costs of earth electrodes installed on existing SWER lines indicated that a single-phase

(2 wire) line might as well have been constructed at the same cost as the cost of a SWER line.

This problem will be resolved in this study. It is believed to be the first theoretical SWER earth electrode designs that will take soil resistivities at specific depths, the soil type which determines the earth electrode configuration to be installed, and the effect of seasonal variations into consideration. The earth electrode designs will also take the practicalities of the earth electrode installation into consideration. The electrodes will also be designed to a safe GPR to ensure safe step, touch and transferred potentials according to the special needs of the Northern Cape region by taking factors such as high soil resistivities, high temperatures, relatively low rainfall and soil variations into consideration, thereby ensuring a cost-effective earth electrode installation.

CHAPTER TWO

METHODOLOGY

2.1 LITERATURE REVIEW

A literature review formed the first stage of research for this thesis. This review consisted of a detailed scan through available literature and was conducted part-time over a period of twelve months. The literature review was divided into two parts, namely:

⇒ SWER systems in Australia and elsewhere.

⇒ SWER systems in Eskom and particularly in the Northern Cape region.

The scope is wide because of the writer's opinion that it is necessary to explain in some technical detail exactly what SWER is.

Although SWER is an old technique in countries such as Australia, India, New Zealand and Canada, very little information on it is available in South Africa. This led to a decision by Eskom to send a delegation of people consisting of Eskom, Telkom and the Department of Labour to Australia, in order to obtain technical information on the latest technologies regarding SWER (April 1997). The delegation consisted of the author of this thesis, Mr A.C. Britten (Mentor of this thesis) Dr H. J. Geldenhuys - all of Eskom , Dr B. Prinn and Mr C. Lourens of Telkom, and Mr W. Benjamin and Mr P. Laubser of the Department of Labour.

2.2 INVESTIGATION OF STANDARD SWER PRACTICES IN AUSTRALIA AND ELSEWHERE

In Chapter 3 the Australian method of supplying customers via the SWER technology will be explained. It will also include information on SWER applications used by other countries, and will go beyound the questions of earthing, in order to give a clear background on SWER.

2.3 INVESTIGATION OF SWER PRACTICES IN ESKOM, PARTICULARLY IN THE NORTHERN CAPE REGION

Chapter 4 contains information regarding existing SWER systems in Eskom, especially those already in use in the Northern Cape region. This is to ensure that practical experience gained on existing SWER lines will not be lost, but be documented for future reference.

2.4 EARTHING OF SWER SYSTEMS IN THE NORTHERN CAPE REGION

Chapter 5 will explain the earthing of a SWER system in detail as listed in the objective of this study (chapter 1, paragraph 1.4).

2.5 CONCLUSIONS AND DISCUSSION

Chapter 6 rounds off the thesis by discussing the direct and indirect results of this research. The direct results are those which are in line with its main aims. Another area for future research is also identified.

CHAPTER THREE

REVIEW OF SWER ELECTRICITY DISTRIBUTION IN AUSTRALIA AND ELSEWHERE

This chapter gives background on basic principles of established SWER systems in Australia and elsewhere. The scope will be wide to provide the reader with some technical detail on what SWER is.

3.1 INTRODUCTION

This is an in-depth review of the recent Australian practice on SWER. In coming to grips with rural electrification (RE), and in particular economic and technical challenges presented in rural projects or development scenarios, serious consideration was given by the Australians to all the options available to meet the prospective customer's needs. Many overseas power authorities have successfully adopted SWER systems to directly underpin RE policy, which is principally aimed at directly supporting economic development, and to improve the standard of living of the community. It appears that the SWER technique was first used in Australasia by the Bay of Islands Board in New Zealand in about 1941 [20, p.1] [44, p.1].

Australia is by far the greatest user of the SWER system with over 183 500 km of SWER lines in operation [9]. Apart from Australia and New Zealand, SWER distribution is now also in use in Brazil, Canada, the USA, India, and on a limited scale in South Africa.

In RE the majority of project proposals relate to making electricity supplies available to single farms or small clusters of farms and houses either in isolation or scattered throughout sparsely populated areas. On occasions, the economics are clearly in favour of connecting new customers via extensions to the existing conventional grid. This has the dual benefit of efficiently making electricity available and increasing revenue from the existing system.

Typically a SWER system is established from a single-phase (2 wire) or three-phase system. It incorporates a single HV conductor and the system has lower design, material, construction and maintenance costs than a single-phase (2 wire) network. The Australians claim savings on capital costs of up to 40% [22, p.2]. This is confirmed by a report written by the Central Board of Irrigation and Power, New Delhi in 1977 [37, p.2].

3.2 FACTORS TO BE TAKEN INTO ACCOUNT FOR A RURAL ELECTRIFICATION (RE) PROGRAMME

Some of the following factors were seen as the prime motivators for an RE programme, with direct government policy support for underprivileged groups or communities in Australia.

⇒ An area without electricity and with a low population and load density.

⇒ The willingness of the consumer to electrify traditional farming operations and household activities.

⇒ The availability of electrical agricultural plant and equipment.

⇒ A need to support population and industry decentralisation.

⇒ A need to directly support primary production, particularly in export industries.

⇒ Political direction leading to policy decisions to bring electricity to the majority of homes and farms in the state.

⇒ Tight monetary policy within the power authority driving a need to minimise capital outlay and realise an appropriate return on outlay.

⇒ Capacity within the community to pay for rural development.

⇒ Technical knowledge, manpower and plant capability to support RE policy and marketing initiatives.

⇒ Positive rural load projections for initial load coupled with manageable load growth projections.

When SWER was first developed it was intended only to be used in remote areas where the loads were small. This was due to a number of difficulties with the SWER system such as the protection and earthing of the system. Through improved design and extensive field experience, the capabilities of SWER distribution has been significantly extended. This is evidenced by the development of large SWER projects in Australia, supplying over 100 customers and by the adoption of SWER by developing countries (most notably Brazil) for the electrification of rural villages.

The largest single SWER scheme in Australia supplies 107 customers with a connected load of 1,37MW via 2300km of SWER line [22, p.4]. Taylor (1988) describes typical SWER schemes in Australia supplying approximately 80 customers via 400km of line, the most remote customer being 150km from the beginning of the SWER line.

3.3 ADVANTAGES AND DISADVANTAGES OF A SWER SYSTEM

This is a review of SWER as a concept and not Australian SWER only.

3.3.1 ADVANTAGES

⇒ **Simplicity:**

The simple design allows speed in the construction of the system. No equalising of sags is necessary as in the case of a conventional three-phase line.

⇒ **Maintenance:**

Reduced maintenance cost, as the possibility of a conductor-to-conductor fault on single-wire lines is removed.

⇒ **Low Capital Cost:**

Savings are achieved by using only one conductor which results in longer span lengths - thus less structures and material.

⇒ **Metering:**

Load growth can be easily checked by inserting low-voltage instruments directly in the earth lead at the isolating transformer.

⇒ **Voltage:**

A unique advantage of SWER is that there is a voltage rise of 1 to 2 percent at the receiving end (light loads only) instead of a voltage drop whereas voltage drop invariably occurs in three-phase systems [37, p.2].

⇒ **Power factor:**

The power factor of SWER systems is not less than 0,9 to 0,95 [37, p.2].

The reason given is that the inductive loads such as flour mills are run in conjunction with static-phase converters which make use of capacitors as one of the components. It is also stated that the State Electricity Commission of Victoria's SWER lines work at unity power factor or very near to unity power factor, particularly those having less motor loads.

3.3.2 DISADVANTAGES

The Australian methods of SWER reticulation show the following disadvantages.

⇒ **Conversion:**

The full advantage of the long design spans cannot be utilised if three-phase conversion is ever desirable. This is because span lengths are optimised for a single conductor.

⇒ **Interference on telephone lines:**

The system, when operating under high density load conditions, increases the degree of interference with telephone and telegraph lines. If this necessitates conversion of telephone lines, considerable costs can be involved. However, with correct planning, trouble of this nature can be avoided [21, p.2].

⇒ **Earthing:**

The system necessitates a periodic check on earth electrode resistances in order to ensure that no hazard exists from voltage gradients across the surface of the ground.

⇒ **Isolating transformer:**

This unit introduces additional system losses, construction and material costs.

⇒ **Load balance of primary distribution line:**

In common with all single-phase systems, the efficiency of the three-phase primary distribution line is reduced when large loads are to be supplied. The maximum load that can be supplied is largely dependent upon the ability of the three-phase primary distributor to supply the unbalanced single-phase loading. This factor is the greatest disadvantage introduced by SWER (and other single-phase) systems, but it can be overcome if arrangements are made to supply three SWER networks from a common point on the three-phase distributor.

3.4 VOLTAGE USED

Normal Australian SWER voltages are 12,7kV and 19,1kV, being the phase to ground voltages corresponding to three-phase 22kV and 33kV systems respectively. These voltages are adopted as they allow the use of standard insulators, surge arrestors and switchgear. In India, the SWER line voltage are 11kV (phase to ground) when supplied via an isolating transformer of voltage ratio 1:1 and 6,34kV (phase to ground) when directly connected onto a 11kV three-phase line [37, p.5]. The choice of voltage depends on the following factors:

3.4.1 CONSUMER DENSITY

The higher the voltage, the more costly are the main substations. A balance between line costs and substation costs must be considered if an overall economy is to be achieved. The voltage regulation will also improve with the higher voltage. However, this aspect alone is usually not sufficient to justify higher voltages, unless long lines are involved. The Australians claim that it is sometimes more beneficial to use a larger size conductor and a lower voltage to satisfy other requirements such as telephone co-ordination. A comment on this statement is that the higher currents at low voltages will cause higher electromagnetic induction on telephone lines.

3.4.2 CHARGING CURRENT

According to the Australians, the higher the voltage, the higher will the charging current be, which may cause overloading of the primary system, increase line and isolating transformer losses and require an unnecessarily large isolating transformer to supply it [20, p.2].

3.4.3 TELEPHONE CO-ORDINATION

It is stated that the greater part of telephone line interference arises from earth return charging current which increases with higher voltages. Due to higher charging currents, a 19,1kV system therefore usually causes about 50% more telephone interference than a 12,7kV system. However, if the load current is much greater than the charging current, the higher voltage can be more beneficial [21, p.4].

3.4.4 COSTS

The higher the voltage, the less costly are power lines (because of smaller conductor size) for a given power transfer, but the more costly are substations. A balance between line costs and substation costs must be considered if overall economy is to be achieved.

3.5 METHOD OF SUPPLYING SWER LINES

SWER lines are not usually supplied directly from the distribution substation, but are normally connected to conventional distribution lines some distance from the substation. SWER lines may be supplied through isolating transformers, or they may be supplied directly from conventional lines. The SWER technology also lends itself to some alternative applications, and will be discussed briefly.

3.5.1 SWER LINES SUPPLIED BY ISOLATING TRANSFORMERS

The utilising of an isolating transformer supplying a SWER line restricts the path of the earth return currents between the distribution transformer and the isolating transformer [20] [34].

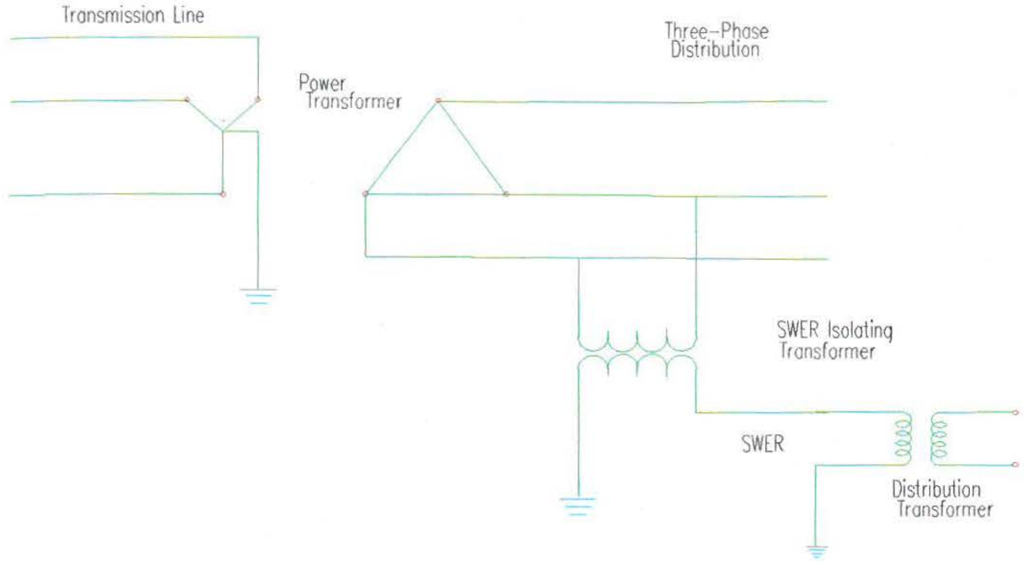


Fig. 3.1 SWER Line Supplied via an Isolating Transformer

3.5.1.1 THE ADVANTAGES OF USING AN ISOLATING TRANSFORMER ARE:

⇒ Isolating transformers enable selection of an operating voltage for SWER lines independent of the voltage of the parent supply system.

⇒ Earth currents which may cause interference in telephone circuits are restricted to areas lying between the individual distribution transformer and the isolating transformer which supplies them.

⇒ Isolating transformers ensure cost-effective voltage control on the SWER lines by providing voltage tapping ranges which permit the use of low-cost, fixed-tap distribution transformers.

⇒ A fault on the SWER line does not bring out the three-phase back-bone line feeding the SWER scheme.

3.5.1.2 THE DISADVANTAGES OF USING AN ISOLATING TRANSFORMER ARE:

⇒ An extra (isolating) transformer is required. This must be rated to supply the entire load connected to the SWER line.

⇒ The isolating transformer is a source of additional voltage drop and losses.

⇒ The relatively high impedance of the isolating transformer will reduce the fault level of the SWER line. This limits the ability of upstream protection (usually overload relays) to detect faults on SWER lines.

⇒ Isolating transformers require a reliable and low-resistance high-voltage earthing system.

⇒ Unforeseen increases (e.g. seasonal changes) in the resistance of the earth electrode of the isolating transformer may result in dangerous step-and-touch voltages at ground level.

3.5.2 DIRECTLY CONNECTED SWER LINES

If SWER lines are to be directly connected to conventional distribution lines, there must be a point of return for the earth currents. For star-connected distribution lines this point is easily established by earthing the star point of the transformer at the distribution substation. For delta-connected distribution lines, earthing transformers must be used to establish the return point. This requires that the earthing transformers be sized to carry the continuous SWER earth return currents. This system is in use on a small scale in countries like Canada, Australia, New Zealand and India [20] [33].

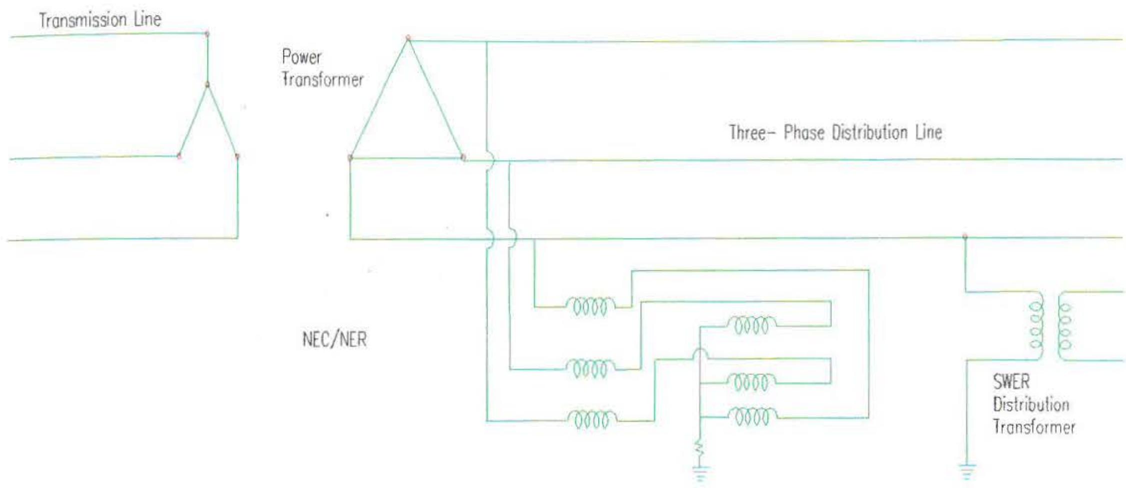


Fig. 3.2 Directly Connected SWER Line

3.5.2.1 THE ADVANTAGES OF SUPPLYING SWER LINES DIRECTLY FROM CONVENTIONAL DISTRIBUTION LINES ARE:

⇒ The main substation earthing mats may be used as the source earth electrode for the SWER lines.

⇒ The substation earthing mats usually have a low resistance, enabling them to carry the SWER return currents.

⇒ The earth currents from SWER lines connected to different phases of the distribution system cancel at the substation earthing mats, if the loads are balanced.

3.5.2.2 THESE ADVANTAGES ARE, TO SOME EXTENT, OUT-WEIGHED BY THE FOLLOWING DISADVANTAGES:

⇒ The earth return currents from the SWER lines have to return all the way to the distribution substation. The path taken by these currents is difficult to predict and they may have an unforeseen effect on underground installations and may cause telephone interference.

⇒ Earthing currents returning to the distribution substation will interfere with sensitive earth fault protection if such protection is used.

⇒ The third harmonic current (if balanced) and its multiples from SWER lines connected to different phases do not cancel, and may cause telephone interference.

3.5.3 THE ISOLATED NEUTRAL TWO-WIRE THREE-PHASE SYSTEM

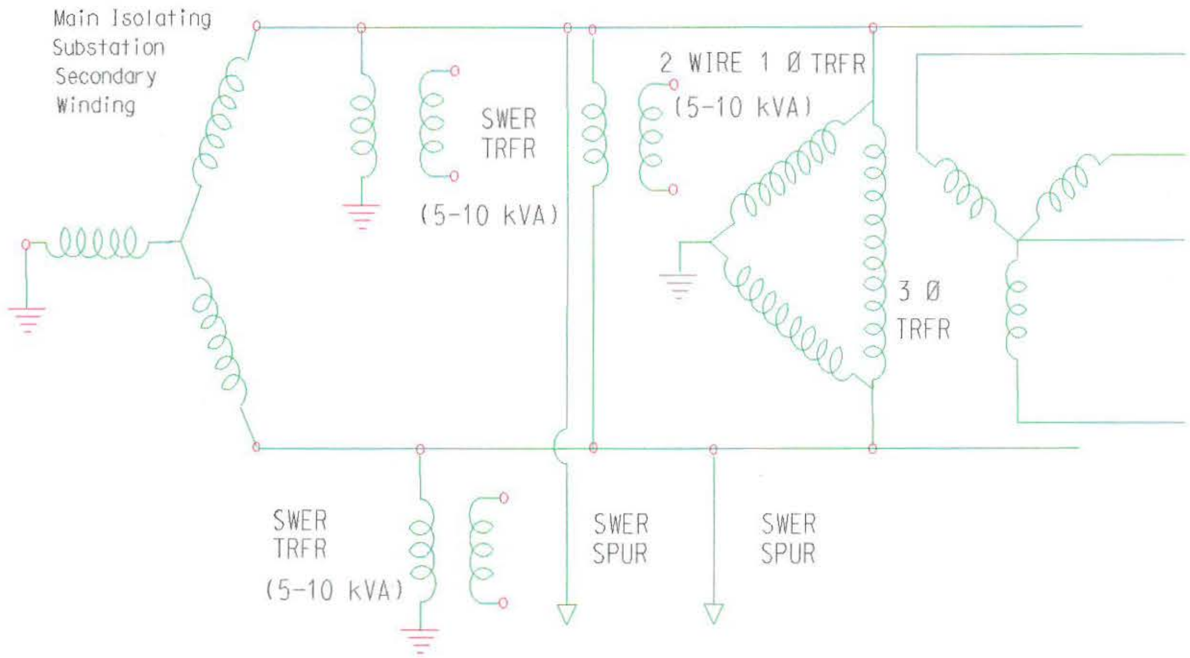


Fig. 3.3 Isolated Neutral Two-Wire Three-Phase System [20, p.14]

This system consists of a two-wire line and a ground return path to form a three-conductor three-phase system. The system requires a specially designed isolating transformer as well as three-phase transformers. [20, p.15]. The single-phase transformers must be fully insulated from ground when connected to the two overhead lines. As in the case of a conventional three-phase system, the three phases are displaced 120 degrees from each other.

This system is used in Rumania and Russia [20, p.15].

3.5.3.1 ADVANTAGES

⇒ The main advantages of this system is that three-phase supply is available if required.

⇒ Open delta wound transformers can be used with graded insulation on the three-phase distribution transformers [20, p.15].

3.5.3.2 DISADVANTAGES

⇒ The insulation levels in respect of ground are high and it has been stated that a basic 22kV three-phase system would require equivalent 28,2kV insulation, and this will also apply to any substation with its transformer windings connected across the two overhead lines.

⇒ The ground return currents do not completely cancel, and the system has only twice the single-phase capacity of a conventional SWER line operating at the same line to ground voltage, and 1,73 times the capacity of a single-wire line when it is used to supply three-phase loads only.

⇒ It is stated that the cost of the line and transformer would be high in comparison with other three-phase hybrid systems [20, p 16].

⇒ Precautions need to be taken to offset the higher charging current to ground compared to other systems by means of reactors or high magnetising current transformers.

⇒ The document claims that the telephone disturbing effect is higher than usual.

⇒ Non-standard voltage three-phase or SWER transformers are required.

⇒ An unbalanced system is caused by the tendency to connect transformers between line and ground and not line to line.

3.5.4 THE GROUNDED NEUTRAL TWO-WIRE THREE-PHASE SYSTEM

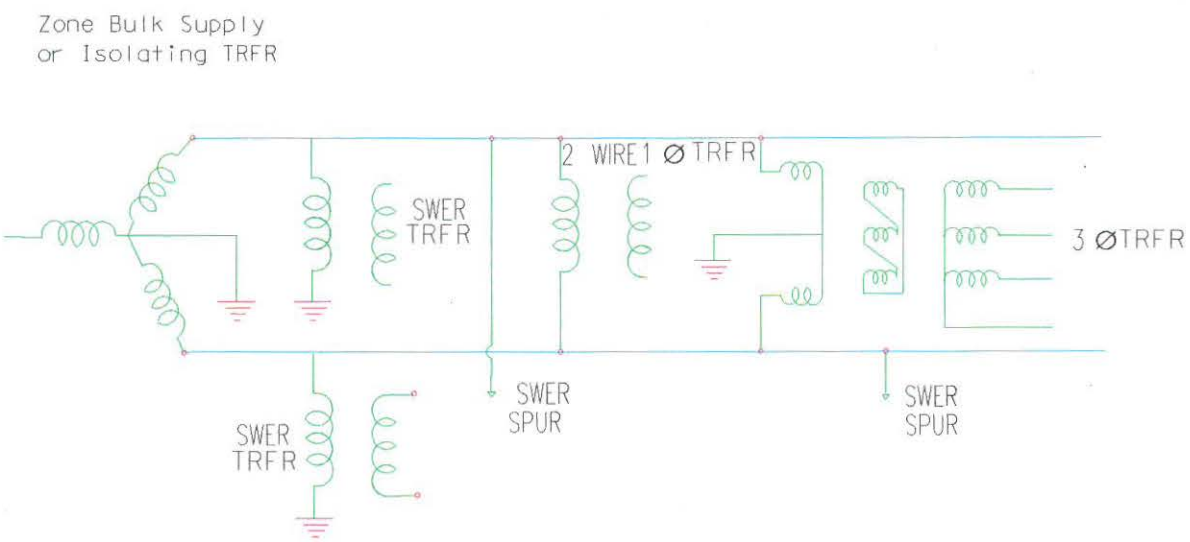


Fig. 3.4 Grounded Neutral Two-Wire Three-Phase System [20, p. 15]

The system consists of a two-wire single-phase circuit which, if required, may be isolated from a three-phase grounded neutral system.

Telkom separation requirements must be met if the system is unisolated because of the earth return route between the load and the neutral earth connection.

With a special wound transformer the supply of three-phase loads is possible [20, p.16].

3.5.4.1 ADVANTAGES

- ⇒ The system is capable of supplying a three-phase supply from a two-wire single-phase line.
- ⇒ The insulation design of the line-to-line and line-to-ground transformers to supply single-phase loads allows for the use of standard transformers.

3.5.4.2 DISADVANTAGES

- ⇒ The earth return currents do not cancel and the system is only capable of supplying twice the load of a conventional SWER line for the same earth return current.
- ⇒ Three-phase loads cause current to flow in the earth return path and are consequently limited. This is not apparent with the three-wire backbone line.
- ⇒ Charging currents along the two-wire route load the ground circuit to the same extent as a single-wire system.
- ⇒ To supply three-phase loads, specially manufactured transformers are required.

3.5.5 DUPLEXED SWER SYSTEM

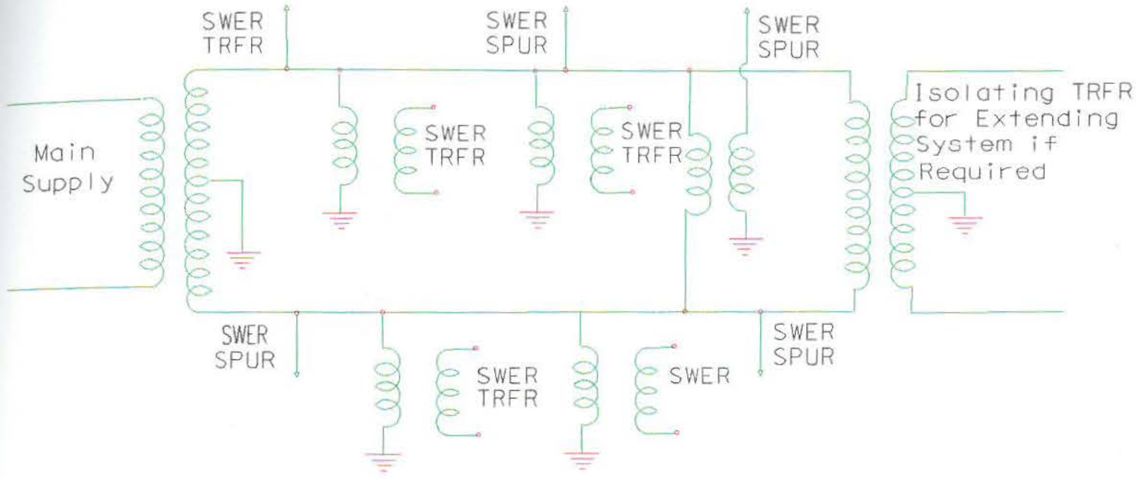


Fig. 3.5 Duplexed SWER System [20, p.16]

The Australians claim that the Duplexed SWER system is an attractive proposition for lines longer than 100 km supplying moderately loaded rural systems.

The system comprises of a two-wire backbone line supplied from an earthed centre tapped isolating transformer as indicated in the above drawing. The line to line voltage on the two-wire section is twice that in relation to ground. The voltages permitted by the system are 19,1kV to ground or 38,3kV line to line.

The Australians claim that, although the line to line voltage is 38,2kV instead of the normal 33kV, no additional insulation is required over that of 33kV [20, p.17]. The system also provides an increase of 34 % in the line rating over 33kV single-phase systems.

The system provides for cheaper construction because a single HV bushing and graded insulated windings are used on the transformers. By balancing substations and line lengths, the load and charging currents in the ground can be kept to a minimum. Charging currents are also kept to a minimum by using high magnetising current transformers or reactors, although stated not necessary for telephone co-ordination [20, p.17].

This system is proposed by the Australians to be used in areas where there is some doubt that conventional SWER systems might cause interference with telecommunication circuits or where the load requirements are to great for a single-phase line. During the Australian visit it was learnt that duplexed systems are less often used.

3.5.5.1 ADVANTAGES

⇒ Judicious balancing of the load keeps the ground currents to a minimum, resulting in an extended length and capacity of the earth return system.

⇒ The Australians claim that the 19,1kV Duplexed system has 20 % greater rating than a three-phase 22kV line using the same conductor after allowing a 1 % voltage drop in the isolating transformer. This system also costs 7 % less [20, p.16].

⇒ High charging currents encountered by long spurs, or unsymmetrically loaded spurs can be counteracted by the use of high magnetising transformers or reactors [20, p.16].

⇒ The balancing of loading cancels harmonics as well as fundamental ground currents thereby reducing telephone interference to about 10% of those caused by conventional SWER lines operating at the same line to ground voltage.

3.5.5.2 DISADVANTAGES

⇒ The system supplies only single phase.

⇒ The extension of the system is limited to the degree of unbalanced loading that can be tolerated at the supply point.

⇒ Unless high magnetising current transformers are used, the line to line charging currents is higher than that of a conventional SWER line.

3.5.6 CONCLUSIONS

When considering the advantages and disadvantages with respect to costs involved by these more elaborate SWER systems as explained in paragraphs 3.5.3; 3.5.4 and 3.5.5 , it appears that the terrain and type of load, (depending on the farming community e.g. irrigation farmers with big motors for pumps or sheep and cattle farms where most of the appliances will only be for household purposes) will determine the type of system required.

With regard to local electrification, these systems are not required as the prospects of load growth and large loads are more often not realistic. It appears that people living in small places far from towns tend to move to bigger towns due to the struggle against unemployment, availability of health services and general life style requirement absence.

The use of non-standard transformers, as in the case of 3.5.2; 3.5.3 and 3.5.5, is against Eskom's policy to standardise and therefore place a bigger burden on these elaborate systems.

Investigations done on existing SWER lines in the Northern Cape region proved that these systems as described in paragraph 3.5.3; 3.5.4 and

3.5.5 would not be required, as the loads are mostly for household purposes.

3.6 LOAD LIMITS ON SWER LINES

When SWER was first applied in New Zealand, the Post and Telecommunication Department laid down a set of regulations to eliminate the possibility of interference between SWER and telephone lines [26, p.6]. Among these regulations, were the maximum earth return current and induced voltage on telephone lines.

3.6.1 MAXIMUM EARTH RETURN CURRENT

The earliest regulation in New Zealand limits the earth return current to a maximum of 8A [10, p.2]. The 8A limit was also adopted in Australia for a number of years, which meant that isolating transformers could not exceed 100kVA at 12,7kV and the line length was restricted to approximately 100km. After electrification of the closely settled areas, the supply authorities were faced with increasing burden of reticulating in the more sparsely settled areas. Practical experience indicates that the 8A ground return current limit can be relaxed, i.e. increased resulting in increased distribution distances over the past thirty years. (see paragraph 3.2). Only the Australian code is known to have relaxed this 8A limit.

3.6.2 INDUCED VOLTAGES ON TELEPHONE LINES

3.6.2.1 REASONS FOR INDUCED VOLTAGES ON TELEPHONE LINES

The earth return current from SWER lines flow deep in the earth, producing extensive magnetic fields. Because of electromagnetic induction, these fields may result in a voltage being induced on parallel telephone lines. The magnitude of the common or longitudinal voltage induced onto telephone lines is determined by the combination of the magnitude of the SWER line current, the distance between the SWER and telephone lines, the length that the SWER and telephone lines run parallel, and the soil resistivity. It is also determined by the frequency and magnitude of harmonic currents, if present.

3.6.2.2 PREVENTION OF INDUCED VOLTAGES ON TELEPHONE LINES

The International Committee (CCITT) now the International Telecoms Union (ITU) on telephones prescribed that the maximum common mode voltage induced on a telephone line from a power line, operating under normal conditions, should not exceed 60V [19, p.3]. Based on a SWER line running parallel to a telephone line for 32km, at a constant separation of 76m, the 50 Hz current required to induce a voltage of 60V on a telephone line was calculated to be 8A. Thus, the 8A load limit for SWER lines was established for safety reasons and not to prevent telephone noise.

The Central Board of Irrigation and Power (New Delhi) conducted field tests in 1977 which showed induced voltages of much lower magnitudes than those predicted by the methods used to established the load limit [37, p14]. These methods will be explained next. It is now recognised that SWER lines operating under normal conditions do not pose a significant hazard to telephone lines due to electromagnetic induction. The 8A limit was thus found to be unnecessary from the point of view of limiting induced voltage on telephone lines [21, p.30].

During the Australian visit it was confirmed that the 8A earth return current restriction no longer exists. Every new SWER network is planned in conjunction with Telstra (Australia's telecoms authority) to ensure that no interferences or danger will occur on their networks [7, p.8]. Most of Australia's telephone networks have been replaced with underground cables.

3.6.3 VOLTAGE ACROSS THE SOURCE ELECTRODE

The entire SWER line current must be carried by the source electrode, resulting in a voltage across this electrode that is equal to the product of the line current and the electrode resistance. The maximum ground potential rise (GPR) of the earth electrode is limited to 20V so as to prevent dangerous step-and-touch potentials [20, p.11] [11, p.12]. This limit of 20V is easily achievable in Australia where soil resistivities vary between 10 ohm metre to 300 ohm metre, and in extreme cases in the deserts between 1000 ohm metre and 10000 ohm metre. SWER lines are unlikely to be constructed in areas where the soil resistivity is higher than 300 ohm metre [27, p.17]. Soil resistivities in India vary between 30 ohm metre and 1000 ohm metre. The maximum SWER line current is limited in accordance with the economically achievable source electrode resistance.

3.6.4 UNBALANCE ON DISTRIBUTION SYSTEM

The greatest disadvantage suffered by SWER (and other single-phase systems) is the effect of these loads on the three-phase backbone lines that feed the SWER lines. Unequal loading among the phases feeding the SWER lines are caused. This results in an unequal voltage drop along the phase conductors and causes NPS (Negative phase sequence) voltages.

This reduces the ability of the three-phase backbone lines to supply loads requiring balanced voltages (e.g. three-phase motors).

3.7 EARTHING OF SWER LINES

The soil performs as one conductor of the current carrying loop in a SWER scheme, and accordingly its properties are a major consideration.

3.7.1 REQUIREMENTS FOR GOOD SOIL CONDUCTIVITY

⇒ A deep cover of soil is needed over rock, as many rock formations have very poor conductivity, e.g. granites, which are exceptionally poor conductors.

⇒ A supply of mobile ions is necessary in the soil structure to enhance conductivity. Soil containing clays will potentially have good or high conductivity.

⇒ The soil must be moist. Without soil moisture there cannot be ionic conduction.

⇒ The soil must be continuous. Cracked clay may meet the above requirements, but due to its discontinuous nature and low pressure contact between adjacent clay damps, it may be a relatively poor conductor.

Any connection between a SWER system and the surrounding soil to create an earth return path, must overcome any soil conductivity problems and seasonal variations. It should have a long life and a low stable resistance characteristic. It should also be relatively low in cost [44, p.4].

3.7.2 FACTORS FOR SAFE EARTHING REQUIREMENTS

The reliability and design of earthing systems is critical to the safety and success of SWER distribution systems. When deciding whether to adopt SWER distribution systems for a particular area, the following earthing factors are taken into consideration by the Australian Power Authorities.

⇒ Soil resistivities determine the complexity and cost of the earthing systems. SWER distribution may not be an economical choice if the area under consideration has high soil resistivities. The seasonal variation of the soil resistivities should also be considered when designing SWER earthing systems. An earthing system carrying load current is subject to resistance loss, and this results in heating and consequent drying of the soil adjacent to the earth electrodes. This factor determines the type and minimum size of a SWER earthing system, particularly in areas subject to drought.

⇒ Expensive earthing materials and fittings may also be necessary to overcome electrode corrosion in acidic soils (e.g. copper).

⇒ Mechanical reliability of the earthing system is very important in areas where cultivation may disturb buried conductors or where passing vehicles or vandalism may damage conductors connecting the transformer to the earthing system. The prime consideration with earthing SWER systems is to safeguard the life of both man and beast.

⇒ The steady state voltage gradients at which stock experience discomfort were found by experiments to be as follows [20, p.11]:

Cow	45 volts per metre of distance
Bullock	13 volts per metre of distance
Lambs	25 volts per metre of distance

This evidence points to the possibility of risk with earthing system voltage drop in excess of 40V. The application of a safety factor of 2 over the voltage gradients at which stock feel discomfort indicates that SWER earthing systems should be designed with a maximum permissible voltage rise on the earth system of 20V under normal operation conditions. With such a limitation, the risk and discomfort are negligible. In line with this, the supply authorities specify the maximum earthing resistances for 12.7kV and 19.1kV system under full load conditions as indicated below [20, p.11].

TABLE 3.1 Distribution Transformers Earth Electrode Resistances

DISTRIBUTION TRANSFORMER	RESISTANCE (Ohms)	VOLTAGE (kV)
5kVA Distribution transformer	30	12.7/19.1
10kVA Distribution transformer	25	12.7/19.1
15kVA Distribution transformer	17	12.7/19.1
25kVA Distribution transformer	10	12.7/19.1

TABLE 3.2 Isolating Transformer Earth Electrode Resistances

ISOLATING TRANSFORMERS	RESISTANCE (Ohms)	VOLTAGE (kV)
20 kVA Isolating transformer	5	12.7/19.1
50 kVA Isolating transformer	5	12.7/19.1
100kVA Isolating transformer	3	12.7/19.1

Although not clear from the literature available, it seems from calculations done on the above that the maximum earth electrode resistances allowed at the distribution transformers are 30 ohm and at isolating transformers 5 ohm (the lower the capacity of the transformer, the higher the resistance).

3.8 SWER LINE ISOLATING TRANSFORMERS

When a SWER line tees off from a three-phase or single-phase distribution line by using an isolating transformer, there are two major factors to consider, namely the isolating transformer itself and the earthing of the isolating transformer.

3.8.1 ISOLATING TRANSFORMERS

In Australia, isolating transformer sizes range from 25kVA to 150kVA and in special cases 300kVA single-phase transformers.

The Electricity Authority of New South Wales (1978) listed the typical technical information on isolating transformers in use in Australia as shown below.

TABLE 3.3 Technical Information on Isolating Transformers [20, p. 31]

RATING (kVA)	25	50	100	150
Weight (kg)	454	773	1 000	1364
Resistance %	2,0	1,8	1,5	1,6
Resistance (12,7kV) ohms	129	58	24,1	-
Resistance (19,1kV) ohms	290	130	54	39
Reactance %	3,0	3,3	3,6	3,8
Reactance (12,7kV) ohms	193	106	58,2	-
Reactance (19,1kV) ohms	434	238	131	92
Impedance %	3,6	3,8	3,9	4,0
No load loss (watts)	140	270	375	700
Copper losses (watts)	500	740	1 500	2 100

3.8.2 EARTHING OF ISOLATING TRANSFORMERS

The earthing of the isolating transformers is critical as the earth electrode must continuously carry the entire SWER line load current and must also be able to carry fault currents.

3.8.2.1 REQUIRED EARTH ELECTRODE RESISTANCE

The earthing of the isolating transformer is usually based on limiting the GPR to 20V during normal operating conditions. (See table 3.2 for maximum resistance of earth electrodes installed at the isolating transformer). To maintain this 20V limit, the required resistance of the earth electrode must decrease as the expected maximum line current increases, as shown in figure 3.6.

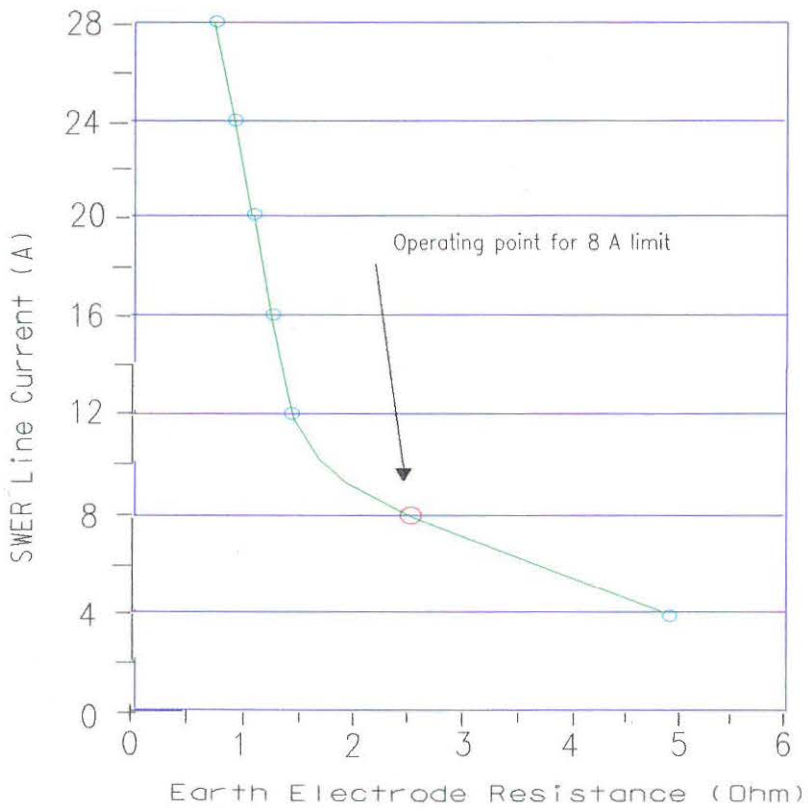


Fig. 3.6 Maximum Isolating Transformer Earth Electrode Resistance Versus SWER Line Load

As indicated in fig. 3.6, the maximum allowable earth electrode resistance for an earth return current of 8A to allow for a maximum GPR of 20V across the earth electrode at the isolating transformer, will be 2.5 ohm.

During line fault conditions the current through the earth electrode can increase causing the 20V GPR limit to be exceeded, resulting in dangerous step and touch potentials.

3.8.2.2 METHOD OF EARTHING

In Australia the method of earthing isolating transformers has undergone a significant change from those first employed [44, p.13].

Initially shallow earthing systems were used with a number of electrodes being driven 2 to 4 metres into the earth. This system of earthing is vulnerable to the drying out of the earth around the shallow electrodes. The immediate problem experienced was thermal runaway and electrode failure due to seasonal variations. After investigations of failure sites, an understanding of the problem readily emerged. The solution was really quite simple. Ensure that the earthing system is always moist, of adequate dimensions, constructed of durable materials (such as copper) and designed to carry the continuous required load current.

After a number of successful field trials, the following procedure was adopted:

⇒ Drill a vertical hole with a diameter of ± 100mm into the ground until it appeared from the drilling soil that water was about to be encountered, or to a maximum depth of 40m. If a substantial band of moist soil is encountered, drill at least another 6m into the moist band. It is important to finish with a hole with relatively dry walls, as wet surfaces will interfere with the placing of filler mix [44, p.13].

⇒ A copper electrode (31,75mm x 3,175mm flat copper strap) must be lowered into the hole and supported so that its lower end is approximately 0,5 metres above the bottom of the hole. The copper strap is vibrated with an ordinary concrete vibration whip bolted to the copper strap, and a dry 4:1 by weight mixture of Bentonite and Gypsum is poured down the hole until full. The vibration helps eliminate the possibility of voids forming along the electrode. The subsequent absorption of moisture by Bentonite causes sufficient swelling to establish a good contact between the electrode and the surrounding ground.

The gypsum is included as a non-toxic conductivity enhancer, mainly for the surrounding soil, as the moist Bentonite is itself a satisfactory conductor.

This type of electrode system is acceptable on environmental grounds, as it is non-toxic. It should be kept in mind that borehole water, into which electrode materials may leach, is used by homesteads as a domestic and stock water supply.

All the joints in the electrode system are phosphor copper brazed with no bolted joints, and copper is the only conductor used in the deep-drilled electrode system.

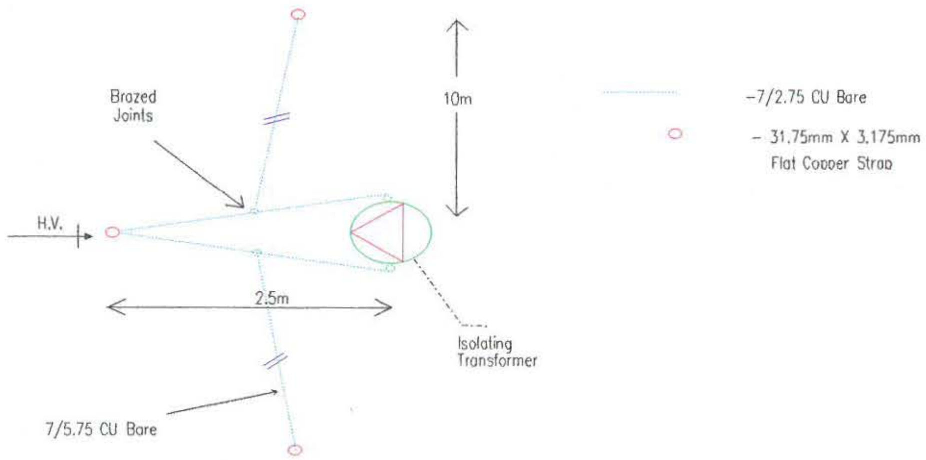


Fig 3.7 Typical Earthing Arrangements of an Isolating Transformer [4]

3.9 DISTRIBUTION TRANSFORMERS

The physical distribution of customers supplied by SWER lines in Australia, generally makes it impossible to connect customers by LV feeders. Thus, in most cases, only one customer is supplied from each distribution transformer.

Initially 5kVA and 10kVA distribution transformers were used on SWER lines. Load growth has led to the 5kVA transformers being regarded as insufficient, whilst 25kVA transformers are becoming widely used.

TABLE 3.4 Technical Information on Distribution Transformers [20, p.31]

RATING (kVA)	5	10
Weight (kg)	136	181
Resistance %	2,6	2,6
Resistance (12,7kV) ohms	840	420
Resistance (19,1kV) ohms	1890	945
Reactance %	2,5	2,5
Reactance (12,7kV) ohms	807	403
Reactance (19,1kV) ohms	1810	905
Impedance %	3,6	3,6
No load loss (watts)	45	60
Copper loss (watts)	130	260

3.9.1 EARTHING OF DISTRIBUTION TRANSFORMERS

The earth electrodes installed at distribution transformers carry a much lower current than the earth electrodes of the isolating transformer. The Electricity Authority of New South Wales (1978) states that under no circumstances should the low-voltage earthing system and high-voltage current carrying earthing system be interconnected, but it should rather be separated so as to prevent any portion of the high voltage system gradient being superimposed on the low voltage system, and so transferred to the customer's installation.

3.9.1.1 SEPARATION OF HIGH-AND-LOW VOLTAGE EARTH ELECTRODES

The separation of high-and low-voltage earths is achieved by:

⇒ Earthing the low voltage neutral one span away from the distribution transformer.

⇒ Locating both earthing systems on the transformer pole but insulating both earth wires below ground level in order to preserve 3m minimum separation between the two systems [20, p.12].

3.9.1.2 REQUIRED EARTH RESISTANCE

The primary earthing electrode of SWER distribution transformers must carry the load current of the transformer while limiting the voltage gradient at the surface of the earth around the electrode. As with isolating transformers, the GPR at the distribution earth electrodes is also limited to 20V. The required resistance of the earth electrodes varies according to the SWER line voltage and the loading of the distribution transformer. The limitation is equivalent to the following maximum earthing resistances under full load conditions and a SWER line voltage of 12.7kV [4]. The same resistances applied for a SWER line voltage of 19,1kV.

TABLE: 3.5 Earth Electrode Resistance at Distribution Transformers

RATING (kVA)	10	15	25
Resistance (ohms)	25	17	10
Voltage (kV)	12.7/19.1	12.7/19.1	12.7/19.1

3.9.1.3 METHOD OF EARTHING

Australian Supply Authorities specify a minimum of 3 x 1500mm long copper clad extensible type electrodes connected to the transformer earthing terminal for each high-voltage earthing system on its SWER network.

This system is successful in ensuring that thermal runaway does not occur under dry soil conditions. To ensure that the system is safe from mechanical damage due to excavations or cultivation near the pole, the supply authorities specify that earthing conductors on the pole are protected by hardwood cover strips, fiberglass battens or galvanised pipes. Conductors below ground level are buried to a minimum depth of 450mm and in a delta arrangement of three earthing electrodes.

For this arrangement, one of the electrodes is placed approximately 2500mm from the pole, another at least 2500mm away from the pole, but on the opposite of the pole and a third electrode is placed so that when the earthing conductors are connected a complete equilateral triangle is formed (See Fig. 3.8) [21].

This arrangement gives an earthing system in the form of a series loop which provides for alternative current paths in the event of one, two or even three earthing conductors being served. For higher resistivity soil, additional electrodes may be necessary to obtain the required values of earth resistance.

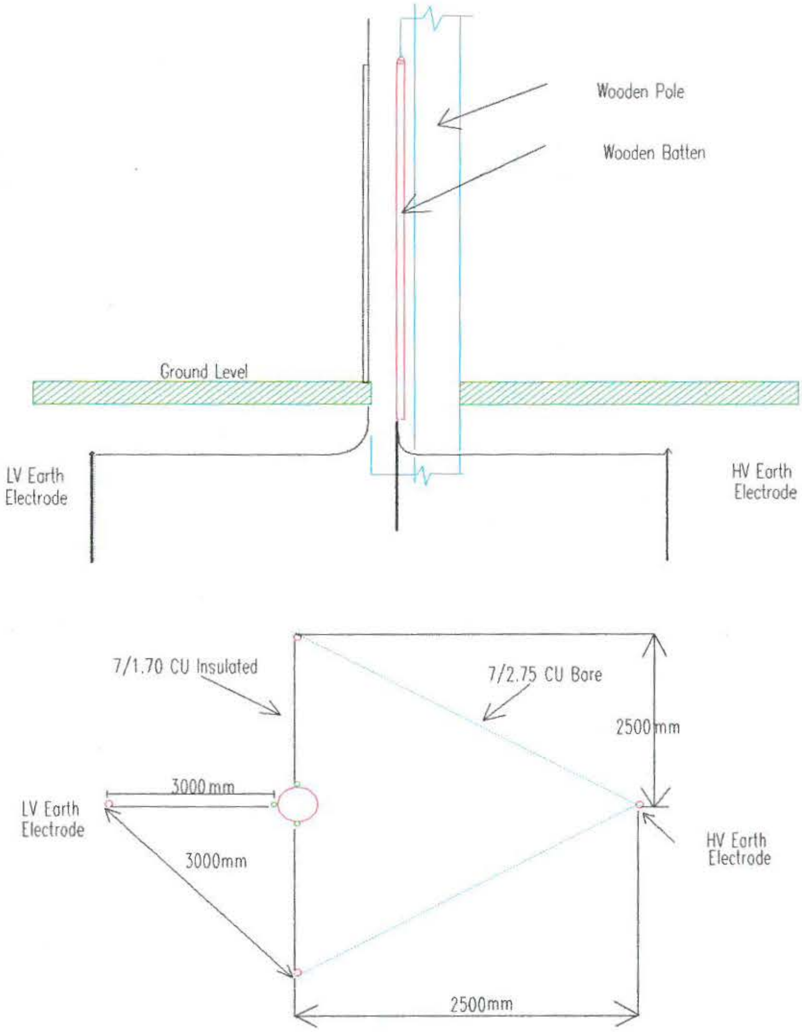


Fig. 3.8 Typical HV Earthing Arrangement at the Distribution Transformer Installation [4].

3.10 PROTECTION OF SWER LINES AND TRANSFORMERS

The only protection available on SWER schemes is O/C (over current) protection. The objective of this protection is to avoid damage to the transformer in the case of a fault on the SWER line and to isolate faulted SWER lines and isolating transformers from the distribution network.

3.10.1 PROTECTION OF ISOLATING TRANSFORMERS

In the early schemes each transformer was protected by an individual high voltage (HV) fuse. When sectionalisers were introduced, a number of Supply Authorities discontinued this practice and in some cases removed the fuses. The added expense of replacing the fuse due to a transient fault such as a lightning strike was seen as unnecessary. One sectionaliser could now do the work of multiple fuses, and also remove transient faults without the need for maintenance personnel.

3.10.2 PROTECTION OF ISOLATING TRANSFORMER EARTH ELECTRODE

Monitoring points are installed to permit "on line" measurement and monitoring of earth current and earth electrode voltage with regard to ground.

The total area now reticulated is vast, and the cost of periodic monitoring and checking of the "health" of each earth electrode system is high. The same time as the main electrode system is installed, a separate earth reference electrode is placed, in general to the same depth as the main electrodes and using similar materials and techniques. A relaying system has been developed to continuously monitor the voltage between the active earth electrode and the reference electrode. There is provision to trip the recloser (and hence the SWER load) if the earth electrode rises above 55 volts for more than 10 seconds [44, p.16].

This voltage and time duration would indicate a failure of the main earth electrode by physical damage, deterioration or dry out. Following such a trip, the isolating transformer installation must be inspected, and if it appears to be safe to do so, the protection can be reset and the reference electrode may be used as the main electrode until repairs can be made.

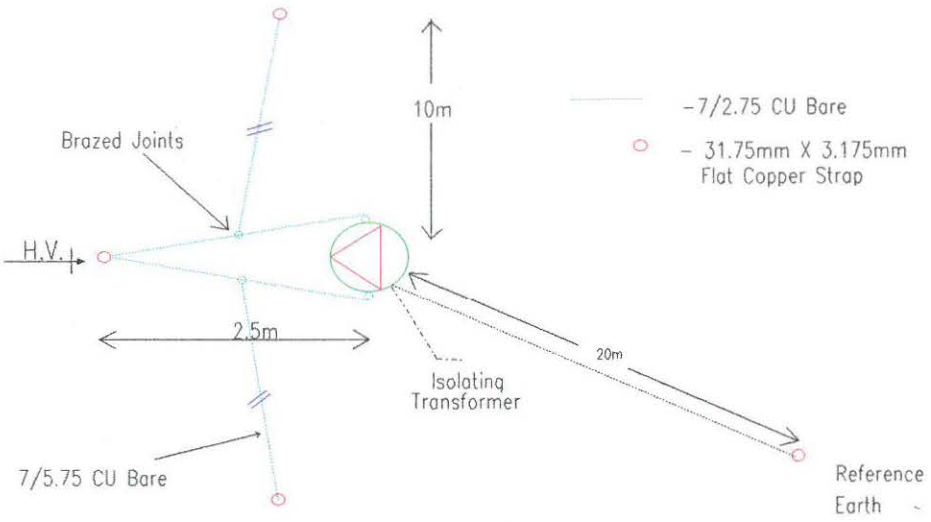


Fig. 3.9. Typical Arrangement for the Installation of a Reference Earth Electrode [44, p.14]

3.10.3 PROTECTION OF DISTRIBUTION TRANSFORMERS

The distribution transformers were protected by drop-out fuses on the primary side of the transformer, but this practice discontinued with the introduction of auto reclosers and sectionalisers.

3.10.4 PROTECTION OF SWER LINES

3.10.4.1 PROTECTION FROM TRANSIENT FAULTS

Up-stream reclosers cannot always be relied on to provide transient fault protection for SWER lines. This is because the impedance of the isolating transformer and the high impedance of the SWER line conductor, usually steel, may limit the fault current to such an extent that it is not picked up by up-stream protection (even if the fault impedance is zero). Thus, it must either be conceded that transient faults on SWER lines will develop into permanent ones and be cleared by the blowing of a fuse, or a single-phase recloser must be installed at the beginning of the SWER line.

Due to the simple design of SWER lines, transient faults are likely to be uncommon and will usually only be caused by lightning strikes (direct or induced). The cost of reclosers must therefore be balanced against the expected frequency of this type of fault. During the author's Australian visit, it was confirmed that almost every SWER line is protected by an auto recloser installed at the isolating transformer with downstream sectionalisers. To prevent nuisance fuse blowing the distribution transformers are connected directly on the SWER line without dropout fuses.

3.10.4.2 PROTECTION FROM PERMANENT FAULTS

If a recloser is installed on the SWER line, it may provide protection against permanent faults by locking open. If a recloser is not used, the drop-out fuses on the primary side of the isolating transformers may be relied on to provide such protection. By limiting the SWER load currents the O/C protection may be set sufficiently low (10A is often used) so as to detect practically all faults.

In Australia the SWER line voltage of 12,7kV is now considered inadequate in some areas, as it is related to protection problems due to high impedance faults. In these areas the SWER voltage is being upgraded to 19,1kV so as to increase the fault current and make the detection of high impedance faults possible [44, p.17].

3.10.5 LIGHTNING PROTECTION

Conventional methods of lightning protection are used on SWER lines. Generally, lightning protection is achieved by insulation co-ordination (150kV BIL on 12.7kV and 200kV BIL at 19.1kV) and by installing surge arresters or sparkgaps to protect all equipment.

3.11 SWER DISTRIBUTION LINES

3.11.1 PHYSICAL CHARACTERISTICS

As SWER lines only have a single conductor, they are extremely simple, this being one of their main advantages over conventional lines.

The electrical loads supplied by SWER lines are usually well within the capabilities of most conductors, thus SWER line conductors are usually selected more for their cost and mechanical properties than for their electrical properties. In Australia, the most widely used SWER conductor is 3/2,75mm galvanised steel, but for relatively heavily loaded lines 4/4/2,5mm ACSR (Aluminium Core Steel Reinforced) conductors are used. However, there seems to be a trend away from steel conductors towards the use of Steel Core Aluminium Class (SCAC) conductors. In India they are using only ACSR conductor on their SWER systems to keep line losses to a minimum [37, p.5].

The conductor on SWER lines is usually located at the very top of the support structure so as to allow for maximum sag.

The effective pole height is usually increased by several centimetres by mounting the insulator on a "L" bracket at the top of the pole.

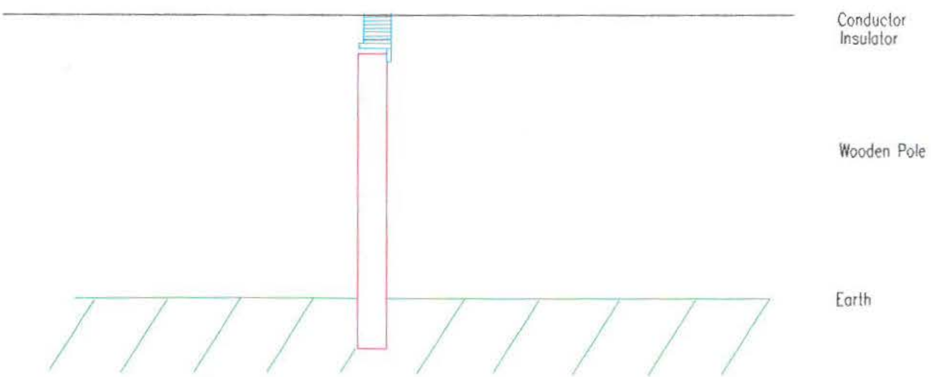


Fig. 3.10. "L" Bracket Installed at the Top of the Pole

In Australia the most common supporting structures are 11m and 12.5m wooden poles. The Australians are moving towards the use of 12m spun concrete poles mainly because of their long lifetime.

Almost without exception, the span length of SWER lines is determined by conductor sag. The use of high strength conductors allows high conductor tensions, thus reducing sag. This in combination with the fact that the conductors are mounted at the very top of the poles, allows for very long span lengths. The typical span lengths achieved in Australia average around 300m.

3.12 CONCLUSIONS

SWER lines have been used by several countries, most notably Australia, to take electricity to remote rural households. Because of its successful adoption by the utilities of Australia, SWER may also offer some cost savings for the South African rural electrification programme. From the literature now documented, it is clear that the soil resistivities in Australia is much lower than in South Africa, and particularly in the Northern Cape region. It is therefore not possible to adopt the earth electrode designs of Australia directly in South Africa, but it is essential to design earth electrodes for the special conditions related to the Northern Cape region, such as high temperatures (soil and ambient), different soil types and high soil resistivities.

CHAPTER FOUR

REVIEW OF EXISTING SWER ELECTRICITY DISTRIBUTION IN ESKOM, PARTICULARLY IN THE NORTHERN CAPE REGION

This chapter will inform the reader on existing SWER lines established in Eskom, and particularly in the Northern Cape region. The scope will be wide, thereby informing the reader on Eskom's experience on SWER lines, as well as the problems experienced.

4.1 HISTORY

High construction costs and a low return on investment owing to relatively small loads make the electrification of remote rural communities in the Northern Cape region uneconomical with conventional three-phase and single-phase rural lines.

This economic dilemma led to the introduction of SWER reticulation systems by Eskom in the Northern Cape region round about 1989. At present, the system only involves tee-offs from existing three-phase or single-phase backbone systems introducing an isolating transformer, preventing the earth return current from tripping the main substation on earth fault. Eskom's electrification plan is part of government policy and is principally aimed at directly supporting economic development and facilitating a standard of living which the community requires.

Currently there are seven SWER reticulation lines in the Northern Cape region. Information on these schemes was gathered (measurements) and analyzed by visiting some of these lines. The literature study on these SWER installations includes the conducting of the following tests.

⇒ Soil resistivity tests at the isolating and distribution transformers.

⇒ Measuring of the earth electrode resistance at these installations.

The following technical information was also obtained:

⇒ Type and configuration of earth electrode installed at the isolating and distribution transformers.

⇒ Protection utilized at the isolating and distribution transformers.

⇒ Earthing of all the relevant equipment, e.g. primary winding, surge arresters, transformer tank and secondary neutral point.

⇒ Type of poles, conductors, insulators, surge arresters, isolating and distribution transformers utilized.

⇒ Problems experienced with telephone interference.

⇒ Voltage used.

⇒ Any other problems experienced with these SWER lines.

4.2 VOLTAGE USED

In Eskom a voltage of 22kV (phase-to-earth) has been adopted for SWER lines supplied by an isolating transformer [14]. This choice allows for standerd single-phase 22kV distribution transformers to be used on SWER lines. The decision to adopt 22kV as the standard SWER line voltage, however, rules out the possibility of using directly connected SWER lines. This is because a voltage of 22kV (phase-to-earth) is not obtainable from any of the standard three-phase voltages, unless special $22/\sqrt{3}$ kV transformers are manufactured resulting in non-standard transformers to be carried by stores. This increases the price.

4.2.1 TELEPHONE INTERFERENCE

The maximum earth return current on SWER schemes in Eskom is limited to 8A rms. by agreement between Telkom and Eskom [14]. It appears that the 8A limit was adopted directly from the Australian practice. The limit restricts the viability and wider use of SWER in rural areas. It was confirmed during the author's Australian visit that the 8A restriction now no longer applies in Australia, and Eskom is investigating the 8A limitation with Telkom under the leadership of Mr A.C. Britten of TRI (Technology Research & Investigation Group). The minimum separation distance between a SWER line and Telkom line is also under investigation by the mentor of this thesis, Mr A.C. Britten [2].

4.2.2 PROBLEMS EXPERIENCED WITH TELEPHONE INTERFERENCE

Telephone interference has been experienced on two of the SWER lines in the Northern Cape region. On the Rooipoort line it was found that arcing was taking place between an insulator spindle, and the earthwire used for BIL (basic insulation level) co-ordination down the pole. The arcing resulted in interference on the telephone line. After a two-metre length of the earthwire was removed the interference on the telephone line was eliminated. It was then decided to remove the earth wire in total. Measurements taken indicate that capacitive coupling caused the interference on the line [2].

Telkom interference was also experienced on the Dreghorn SWER scheme. No measurements were taken to determine the reason for the interference, but it is expected to be caused by electrostatic coupling between the Telkom and Eskom SWER line. The Telkom line was moved to ensure a minimum separation of 100m between the two lines. The costs were for Eskom's account. The 100m separation distance is believed to be adopted from Australian practice and is adhered to on all the SWER schemes in the Northern Cape region. This practice must continue until the investigations on minimum separation distances between SWER and Telkom lines are completed by Mr A.C. Britten.

4.3 METHODS OF SUPPLYING SWER LINES

4.3.1 SWER LINES SUPPLIED BY ISOLATING TRANSFORMERS

The SWER lines in the Northern Cape region are connected onto three-phase or single-phase networks via an isolating transformer. These isolating transformers are pole mounted and rated 100kVA or 200kVA. The phase-to-earth voltage of these transformers is 23kV, as specified by Eskom [14].

4.3.2 DIRECTLY CONNECTED SWER LINES

In addition to the isolating transformer principle, a single-phase 16kVA, 12,7kV pilot distribution point is installed in the Kuruman area without an isolating transformer. Feedback received on this project is that no problems are experienced refering to the ground return current directly to the main substation. This was expected, because the earth return current is very small (1.25A on full load), therefore not effecting the SEF (sensitive earth fault) protection installed at the main substation.

4.4 SWER LINE ISOLATING TRANSFORMERS

The Eskom specified ratings of the isolating transformers are (single-phase) 100kVA, 150kVA and 200kVA on 22kV SWER lines according to SABS 780. These transformers also comply with the requirements of NWS 1631 Rev. 6 for distribution transformers [14]. Isolating transformers installed in the Northern Cape region are mainly rated 100kVA and 200kVA. Technical information on these transformers available, is listed below.

TABLE 4.1 Technical Information on Eskom Isolating Transformers [14].

Rating (kVA)	100	200
Weight (kg) (total)		600
Resistance %	2,2	1,01
Impedance %	5	6,5
Reactance %	4,5	6,42
Primary voltage (kV)	11 or 22	22
Secondary voltage (kV)	22	23

4.4.1 PROBLEMS EXPERIENCED ON ISOLATING TRANSFORMERS

Voltage regulation problems on SWER schemes utilizing 100kVA isolating transformers could not be solved, because these transformers were not equipped with tap changing facilities. A few isolating transformers were replaced due to lightning and internal failure problems. It appears that some isolating transformers were damaged when simulating broken conductor conditions. These tests were conducted by connecting the conductor to the ground and then recording the short-circuit current as well as the rupturing time of the fuse. These transformers were not long in operation before they failed. The reason for the failures as received from the manufacturer was that the LV and HV coils had moved due to an external short-circuit current and a long time duration for the fuse to blow. The fault current measured was 17A and the fuse took 45 sec. to blow. (± 400kVA from a 100kVA transformer for 45 sec.) These broken conductor simmulations are no longer conducted on SWER lines in the Northern Cape region.

4.4.2 EARTHING OF ISOLATING TRANSFORMERS

As previously mentioned, the earthing of the isolating transformer is critical, because the system must be designed to carry a continuous earth return current of 8A under normal conditions. The Eskom standard requires the installation of two earth electrodes per transformer and stated a maximum resistance of 2,5 ohm under the worst expected soil conditions [14]. This is to limit the GPR to not more than 20V across the earth electrode during normal operating conditions.

4.4.2.1 METHOD OF EARTHING

The earliest practice in the Northern Cape was to drill two holes for the isolating transformer's earth electrodes. The holes were drilled to a depth where the soil became moist. The earth electrodes were installed ± 50m from fences to avoid the possibility of unsafe touch potentials developing on the fences. This was done by installing the earth electrodes of the isolating transformer some distance away via an overhead conductor, known as the earth return conductor, or by using insulated copper earths and moving the earth electrode 50m from the fence. The first practice was abandoned because a broken overhead earth conductor may occur and result in a dangerous unearthed system. The earth electrode consisted of 3,15 x 50mm flat copper strap placed into the drilled holes before it was filled with a mixture of Marconite and cement.

4.4.2.2 EARTHING PROBLEMS EXPERIENCED ON ISOLATING TRANSFORMERS

Problems were experienced on two of the projects because of the sandy soil conditions. On the one project (Dreghorn Scheme) casings were installed into the holes to prevent the hole from caving in. On the other project the problem was overcome by installing a trench earth at very high cost, because approximately 600kg of 10mm diameter copper rod was installed to achieve the resistance of 2,5 ohm required. This could have been prevented if soil resistivity tests had been conducted prior to the installation of the earth electrode. Drying out of the sand might have increased the resistance of the earth electrode, so resulting in dangerous step-and-touch potentials.

4.5 SWER DISTRIBUTION LINES

The practice adopted by Eskom is described below:

4.5.1 STRUCTURE

In order to standardize, the proposed structures are in accordance to the Electrification Standard. Structures in use in the Northern Cape region are with the "L" bracket on top of the pole as in Australia, but the most common practice in use is where the insulator is installed on the side of the pole, known as the vertical configuration.

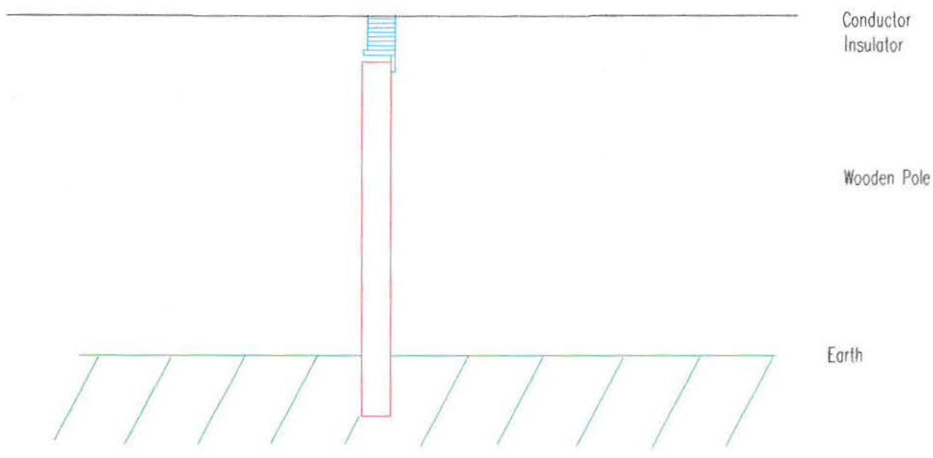


Fig. 4.1 "L" Bracket Installation

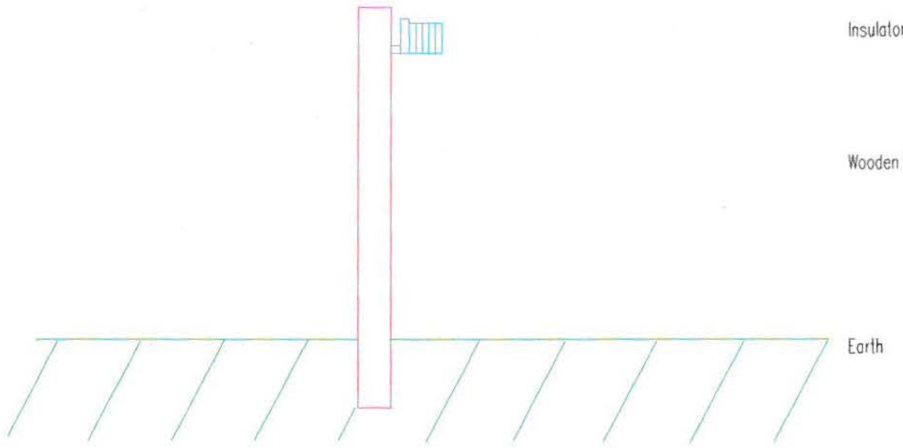


Fig. 4.2 Vertical Configuration

The supporting structures in use are 12m wooden poles, which allows for greater conductor sag and thus increased span lengths. Span lengths on the existing SWER lines are not profiled and are between 200 and 250 metres. In some cases span lengths are determined by the environmental conditions and not by the strength of the conductor or wooden poles.

4.5.2 CONDUCTORS IN USE

Almost without exception, the span length of SWER lines is determined by conductor sag. The use of high strength conductors allows high conductor tensions, thus reducing sag. It was therefore suggested to use 3/4/2,12 mm ACSR (code name: Magpie) for SWER lines in Eskom [36]. SWER lines in the Northern Cape region are built with "Fox" conductors, except for the Dreghorn Scheme which is build with "Magpie".

4.5.3 INSULATORS

The first 22kV SWER line constructed in the Northern Cape region was on 33kV (phase-to-phase) cycloalaphatic insulators, as prescribed in the Electrification Standard [14]. The reason for this being the fact that the 33kV phase-to-phase insulators are rated for a 19.1kV phase-to-earth voltage. It was believed that the 22kV phase-to-phase insulators will be overstressed when utilized on these lines. (The phase-to-earth voltage for a 22kV insulator is 12,7kV). This, however, were proved wrong, as no problems have been experienced on these lines over the past seven years. The practice now is that SWER lines are build on 22kV (phase-to-phase) porcelain or cycloalaphatic insulators [14]. In high pollution areas like the West Coast where the marine pollution is very high, the use of 22kV (phase-to-phase) insulators will not be possible, and 33kV insulators are to be used.

4.5.4 SURGE ARRESTERS

On the 22kV SWER lines, 33kV distribution type surge arresters are used. These surge arresters are mounted directly on the isolating and distribution transformers to protect the transformers against lightning.

4.5.5 PROBLEMS EXPERIENCED ON SWER DISTRIBUTION LINES

It appeared that there are no approved crimp joint available for "Magpie" conductor, and a "Gopher" joint was recommended, which required a reduced tension of the "Magpie" conductor. This resulted in greater sags, losing the expected saving on structures. The use of "Magpie" conductor was discontinued, and only "Fox" conductor is now in use in the Northern Cape region.

4.6 DISTRIBUTION TRANSFORMERS

4.6.1 APPLICATION OF DISTRIBUTION TRANSFORMERS

SWER projects (22kV, phase to ground) to date in South Africa have relied on the use of existing 22kV phase-to-phase single-phase transformers, resulting in all distribution transformers installed to be rated at 16kVA. These transformers are used to supply either a single customer, in the case of a farm house, or several customers, such as farm worker houses. If a customer requires a load of more than 16kVA, two transformers are paralleled, providing an installed capacity of 32kVA.

4.6.2 DIFFERENCE BETWEEN SWER DISTRIBUTION TRANSFORMERS AND CONVENTIONAL SINGLE-PHASE TRANSFORMERS

There are three notable differences between distribution transformers used on SWER lines and those used on conventional single-phase, phase-to-phase lines:

⇒ The primary side of SWER transformers only requires one MV bushing, as the earth connection may be made through an LV (400 V) bushing.

⇒ In some cases, high magnetising current distribution transformers may be appropriate for use on SWER lines. These are used to compensate the line charging currents. High magnetic current transformers are produced by introducing an air gap into the transformer's magnetic circuit.

These SWER distribution transformers are available on request from manufacturers.

4.6.3 EARTHING OF DISTRIBUTION TRANSFORMERS

As in the case of Australian SWER systems, the maximum recommended permissible voltage rise (GPR) on the earth lead is to be 20V.

4.6.3.1 REQUIRED EARTH ELECTRODE RESISTANCE

The required resistance of the earth electrodes varies according to the SWER line voltage and the loading of the distribution transformer. Eskom [14] limits the required earth resistance for various sizes of transformers supplied by 22kV phase-to-earth SWER lines to the values shown in the table below. The earth electrode resistance values do not allow for transformer overload.

TABLE 4.2 Distribution Transformer Earth Electrode Resistance

DISTRIBUTION TRANSFORMER (kVA)	RESISTANCE AT 22kV (ohm)	RESISTANCE AT 12,7kV (ohm)
5	80	40
10	40	20
16	30	15
25	17	8
100	4.4	2.2

4.6.3.2 METHOD OF EARTHING

The practice recommended by Eskom is to install three driven rods in a crowsfoot configuration. The length of the rods is 1,5m and they are inter connected with 10mm diameter solid copper rod with radial lengths between 5 and 10 metres. These radial copper lengths are buried in a trench with a minimum depth of 500mm. The depth to which the rods are to be driven is dependent on the soil resistivity found in the area of installation, and was not taken into consideration. In areas with poor earth conditions (high resistivities) in the upper soil layer, the use of driven rods is insufficient, and deep drilled electrodes are required. The MV (medium voltage) and LV (low voltage) earths must under no circumstances be connected to one another. They are separated by at least 5 metres according to Eskom Standards. Some installed earth electrodes at the distribution transformers on the Northern Cape region SWER lines are deep-drilled with great costs involved. A conservative approach was adopted in the first two SWER lines concerning the installation of earth electrodes near fences. It was believed that dangerous step and touch potentials might develop on the fence in the vicinity of the earth electrode. This safety precaution led to the introduction of an overhead earth return conductor as shown in figure 4.4.

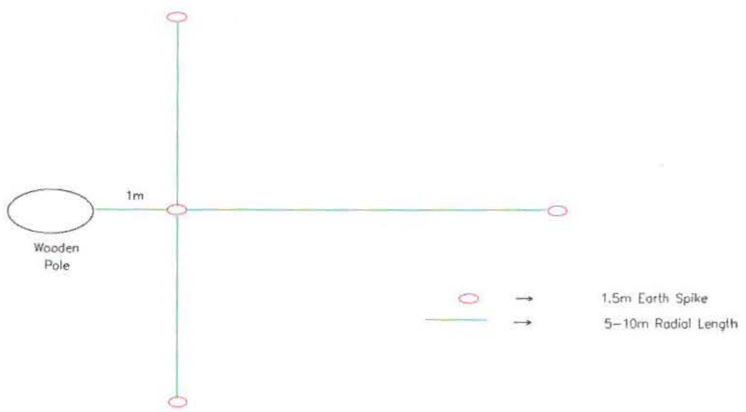


Fig. 4.3 Earthing Electrode Installed at Distribution Transformer

All the wooden poles are earthed using 3/3,35 steel-wire. This practice was implemented for insulation co-ordination purposes concerning lightning. The wire is taken up the pole and terminated ± 460mm from the insulator to provide a woodpath and thus creating a BIL of 300kV (150kV by the insulator and 150kV wood path) [15].

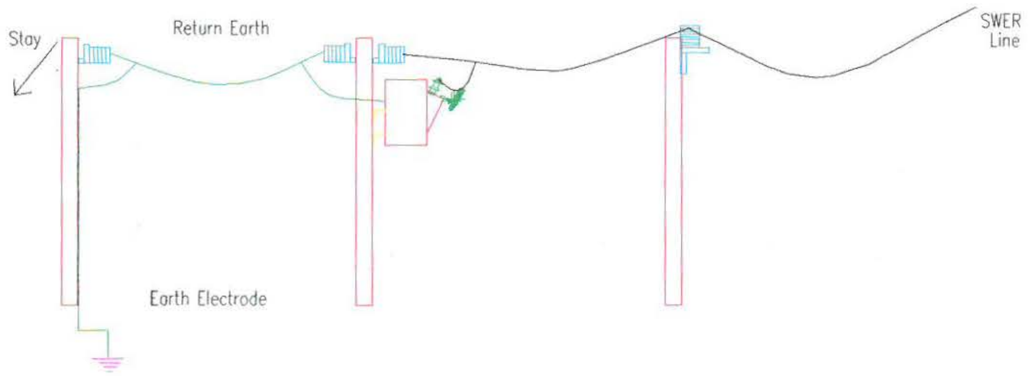


Fig: 4.4 Earth Return Installation

4.6.4 PROBLEMS EXPERIENCED REGARDING THE EARTHING OF DISTRIBUTION TRANSFORMERS

The absence of a design guide to prescribe the type of earth electrode to be installed for the specific soil condition and earth resistivity resulted in the installation of overdesigned, expensive or underdesigned ineffective earth electrodes. This was experienced while conducting tests on installations in the field. Soil resistivity tests were conducted by the author, finding that the results on one of the schemes indicated that a more cost-effective earth electrode could have been installed at a depth of 3 metres, although the electrodes installed were at a depth of 20 metres.

4.7 PROTECTION OF SWER TRANSFORMERS

4.7.1 PROTECTION OF ISOLATING TRANSFORMERS

SWER isolating transformers in the Northern Cape region have been protected by a set of drop-out fuses rated at 2A on the transformer's primary side. As a result of nuisance fuse blowing due to lightning, these fuse ratings were increased to 20A. The isolating transformer is protected by a K-type fuse on the secondary side, rated 5A or 10A.

4.7.2 PROTECTION OF DISTRIBUTION TRANSFORMERS

SWER distribution transformers are protected by 3A, K-type fuses.

4.7.3 LIGHTNING PROTECTION

Lightning protection is achieved by installing 33kV surge arresters to protect all equipment. As mentioned earlier, Eskom's standard practice is to earth all poles by 2MV to 300kV. This limits the damage caused by direct strikes, but avoids flash overs caused by induced surges.

4.8 PROBLEMS EXPERIENCED WITH PROTECTION UTILISED ON SWER SCHEMES

Nuisance fuse blowing at the isolating transformer due to lightning resulted in complaints on the performance of the line. The fuse concept as the only protection on the SWER lines causes a serious concern on the safety of the system for the public as well as for animal life. It was found during the field studies that the main reason for nuisance fuse blowing was caused by the replacing of blown fuses with incorrectly rated fuses. The investigation of an auto reclose facility might result in cost savings by reducing outages.

4.9 PROPERTIES OF SWER DISTRIBUTION

The effect of the various aspects of SWER line design, considered above, on the line properties (construction cost, quality of supply, safety and ability to upgrade), are now considered.

4.9.1 CONSTRUCTION COST

The objective behind the development of SWER distribution was to reduce the costs of supplying rural customers. SWER lines have several advantages over other types of lines which result in savings on construction costs. The most significant of these are:

⇒ SWER lines only require a single conductor.

⇒ The supporting structure is very simple and only requires one insulator.

⇒ No cross-arm is required to support the conductor.

⇒ The conductor may be located at the very top of the pole, increasing the allowable sag. This allows for longer spans and thus fewer poles per km, less insulators and holes.

⇒ The tension of only one conductor has to be countered, allowing for smaller and fewer stays.

⇒ SWER distribution transformers only require one MV primary bushing.

These savings must be weighed against some extra costs:

⇒ Special attention must be given to the earthing of SWER lines. This increases the cost of earthing distribution transformers, and where isolating transformers are used, it introduces the cost of additional earthing.

⇒ An additional transformer (isolating transformer) is usually required.

⇒ In most cases, providing transient fault protection of SWER lines requires the purchase of additional single-phase reclosers at the isolating transformer.

4.9.2 QUALITY OF SUPPLY

The most important limit on the quality of supply offered by SWER lines is their inability to supply three-phase loads. This is, however, the same as any other single-phase system. The following factors also influence the quality of supply of SWER lines:

⇒ Transient faults on SWER lines fed by isolating transformers, without reclosers at the head of the lines, are likely to develop into permanent faults.

⇒ It is reasonable to assume that the number of faults per km of distribution lines is related to the number of phase conductors (e.g. conductor clashing). SWER lines, with only a single-phase conductor, will thus experience fewer faults than single-phase, phase-to-phase or three-phase lines.

⇒ SWER lines are vulnerable to unforeseen increases in the resistance of their isolating and distribution transformer earth electrodes (for example due to prolonged drought). This will result in a ground potential rise across the earth electrodes resulting in dangerous step-and-touch potentials [20, p.12].

4.9.3 SAFETY

The safety hazard of SWER lines is more than that of conventional lines for the following reasons:

⇒ Because SEF (sensitive earth fault) protection is not compatible with SWER lines, protection against high impedance faults is difficult.

⇒ The resistance of the isolating and distribution transformer's earth electrode may increase due to mechanical damage or seasonal variations, thereby increasing the voltage across the electrodes. This may lead to dangerous touch and step potentials.

⇒ For all faults on SWER lines the source earth electrode must carry the fault current until the fault is cleared. These currents will cause an increase in the potential across the electrode, with resultant safety hazards.

The safety problems of SWER lines are not unacceptable, as demonstrated by the wide use of SWER in Australia and other countries.

4.9.4 ABILITY TO UPGRADE SWER

Because of the types of systems utilizing SWER lines, the upgrading of SWER lines has usually meant conversion to single-phase, phase-to-phase or to three-phase lines. Unless the SWER line was initially designed with the upgrade in mind, the planting of additional poles will be required. This is because of the longer span lengths of SWER lines compared with conventional lines. Designing SWER lines for future upgrading thus requires limiting the span length, which eliminates one of the main advantages of SWER lines. Eskom is not in favour of upgrading SWER lines, and recommends that they only be used to supply customers that have "little or no prospect for load growth".

4.10 CONCLUSIONS

It was found that the SWER systems using the isolating transformer principle were successfully implemented in the Northern Cape region, except for a few problems experienced as described earlier in this chapter. These problems can be overcome by the compiling of a design guide. Cost comparisons as obtained from planning proposals indicate cost savings comparing SWER systems with conventional single-phase and three-phase systems, making it a technology clearly worth investigating further for Eskom's rural electrification programme.

CHAPTER FIVE

EARTHING GUIDE FOR SWER IN THE NORTHERN CAPE REGION

The intent of this guide is to provide Eskom designers, planners, maintenance personnel and contractors with critical information regarding the design and installation of safe and reliable SWER earth electrodes.

The design of the Northern Cape SWER earth electrodes (see table 5.10 and tables 5.13 to 5.15) is based on experimental results obtained during field tests on the Rooipoort and Rooiwal SWER schemes. Chapter six provides the reader with technical findings and conclusions regarding the outcome of the field tests.

During the design process of the SWER earth electrodes, the essential information listed below was found to be taken into consideration for the first time.

⇒ Safe ground potential rise (GPR) limit related to the special conditions of the Northern Cape region.

⇒ The effects of seasonal variations.

⇒ Soil types related to the Northern Cape region.

⇒ Thermal resistivity of different soil types.

⇒ Current density limit and maximum permissible earth electrode resistance to prevent thermal runaway taking place.

⇒ Soil resistivity and earth electrode resistance measurements.

⇒ Maintenance of earth electrodes (i.e. monitoring of resistance values).

The design of the SWER earth electrodes to be installed at the isolating and distribution transformers is based on the following ratings:

⇒ SWER system voltage 20 kV (line to ground)

⇒ Isolating transformer 200 kVA

⇒ Distribution transformer 16 kVA

5.1 INTRODUCTION

Earthing includes the provision of an electrical connection to the general mass of the earth. The reliability and design of earth electrodes are critical to the safety and success of SWER systems. Earthing of a conventional high voltage system is merely a protective measure and current flows in the earthing circuit only for the duration of an electrical fault. However, in a SWER scheme the earth electrode installed must be designed to carry the load and charging currents indefinitely as well as any fault currents that might occur, and be sustained.

5.2 SAFETY

A safe grounding design has in general two objectives, namely:

⇒ To allow conduction of electric currents into the earth under normal and fault conditions, without exceeding any operating and equipment limits, thereby adversely affecting continuity of service.

⇒ To ensure that a person, animal or livestock in the vicinity of grounded facilities is not exposed to the danger of critical electric shock [23, p.23].

The probability of an accident depends on the coincidence of several adverse factors, such as [45, p.5]:

⇒ The fault current must generally be high in relation to the area of the earth electrode and the resistance to remote earth.

⇒ The soil resistivity must generally be high and the distribution of the fault current through the earth electrode must be such as to produce high-voltage gradients in the soil surface.

  During rainy seasons the soil is usually moist, thereby decreasing the soil resistivity of the top layer. This will decrease the surface contact resistance between the person in the close proximity of the earth electrode and the earth and therefore may result in dangerous step, touch and transferred potentials.

⇒ An individual must be bridging two points of high potential difference during the period when fault currents are flowing into the soil through the earth electrode.

  In the case of SWER systems there is a **continuous current flowing** in the earth electrode, making it extremely important to limit the GPR under normal load conditions and thereby ensuring safe step, touch and transferred potentials.

⇒ Any significant contact resistance (e.g. rubber-soled shoes, dry hands) that may limit the current through the body has to be absent.

⇒ The magnitude of the current flowing through the body and the time duration thereof must be sufficient to cause harm.

Although voltage gradients may be theoretically hazardous, and while it is impossible to ensure complete safety at all times and places, the low probability of the above adverse factors occuring simultaneously makes it possible to design an earthing system with reasonable dimensions.

Because of the continuous flow of current in the SWER earth electrodes, the ground potential rise must be limited to ensure safe step, touch and transferred potentials. The "safe" limitation of GPR under normal operating conditions will now be investigated (Formulas for the calculation of ground potential rise step, touch and transferred touch potentials are indicated in Appendix A).

5.3 GROUND POTENTIAL RISE (GPR)

The earth return currents of a SWER system through an earth electrode produce a potential difference between the electrode and the body of earth at a remote point. This potential difference is referred to as electrode ground potential rise (GPR). With SWER systems the GPR must be limited within safe values because of the continuous load current that flows in the earth electrode. The limitation of the GPR will ensure safe step, touch and transferred potentials under normal load conditions.

Since the implementation of SWER in New Zealand and Australia, earthing systems have been limited to a GPR of 20V under normal operating conditions. This limitation is also adopted in countries such as India and South Africa [37], [14]. The limitation on the GPR has a direct influence on the safety of SWER systems as well as on the earthing costs involved.

The 20V GPR limit in Australia is still in use as confirmed during the visit to Australia by the author, in April, 1997. Reasons given by the Australians on the selection of a 20V GPR were not clear. The 20V limitation seems to be conservative but it is clear that there is no need for the Australians to increase the limit. In the author's opinion this is because earth electrodes installed are relatively cheap due to the low soil resistivities found in Australia (e.g. between 10 and 100 ohm metre). In rocky areas the soil resistivities are as high as 1000 ohm metre, but SWER lines are unlikely to be constructed in areas where the soil resistivity is higher than 300 ohm metre [27, p.17]. The 20V GPR limit has also proved to be safe for the past forty years.

Literature available (as old as 1967) indicates that the 20V GPR limit originated from tests done by the Australians on livestock. These tests indicated that live stock reaches discomfort at the following steady state voltage gradients [21, p.45]:

Cow	45 volts per metre of distance
Bullock	13 volts per metre of distance
Lambs	25 volts per metre of distance

It is not clearly explained, but from the results above it appears that the average voltage gradient at which live stock start feeling discomfort is in the region of 27V per meter of distance. If assumed that the legs of the animals are 1,5m apart, the total voltage will be about 40V (27V x 1,5).

In the opinion of the Australians there is a possibility of risk if earthing systems have a voltage drop in excess of 40V. To ensure a safe earthing system a "safety factor" of 2 was applied and from there the GPR limit of 20V came about [6, p.45]. The author is of the opinion that the selection of this low GPR limit is directly related to their low soil resistivities.

In South Africa and particularly in the Northern Cape region with its high soil resistivities (between 100 and 3000 ohm metre), it will not be possible to achieve a GPR limit of 20V without designing very expensive earth electrodes, thereby not making SWER an option to electrify sparsely populated areas. This led to the initiative by the author to investigate the possibility to increase the GPR limit, thereby reducing the earth electrode costs without sacrificing safety.

Tests done by the author on an existing SWER line (see Appendix B) in the Northern Cape region indicated that the biggest concern regarding the increase of the GPR limit, is that a high portion of the GPR at the earth electrode is transferred to a remotely earthed electrode (e.g. fence built with wooden droppers and only earthed at a remote point via a metal pole).

It is therefore essential to limit the GPR to a value that will ensure safe step, touch and transferred potentials.

The GPR is proportional to the soil resistivity, the magnitude of the current that flows in the soil via the earth electrode and the resistance of the earth electrode to true earth [35, sec 5, p.2].

The magnitude of the transient and continuous current through the human body, when in contact with a remotely earthed electrode (earth leads down the pole at the isolating and distribution transformers will be insulated), is dependent on the following factors [8, p.33]:

⇒ Internal body resistance (which is low).

⇒ Skin resistance (usually high but varies greatly from person to person).

⇒ Contact resistance between the skin and the remotely earthed electrode (which depends on the type and pressure of contact, humidity and the state of the surface of the skin, for example whether the skin is sweaty, wet,etc.).

⇒ Contact resistance between body and the surface of the earth (usually 1,5 times the surface resistivity for touch potentials and 6 times the surface resistivity for step potentials) [23, p.38].

For the purpose of this guide, the resistance of the human body from hand to both feet and also from hand to hand, or from one foot to the other foot is taken as 1000 ohm. This is in line with the values given in an American National Standard [23, p.35].

Tests done on the human body to determine the physiological effects of different magnitudes of currents are indicated in figure 5.1 and table 5.1. These tests are based on a hand-to-hand flow of electric current [5].

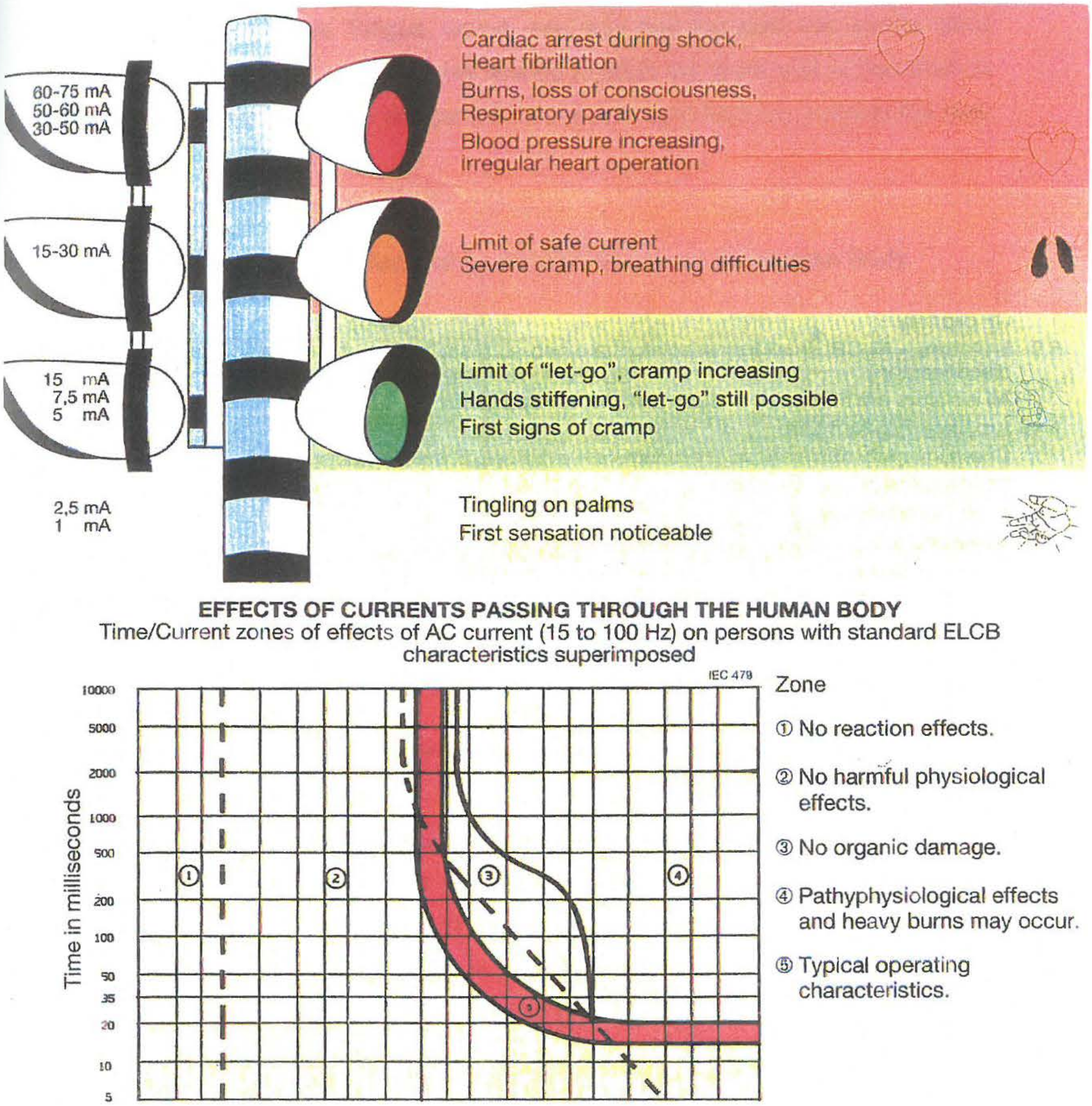


FIG 5.1 **Effects of Transient Sinusoidal Currents on the Human Body Assuming Hand-to-Hand Flow of Electrical Current [5,Sec 2]**

The physiological effects are dependent on the physical condition of the person at the time of the shock (fitness, fatigue, worry), sex, age and the path the current takes through the human body (e.g. currents flowing through the lower part of the brain or the heart are particularly more dangerous than a path right from the hand to the feet) [8, p.3,4].

TABLE 5.1 Physiological Effects of an Electric Shock on the Human Body [8, p.3,4]

Current(mA)		Effects on body (hand-to-hand path)
1	SAFETY ZONE	First sensation noticeable
2.5		Tingling on palms
5		First signs of cramp
7.5		Hand stiffening -"let go" still possible
10-15		Cramp increasing - limit of "let go"
25-30		Severe cramp extending to thoracic region, limit of safe current
30-50	DANGER ZONE	Blood pressure increasing , irregular heart operation
50-60		Interference with respiratory system, loss of consciousness
60-75		Heart fibrillation

Based on an average body resistance of 1000 ohm, a surface contact resistance of 1,5 times the surface resistivity of the soil (see Appendix A) and a maximum safe body current of 30mA (see table 5.1), the continuous safe-touch potentials are to be as indicated in figure 5.2. The graph is also in agreement with tests done on human beings and available from IEC 479 - 1 (1994) [14].

An example of the calculations done to determine the safe GPR limit at different surface soil resistivities ($\wp$ = 100 ohm metre) at a safe current of 30 mA (see table 5.1) is as follows:

$$GPR\,(V) = I \times R_{body} + 1{,}5\,\wp \times I \qquad [45, p.7]$$

$$= 0{,}030 \times 1000 + 1{,}5 \times 100 \times 0{,}030$$

$$= 30 + 4{,}5$$

$$= 34{,}5\ V$$

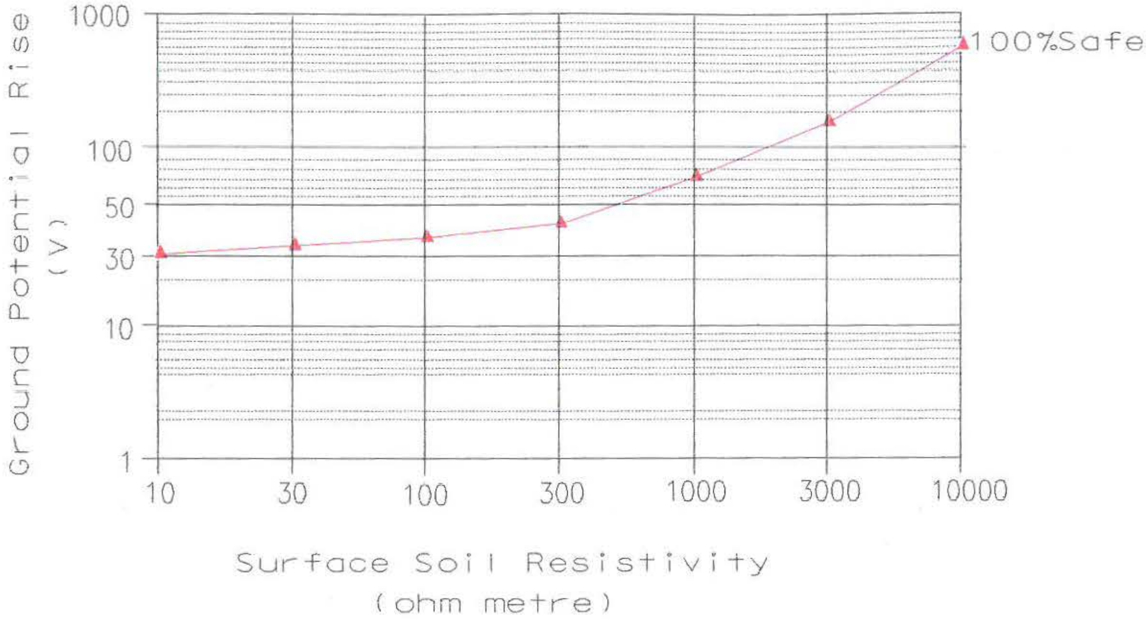


Fig.5.2 Continuous Safe-touch Potentials

A 100% safe GPR limit for the Northern Cape region will be between 35V (100 ohm metre) and 165V (3 000 ohm metre). These limitations, however, do not take the effects of seasonal variations (e.g. rain, high temperatures) on the surface resistivity of the soil into consideration.

Further studies indicate that the effects of chemicals, moisture content and the temperature of the soil, which are all subject to seasonal variations, need to be taken into consideration as indicated in fig. 5.3, curve 1, 2 and 3 [23, p.71].

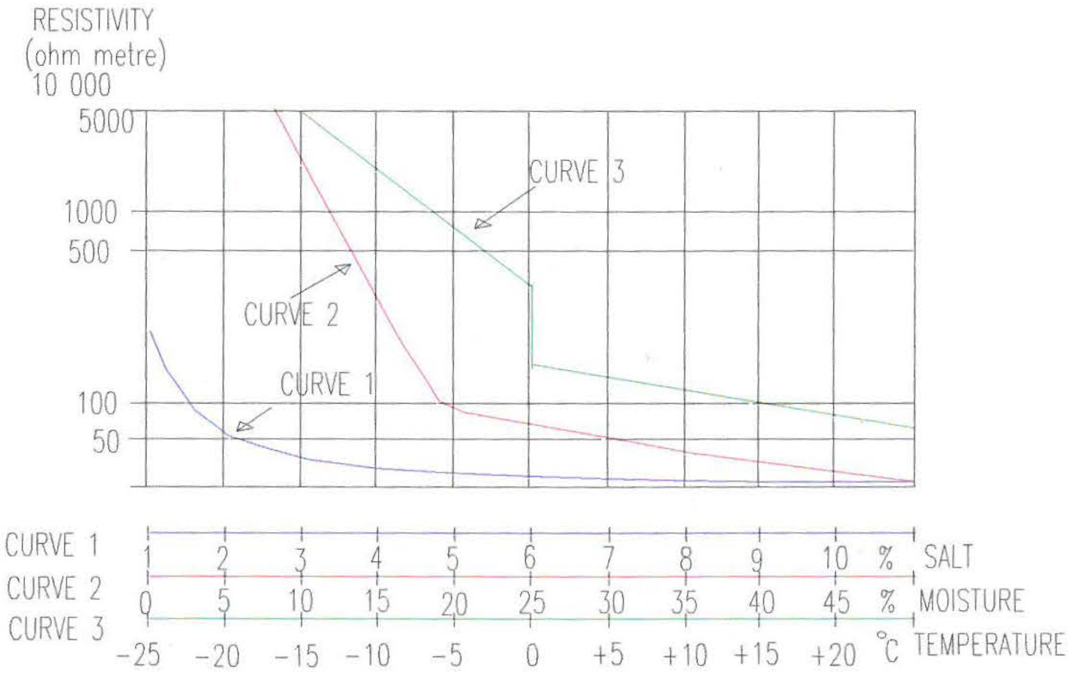


Fig. 5.3 Effects of Moisture, Temperature and Salt on Soil Resistivity [23, p.71]

The indication is that high soil resistivities (>100Ωm) are more affected by seasonal variations than lower soil resistivities. This is evident from curve 2, which indicates that the soil resistivity of the soil may decrease from 5 000 ohm metre to about 100 ohm metre with an increase of 10% moisture in the soil (from 8% moisture content to 18%). It will therefore be a safety risk to increase the GPR proportional to the soil resistivity without taking the effects of seasonal variations into consideration. In the Northern Cape region with its low rainfall statistics and high surface soil resistivities (>100 Ωm) a minimum surface soil resistivity of 100 ohm metre was adopted under all seasonal conditions.

From the studies conducted, it is clear that the effects of an electric shock on a person standing in the vicinity of a SWER earth electrode and his hand in contact with a remotely earthed electrode (e.g. a fence) will mainly be dependent on the following factors:

⇒ The ground potential rise at the earth electrode, which is dependent on the magnitude of the load current and the resistance of the earth electrode which itself is dependent on the soil resistivity.

⇒ Resistance of the human body.

⇒ The contact resistance between the human body and the earth which will be influenced by seasonal variations of the soil resistivity (see figure 5.3).

By taking the factors as listed above and the assumption of a minimum surface soil resistivity of 100 ohm metre under all seasonal conditions into consideration, the author concludes that the GPR of SWER earth electrodes in the Northern Cape region can only be raised from 20 V to a maximum of 35V. This will ensure safe step, touch and transferred potentials under steady state / continuous conditions.

5.4 SAVINGS ACHIEVED BY INCREASING THE GROUND POTENTIAL RISE

As already mentioned in paragraph 5.3, the feasibility of a SWER scheme is dependent on the earthing costs involved. The implications of increasing the GPR limit from 20V to 35V will therefore be measured against the savings achieved.

This was done by doing a cost comparison on an earth electrode to be installed at an isolating transformer and in uniform soil of 500 ohm metre (related to Northern Cape region).

Costs were based on the following:

⇒ Drilling costs R140-00/m

⇒ 10mm dia solid copper rod R11-39/m

⇒ Load current 10A (200kVA @ 20kV)

An example of the costs involved to design SWER earth electrodes not exceeding the prescribed GPR values is indicated below.

TABLE 5.2 Earth Electrode Costs for Different Ground Potential Rise ($\wp$ = 500 ohm metre)

GPR	DEEP-DRILLED ELECTRODES	MATERIAL COSTS	DRILLING COSTS	TOTAL COSTS
20 V	4 X 160m	R 7289-60	R 89600-00	R 96889-60
22 V	4 x 140m	R 6378-40	R 78400-00	R 84778-40
26 V	4 x 110m	R 5011-60	R 61600-00	R 66611-60
30 V	4 x 90m	R 4100-40	R 50400-00	R 54500-40
35 V	4 x 70m	R 3189-20	R 39200 00	R 42389-20
40 V	4 x60m	R 2733-60	R 33600-00	R 36333-60
44 V	4 x 50m	R 2278-00	R 28000-00	R 30278-00
50 V	4 x 40m	R 1822-40	R 22400-00	R 24222-40

When plotting the results of table 5.2, the author is of the opinion that the savings achieved by increasing the GPR above 35 V is outweighed by the risk of dangerous step, touch and transfer potentials that might occur (see figure 5.4).

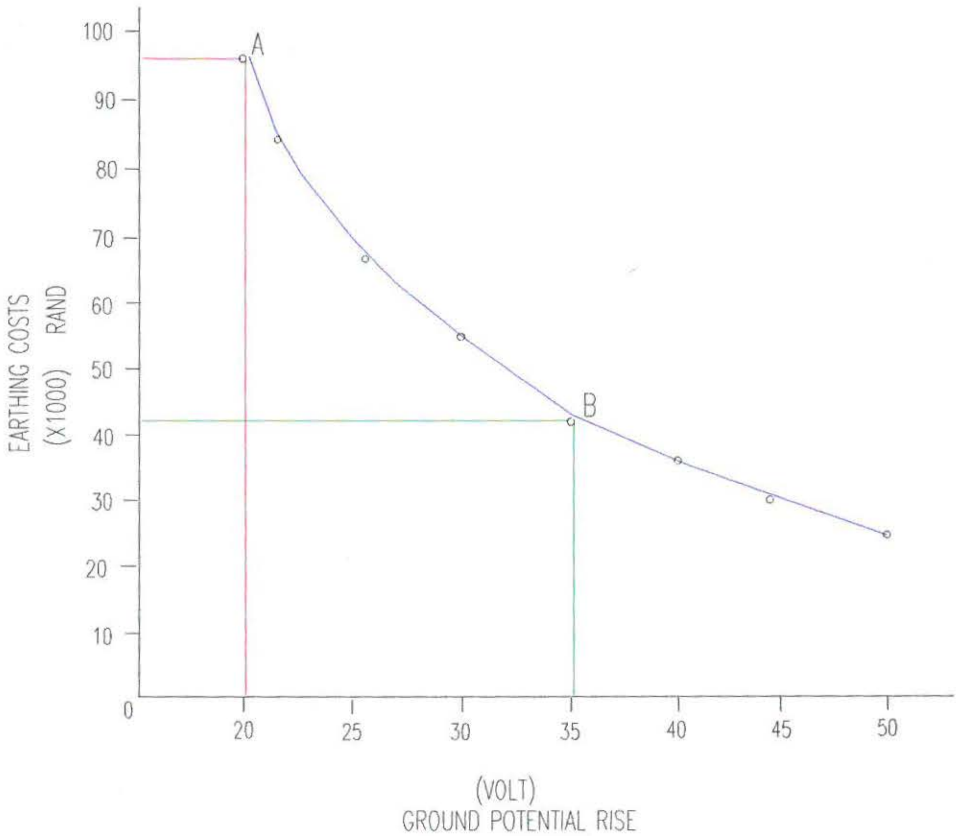


Fig. 5.4 Graph Indicating Earthing Costs Related to Different GPR Limits

Savings achieved by increasing the GPR from 20 V, point A to 35 V, point B is estimated at R 50400-00, thus a saving of 56.25%.

It is thus evident that large savings were achieved by increasing the GPR from 20 V to 35 V without sacrificing safety.

5.5 SOIL RESISTIVITY IN THE NORTHERN CAPE REGION AND ELSEWHERE

The resistance to true earth of an earth electrode is influenced by the resistivity of the surrounding soil. The measurement of soil resistivity at the exact position of installation is therefore extremely important and **must form an integral part of the overall earth electrode design.**

The map below indicates the soil resistivity for the South African region measured in ohm metres. From the map it can be seen that soil resistivity in the Northern Cape region is between 100 to 3333 ohm metre [1].

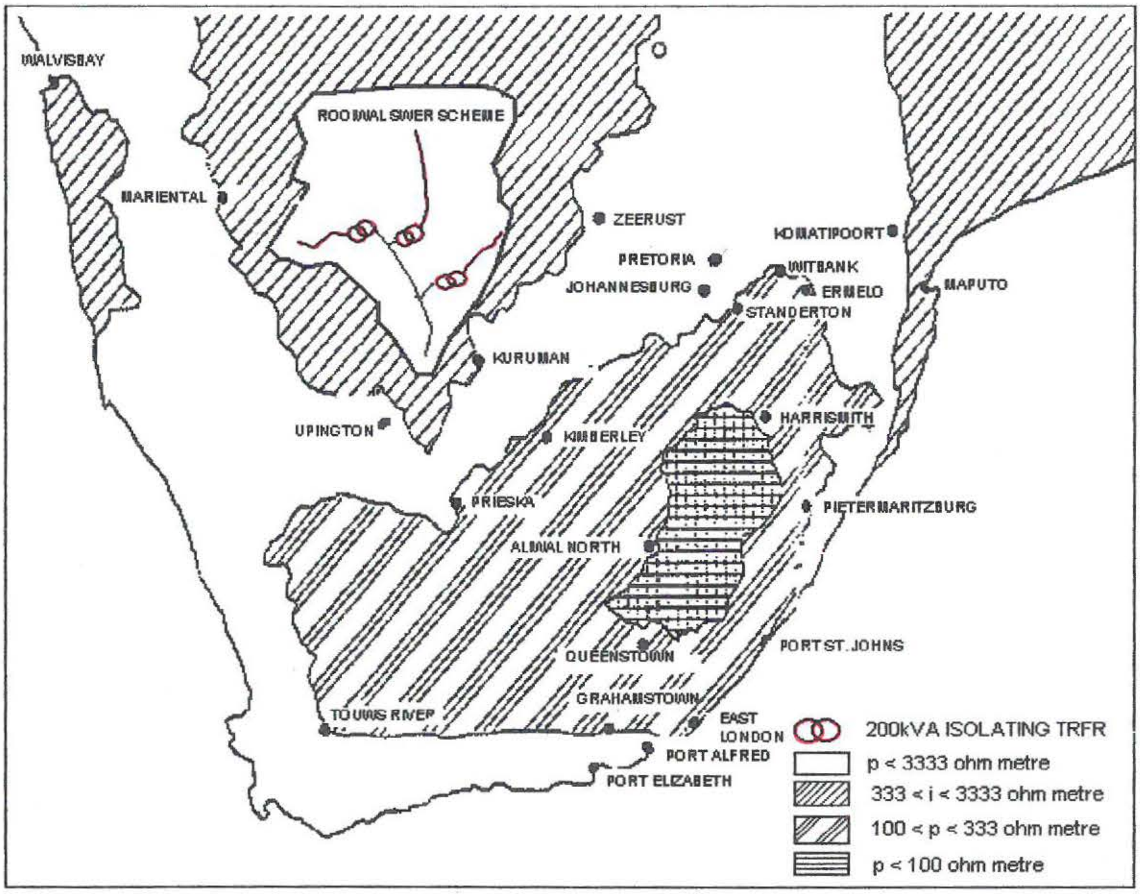


Fig.5.5 Soil Resistivity Map of South Africa

The electrical properties of the soil, particularly the specific resistance or resistivity, determine the resistance of any earth electrode. Soil resistivity tests are therefore essential because they determines the size of the earth electrode to be installed and the costs involved.

5.5.1 FACTORS DETERMINING THE RESISTIVITY OF SOIL

Studies indicate that soil resistivity is influenced by the following factors [18].

⇒ Soil type, depth of measurement, compactness, texture and grain size.

⇒ Geological composition, particularly the concentration and nature of dissolved salts.

⇒ Moisture content (see fig. 5.3).

⇒ Temperature (see fig. 5.3).

Since soil resistivities are particularly dependent upon the moisture content, such measurements are best done during a dry season, in order to obtain "worst case" readings.

5.5.2 SOIL RESISTIVITY TEST RESULTS

Soil resistivity tests were found to be essential before designing earth electrodes.

The information is required for:

⇒ Deciding on the type of system to install, e.g. single-phase or SWER, etc.

⇒ Estimating the earth electrode resistance for a proposed installation.

⇒ Estimating possible values for touch, step and transferred potentials.

⇒ Updating the soil resistivity area map.

⇒ Determining the type of electrode to be installed.

⇒ Cost estimation of the earth electrode to be installed.

5.6 SOIL RESISTIVITY MEASUREMENTS

There are two basic configurations of electrode arrangements to measure soil resistivity. These are the Wenner array and the Schlumberger array method. These two methods are very similar but differ in the spacing between the various electrodes.

The existing practice in Eskom is to apply the Wenner method of measuring soil resistivity [13].This method proved to be successful because the resistance values of the earth electrodes installed on the Rooiwal SWER line correspond with the theoretical earth electrode resistance values.

Based on the above, the author recommends the Wenner method of measuring soil resistivity, where a knowledge of resistivity is required for an earth electrode design.

The Wenner method of measuring soil resistivities is described in Appendix C [23, p.76] [40, sec.3] [13].

5.6.1 IMPORTANT FACTORS TO BE CONSIDERED WHEN CONDUCTING SOIL RESISTIVITY TESTS

Practical experience gained during field trials indicated that the factors listed below have an influence on the reliability of the measurements. To save time, and to prevent the redesigning of earth electrodes due to wrong measurements, it is very important to adhere to the following factors when conducting soil resistivity tests:

⇒ Ensure that the probes are installed in a straight line.

⇒ Do not install the probes parallel to fences.

⇒ Obtain the rainfall data of the last few months (± 6 months).

⇒ Ensure there are no buried conductors in the area studied because the soil resistivity measurements are of little value in an area where buried conductors have already been installed.

⇒ Ensure that the soil resistivity meter is calibrated (yearly).

⇒ Ensure that the separation of the probes is representative of the size / depth of the earth electrode to be installed.

⇒ Ensure that the depth of the probes is not more than 5% of the separations between the probes.

⇒ When conducting soil resistivity tests in areas with high resistivity, it might be necessary to measure the current injected into the current probes. If this current is low (less than 5mA), it may be necessary to reduce the earth resistance of both the potential and current probes by "watering" the area immediately around the probes.

5.7 SOIL TYPES

The composition of the soil is critical when deciding on the configuration of the earth electrodes to be installed. In rocky areas trenching of earth electrodes might be impossible, thereby enforcing deep-drilled earth electrodes. The feasibility of deep-drilled earth electrodes is dependent on the hardness of the rock, the drilling costs involved and the soil resistivity at the point of installation (e.g. soil resistivity may increase with depth). In pickable soil, with low top-layer soil resistivities (< ±5m), the installation of deep-drilled earth electrodes will not be cost-effective compared to the installation of trench earth electrodes or a combination of trench earth electrodes and earth spikes (crowsfoot earth electrodes).

It is thus clear that the soil type on site determines the configuration of the earth electrode to be installed.

Tables 5.3 and 5.4 can be used to evaluate and identify various soil types on site, although the author discovered that the most accurate information on the soil type and the depth of water tables, which could be very valuable in high resistivity areas, were received from people living in the area (e.g. farmers). A method previously used to determine the soil type was to compare the soil resistivities on site with the materials indicated in column 1 and 2 of table 5.5. This method is not recommended, because the range of soil resistivities could incorporate different soil types in the same range, for example, the resistivities of loam and garden soils are given between 5-50 ohm metre compared to those of clay and chalk between 10-70 ohm metre, thus four different soil types in the same soil resistivity range.

Table 5.3 Identification of Soils[43]

SOIL TYPES	VISUAL IDENTIFICATION	NATURE AND COLOUR
Loam	Predominantly plant remains	Firm to plastic brown to black silt, clay and peat often with a distinctive smell with a low bulk density.
Garden soils	Substantial organic matter with clay, silt or sand.	Medium dense to firm light brown to dark brown clayey sands.
Clays	Smooth to the touch. Sticks to the fingers. Shrinks appreciably on drying.	Intermediate to high plasticity in any colour. Dries slowly.
Silts	Only coarse silt barely visible. Slightly granular or silky to touch.	Light brown silty. Easily powdered between fingers. Disintegrates in water. Non-plastic.
Sands	Visible to naked eye. Little or no cohesion when dry. Grading can be described.	Smooth to rough, light brown to yellow, loose to slightly cemental particles.
Gravel	Easily visible to the naked eye. Particle shape can be described. Grading can be described.	Angular, rounded, flat or elongate shapes in various colours.
Cobbles Boulders	Difficult to recover from boreholes, sometimes only seen in open excavation.	Different shapes, sizes and colours.

Table 5.4 Guide to the Evaluation and Identification of Various Soil Types [43]

Term	Field Identification
Loose	Easily crushed in the fingers. Excavated with a spade. 50mm wooden peg can easily be driven in.
Dense	Requires pick for excavation. 50mm wooden peg hard to drive.
Very soft	Exudes between fingers when squeezed in hand.
Soft	Moulded by light finger pressure.
Firm	Can be moulded by strong finger pressure.
Stiff	Cannot be moulded by fingers. Can be indented by thumb. Very stiff. Can be indented by thumb nail.
Spongy	Very compressible and open structure.
Plastic	Can be moulded in hand and smears in fingers.
Homogeneous	Deposit consists essentially of one type.
Inter-stratified	Alternating layers of varying types or with bands or lenses or other materials.
Heterogeneous	A mixture of types.
Weathered	Particles may be weakened and may show concentric layering.
Fissured	Breaks into polyhedral fragments along fissures.
Intact	No fissures.
Fibrous	Plant remains recognizable and retains some strength.
Amorphous	Recognisable plant remains absent.

Table 5.5 Resistivities for Different Types of Materials [43]

1	2
Materials	**Resistivity (Order of magnitude) Ωm**
Types of rock	
Compact granite, gneiss	10^6 - 10^7
Syenite, diorite, dioritic gneiss	10^3 - 10^6
Compact rock, ordinary concrete	10^6
Coal	10^5 - 10^8
Master rocks, basalt, diabase	10 000
Dry and fine sand	1 000
Gabbro (type of rock)	100 - 1 000
Water	
Chemically clean water	25×10^4
Distilled water	5 000
Rain water	100 - 1 000
Surface water (lakes, rivers)	100 - 500
Ground water, well water, spring water	10 - 150
Sea water	0,1 - 1
Soils	
Loams, garden soil	5 - 50
Clay, chalk	10 - 70
Clay, sand and gravel mixture	40 - 250
Peat, marsh soil and cultivated soil	50 - 250
Diabase, shale, limestone and sandstone	100 - 500
Moraine, coarse sand and gravel	1×10^3
Igneous rocks, granite	3×10^5 - 4×10^7
Wet concrete	50 - 100
Dry concrete	2×10^3 - 1×10^4
Minerals, metals	
Copper	$1{,}2 \times 10^{-8}$ - 30×10^{-8}
Refined copper	$1{,}6 \times 10^{-8}$
Refined aluminium	$2{,}5 \times 10^{-8}$
Graphite	28×10^{-8} - 99×10^{-4}
NOTE - The origin of the resistivity figures for types of rock is not known. The remaining resistivity figures have been extracted from the technical manual issued at the seminar on "Grounding, Electromagnetic Fields and Interference Analysis" presented by F. Dawalibi of Canada and held in South Africa during November 1994.	

Defining of the soil type was found to be of great importance while on site because it will determine a reasonably cost effective earth electrode design at a preliminary stage.

During the investigation of SWER as a technology to electrify farmers in the Olifantshoek district, (Rooiwal scheme) it was found that more information than only soil resistivity tests are required to design an optimum earth electrode.

Listed are valuable information required to assist in the design of an optimal earth electrode:

⇒ Type of soil that will give an indication of the corrosiveness and thermal resistivity of the soil.

⇒ The depth of the water table. This information could be valuable, especially in areas where the top layer of the soil has a high soil resistivity, thereby making SWER not an option to consider. A high water table within a reasonable depth may then make SWER feasible.

⇒ Determine if the soil type will allow the installation of trench earth electrodes (no earth spikes), an earth electrode that consists of a combination of trench and earth spikes (further in this document referred to as crowsfoot earth electrodes) or whether the soil will enforce the installation of deep-drilled earth electrodes.

Soil types found during a survey in the Northern Cape region vary from clay, dry and fine sand to lime and different types of rock, thereby indicating the need of all three earth electrode configurations as mentioned above.

The soil type may also give an indication of the corrosiveness of the soil and the ability thereof to dissipate heat (I^2R losses) into the soil. This will be explained in paragraphs 5.7.1. and 5.7.2.

5.7.1 SOIL CORROSIVENESS

The soil pH is a very important factor to be considered when deciding on the materials to be used for the earth electrode, thus preventing corrosion from taking place.

Corrosion of earth electrodes may result from the following [18]:

⇒ Differential aeration of the soil - arising during the backfilling process and through uneven distribution of moisture in the vicinity of the electrode.

⇒ The acidity and chemical content of the soil, as well as the presence of foreign materials including cinders, scrap metal, or organic material.

⇒ The presence of stray electric currents - particularly originating from nearby traction lines.

⇒ The interconnection of dissimilar metals in the soil or in the open where moisture is present.

To prevent corrosion of the earth electrode it is thus very important to do a visual inspection while on site, describing the possible soil type, e.g. sand, loam, lime, clay, rock or any combination of these. Include the colour and, where necessary, physical characteristics such as particle size and uniformity.

The next step will be to do soil resistivity measurements, because it may give an indication of the corrosiveness of the soil. Table 5.6 can then be used as a general guide, indicating the relationship between the soil resistivity tests and the corrosiveness of the soil [40, chapter 4 paragraph 4.3.1].

Table 5.6. **Resistivity versus Corrosiveness of Soil Type [40]**

Soil Resistivity (Ω m)	Corrosiveness
0 - 10	Very severe
10 - 100	Moderate to severe
100 - 1000	Mild
>1000	Probably not corrosive

To prevent corrosion of the earth electrode, the following materials are proposed for the different soil resistivities indicated in Table 5.6 [40, Chapter 5.2]:

⇒ **Copper electrodes**

Copper is a durable metal and can be used in corrosive soils.

⇒ **Galvanised electrodes**

Galvanised electrodes are generally acceptable in moderately corrosive soils provided that they are not used in the vicinity of buried copper.

This is because the copper being more noble acts as the cathode while the galvanised steel acts as the sacrificial anode, resulting in the galvanised consisting of zinc corroding away and then allowing the mild steel to corrode [46].

Table 5.7 indicate the electrode potential series. The aluminium end is known as the active end and the gold end of the series as the noble end.

Table 5.7 Electrode Potential Series [40, Chapter 5.1.1]

1	2
Metal	**Standard electrode potential at 25°C**
Aluminium	-1,67
Zinc	-0,76
Mild steel	-0,44
Cadmium	-0,40
Stainless steel (active)	-0,30
Nickel	-0,25
Tin	-0,14
Lead	-0,13
Copper	+0,34
Stainless steel (passive)	+0,50
Silver	+0,80
Carbon	+0,81
Mercury	+0,85
Platinum	+1,20
Gold	+1,7

The less noble of the two metals will become the anode and will corrode. The wider apart the metals in the series, the higher the potential difference and hence the greater the galvanic corrosion.

Measurements taken in the Northern Cape region showed high resistivities, (>100 Ωm) and therefore corrosion of electrodes should not be a problem.

Because of the importance of the SWER earth electrode, with special reference to safety and reliability, it is recommended that copper be the only earthing material to be used on SWER lines in the Northern Cape region.

5.7.2 THERMAL RESISTIVITY AND STABILITY OF SOIL

The thermal resistivity (T/R) and stability of soil are very important factors in the determination of the current ratings of underground carrying conductors (e.g. earth electrode in the case of SWER lines).

When the earth electrode is loaded continuously as in the case of SWER, it is very important to take heat dissipation as well as the evaporation of moisture from the soil into consideration. The size of the earth electrode plays an important role because a sustained current of high density penetrating the soil via a relatively small earth electrode will increase the thermal resistivity of the soil due to the heating of the soil. The thermal resistivity of soil is a measure of the resistance of the soil to the flow of heat and its value is inversely related to the moisture content of the soil.

Tests done on underground electric cables indicate that sheath temperatures as low as 55°C cause the moisture in the soil surrounding the cable to migrate away from the cable. This migration results in an increase of the thermal resistivity of the soil and consequently an increase of soil temperature leading to further drying of the soil [24, p.3]. This condition is known as thermal runaway.

Thus the higher the electrical resistivity of the soil, the higher the rate of heat discharge from the earth electrode (I^2R losses). Conversely, the higher the thermal resistivity of the soil, the greater the rise in temperature of the earth electrode due to the lower rate of heat dissapation through the soil. This cumulative effect may lead to complete evaporation of the moisture in the soil around the grounding system followed by destructive arcing and, ultimately, complete isolation of the earth electrode system from remote earth. This process may take a few minutes to several hours or days depending on the magnitudes of the fault current, earth return currents, charging currents, earth electrode configuration, ambient soil temperature and moisture content.

The thermal resistivity and the percentage moisture content of the different soil types found in South Africa are indicated in table 5.8 [39].

Table 5.8 Range of values of soil thermal resistivity and moisture content likely to be encountered in South Africa

1	2					3
Type of soil	**Thermal Resistivity K.m/W**					**Range of moisture content**
	1,0	2,0	3,0	4,0	5,0	
Clay						5 - 27 %
Sand						1,5 - 20 %
Sand/Gravel						2 - 18 %
Sandy clay						6 - 30 %
Loam						5 - 18 %
Chalk						2 - 20 %
Ouklip						5 - 24 %
Peat						5 - 100 %+
Made up soil						5 - 30 %

Because of the continuous load current that flows in the earth electrode and the effect that it may have on the heating of the soil (I^2R), it was decided to determine the maximum resistance allowed on SWER earth electrodes to prevent thermal runaway.

The following equation determines the temperature rise of the soil at the surface of an earth electrode, regardless of its shape.

$$\theta = \frac{R^2 I^2}{2\lambda \wp} \qquad [32, p.5\text{-}52]$$

Where θ = The temperature rise at any point in the soil

R = Earth electrode resistance (ohm)

I = Current (Ampére)

*λ = Thermal conductivity of the soil (W/m.°C or W/K.m)

$\wp$ = Average soil resistivity (ohm metre)

* Thermal conductivity is the inverse of thermal resistivity (m.°C/W or K.m/W).

Thus the maximum continuous current (I_m) which can flow in the earth electrode without exceeding the allowable temperature rise (θ_m) is:

$$I_m = \frac{1}{R}\sqrt{2\lambda \wp \theta_m} \qquad [32, p.5\text{-}52]$$

[23, p.263]

From the formulae above, the maximum earth electrode resistance can be calculated for different load currents to prevent the soil from heating and thus preventing thermal runaway.

$$R = \frac{\sqrt{2\lambda \wp \theta_m}}{I_m}$$

θ_m = Temperature at which migration of moisture in the soil takes place - soil temperature.

= 55°C - 25°C

= 30°C

25°C = Taken to be the ambient soil temperature

$\wp$ = Average soil resistivity (ohm metre)

λ = Thermal conductivity (W/K.m)

According to calculations, the maximum earth electrode resistance for different earth return currents and soil resistivities to prevent thermal runaway appears to be:

Table 5.9 Maximum Earth Electrode Resistance to Prevent Thermal Runaway

	R max (Ω)			
Im (A)	**℘ max (ohm metre)**	**0-100**	**100-500**	**500-4 000**
	λ (W/m °C)	**1,4 (Damp Clay)**	**0,83 (Loamy Soil)**	**0,5 (Sand)**
0,8		114,5	197,24	433,01
1,6		57,2	98,62	216,5
5		18,3	31,55	69,28
10		9,16	15,77	34,64

It is clear that thermal runaway will not be a problem at SWER earth electrodes by comparing the earth electrode resistance at which thermal runaway will start taking place (see table 5.9) with the maximum allowable earth electrode resistance at the isolating and distribution transformers, indicated in tables 5.11 and 5.16.

5.8 THE EFFECTS OF SEASONAL VARIATIONS ON THE EARTH ELECTRODE RESISTANCE

The seasonal variation in the value of earth resistance should be monitored particularly during the dry summer months. Drying out of the soil will result in an increase of the I^2R losses, causing the soil to heat. The heating of the soil will cause a further increase in the I^2R losses generating more heat. During drought conditions this repetitive action could result in thermal runaway.

The above-mentioned problem led to investigations done by H.G. Taylor who found that electrodes buried in loamy soil could dissipate 3 to 5kW per m^2 continuously but with slight increase in resistance. Tests were conducted on a three-star pattern earth electrodes, having an earth contact area of about 0,7 m^2, and hence it should be capable of dissipating 2,1 to 3,5kW continuously per day without appreciable increase in earth resistance [20, p.11] It was found that at isolating transformer installations, supplying long networks of line, particularly those operating at 19,1kV, the shallow earth electrodes cause the soil to dry out due to continuous earth return and charging currents. During drought seasons this problem was effectively overcome by installing earth electrodes at isolating transformers at a depth of not less than 4,8m. Test results indicate that the surface conditions do not influence electrode resistance at this depth [20, p.11].

These test results are confirmed by information provided by the suppliers of earth rods, which suggests the installation of earth electrodes deeper than 4 to 6m to prevent the effect of seasonal variations on the resistance of the earth electrode. This is also confirmed by tests done by Mr R.J.C. Moore of Eskom [29, p.5].

Due to the high temperatures and soil resistivities found in the Northern Cape region, and by taking the experimental work done by H.G.Taylor and R.J.C. Moore as described above into consideration, the following decision was taken during the design of earth electrodes installed at the isolating transformers:

Earth electrodes at the isolating transformers should consist of a minimum of two deep-drilled earths to a minimum depth of 10 m to prevent drying out of the soil during dry seasons.

5.9 SWER EARTH ELECTRODES IN THE NORTHERN CAPE REGION

Earthing in the Northern Cape region is different from other areas in South Africa because of the high soil resistivities, high temperatures and low rainfall statistics normally applicable to the area.

Calculations done to determine the appropriate earth electrode to be installed at the isolating and distribution transformers are based on a two-layer soil model (Top layer to a depth of 3,2m and bottom layer to a depth of 70m) by using a specialised computer software package called CDEGS. This is a commercial software package developed in Canada, and it uses the finite element principle [35].

The decision made in favour of the two-layer soil model instead of the uniform soil model was because of the following [23, p 27]:

⇒ Calculations will assume 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, and it was confirmed during soil resistivity tests conducted in the Northen Cape region.

The two-layer soil model was therefore found to be a more realistic approach than the uniform soil model and all calculations were done accordingly.

CDEGS was chosen because of the ability of the programme to indicate the voltage gradients, as well as step-and-touch potentials around the earth electrode. This information can be used to determine the minimum safe installation distance of the earth electrode to a fence, pipeline or steel structure, thereby preventing electrical shock to man and animals.

5.10 EARTH ELECTRODE DESIGN CONSIDERATIONS

To ensure the design of a safe earth electrode installation at the isolating and distribution transformers, the following factors were taken into consideration:

⇒ The earth electrodes are designed to a maximum GPR of 35V as explained in paragraph 5.3. This will ensure safe step-and-touch potentials if the load current at the isolating transformer is limited to 10A (200kVA @ 20kV) and at the distribution transformer to 0.8A (16kVA @ 20kV). An example of the voltage gradients around an isolating transformer earth electrode is attached in Appendix D.

⇒ The earth electrodes are designed to be as cost-effective as possible. This was done after investigations into materials used on existing SWER lines proved not to be cost effective. Calculations done indicated the following savings (see Appendix E):

Earth electrodes installed at isolating transformers on existing SWER lines consist of 50 X 3,15mm flat copper straps. Calculations based on earth contact area and material costs indicated that the use of 10mm dia. solid copper rod could result in savings of up to 60% .

Trench earth electrodes installed at a distribution transformer consist of 10mm dia. solid copper rod. The use of 10mm bare stranded copper indicates that savings of up to 87% could be achieved compared with the copper rod.

⇒ The earth electrodes are designed to be as practical as possible. This was done by taking the problems experienced (e.g. fences) during the installation of the Rooiwal SWER line earth electrodes into consideration. The radials of the trench earth electrodes (20m) and the depth to which drilled earth electrodes (70m) are to be installed were limited within a reasonable range.

5.11 EARTHING OF THE ISOLATING TRANSFORMER

The medium voltage (MV) earth electrode to be installed at the isolating transformer is critical, as this earth electrode must continuously carry the entire load current of the SWER line. The installed earth electrodes on existing SWER lines were found to be very expensive, mainly because of the following:

⇒ High soil resistivities related to the Northern Cape region.

⇒ Electrodes are designed to the Australian GPR limit of 20V as mentioned previously.

⇒ Earth electrodes designed did not take the soil types on site into consideration (e.g. rather drill if the lower soil resistivity is deeper and more cost-effective than a trench earth electrode installed in a high top layer soil resistivity).

⇒ Lack of experience and knowledge by not taking the critical factors as explained in paragraphs 5.1 to 5.8 into consideration.

5.12 MV EARTH ELECTRODE CONFIGURATION

The layout / configuration of the MV earth electrodes to be installed at the isolating transformer was determined by the following factors found on site:

⇒ The earth electrodes are designed to be installed in the smallest area possible. This is because the isolating transformer will be installed on privately owned property (e.g. a farm) and therefore may limit farming activities such as ploughing (may damage earth electrodes).

⇒ The deep-drilled electrodes are so connected that in the event of losing one of the interconnected radials, the earth electrodes will still be connected.

⇒ Earth electrodes are to be installed to a minimum depth of 10m. This is to prevent the resistance of the earth electrodes being influenced by seasonal variations in the soil resistivity.

By taking the above into consideration, the configurations decided on are indicated in table 5.10.

5.12.1 STEPS TO DETERMINE THE REQUIRED EARTH ELECTRODE CONFIGURATION AT THE ISOLATING TRANSFORMER

⇒ Conduct soil resistivity tests at the exact position where the earth electrode is to be installed. The test readings must be recorded on the form attached in Appendix C.

⇒ From the soil resistivity tests, determine the maximum resistivity ($\wp$max.) to a depth of 3,2m (clear cut on the soil resistivity record sheet). From this value a corresponding column can be found from table 5.10.

⇒ Determine the average soil resistivity ($\wp$avg.) between a depth of 3,2m and 70m. From this value a corresponding row can be found from table 5.10.

⇒ Where the corresponding row intersects with the corresponding column, an earth electrode for the appropriate soil conditions can be found.

privately owned property (e.g. a farm) and therefore may limit farming activities such as ploughing (may damage earth electrodes).

⇒ The deep-drilled electrodes are so connected that in the event of losing one of the interconnected radials, the earth electrodes will still be connected.

⇒ Earth electrodes are to be installed to a minimum depth of 10m. This is to prevent the resistance of the earth electrodes being influenced by seasonal variations in the soil resistivity.

By taking the above into consideration, the configurations decided on are indicated in table 5.10.

5.12.1 STEPS TO DETERMINE THE REQUIRED EARTH ELECTRODE CONFIGURATION AT THE ISOLATING TRANSFORMER

⇒ Conduct soil resistivity tests at the exact position where the earth electrode is to be installed. The test readings must be recorded on the form attached in Appendix C.

⇒ From the soil resistivity tests, determine the maximum resistivity ($\wp$max.) to a depth of 3,2m (clear cut on the soil resistivity record sheet). From this value a corresponding column can be found from table 5.10.

⇒ Determine the average soil resistivity ($\wp$avg.) between a depth of 3,2m and 70m. From this value a corresponding row can be found from table 5.10.

⇒ Where the corresponding row intersects with the corresponding column, an earth electrode for the appropriate soil conditions can be found.

NOTE: When the soil becomes moist, continue to drill for 6 metres when installing deep-drilled earth electrodes (stop drilling when water is encountered).

If the resistivity values determined ($\wp$max. and $\wp$avg.) are not within the limits of table 5.10, it will be necessary to do a specific earth electrode design to suit the circumstances on the site or it may be more cost-effective to move the installation position of the isolating transformer to a site with lower soil resistivities.

Table 5.10 Isolating Transformer MV Earth Electrodes

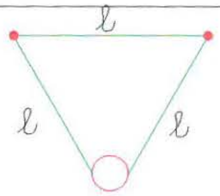
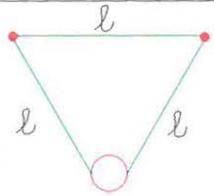
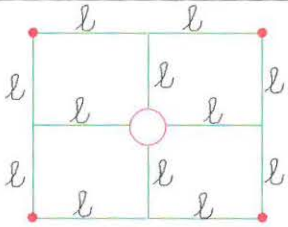
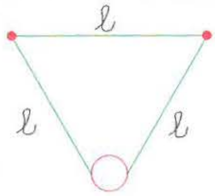
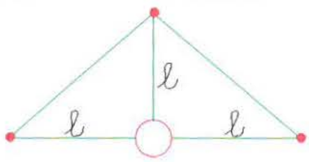
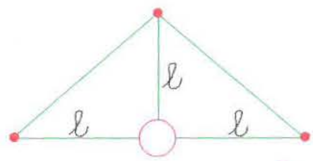
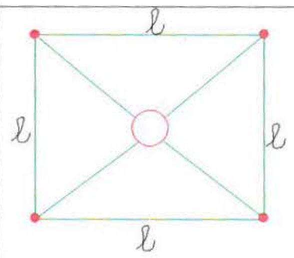
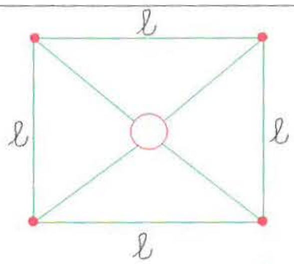
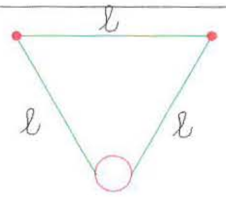
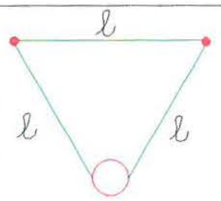
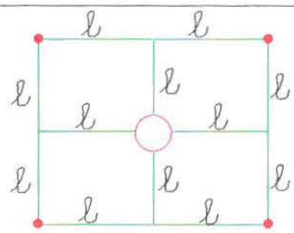
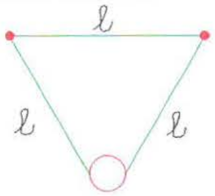
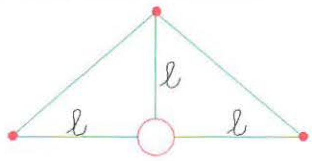
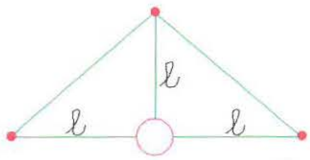
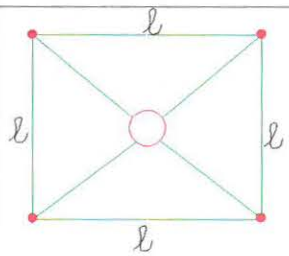
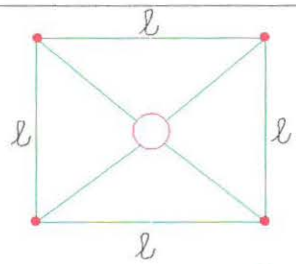
		ρ MAX TO A DEPTH OF 3.2m	
	Ωm	≤ 200	≤ 500
ρ AVERAGE BETWEEN A DEPTH OF 3.2m AND 70m	100	 POLE – ○ EARTH ROD 20m DEEP – ● RADIAL LENGTH(ℓ) = 15m – —— TRENCH DEPTH – 0.5m DISTANCE TO FENCE – 10m	 POLE – ○ EARTH ROD 25m DEEP – ● RADIAL LENGTH(ℓ) = 15m – —— TRENCH DEPTH – 0.5m DISTANCE TO FENCE – 10m
	200	 POLE – ○ EARTH ROD 10m DEEP – ● RADIAL LENGTH(ℓ) = 15m – —— TRENCH DEPTH – 0.5m DISTANCE TO FENCE – 10m	 POLE – ○ EARTH ROD 50m DEEP – ● RADIAL LENGTH(ℓ) = 15m – —— TRENCH DEPTH – 0.5m DISTANCE TO FENCE – 15m
	300	 POLE – ○ EARTH ROD 40m DEEP – ● RADIAL LENGTH(ℓ) = 20m – —— TRENCH DEPTH – 0.5m DISTANCE TO FENCE – 20m	 POLE – ○ EARTH ROD 50m DEEP – ● RADIAL LENGTH(ℓ) = 20m – —— TRENCH DEPTH – 0.5m DISTANCE TO FENCE – 10m
	500	 POLE – ○ EARTH ROD 60m DEEP – ● RADIAL LENGTH(ℓ) = 20m – —— TRENCH DEPTH – 0.5m DISTANCE TO FENCE – 30m	 POLE – ○ EARTH ROD 70m DEEP – ● RADIAL LENGTH(ℓ) = 20m – —— TRENCH DEPTH – 0.5m DISTANCE TO FENCE – 25m

Table 5.10 Isolating Transformer MV Earth Electrodes

<table>
<tr><td colspan="4">ρ MAX TO A DEPTH OF 3.2m</td></tr>
<tr><td></td><td>Ωm</td><td>≤ 200</td><td>≤ 500</td></tr>
<tr><td rowspan="4">ρ AVERAGE BETWEEN A DEPTH OF 3.2m AND 70m</td><td>100</td><td>
POLE – ○
EARTH ROD 20m DEEP – ●
RADIAL LENGTH(ℓ) = 15m – —
TRENCH DEPTH – 0.5m
DISTANCE TO FENCE – 10m</td><td>
POLE – ○
EARTH ROD 25m DEEP – ●
RADIAL LENGTH(ℓ) = 15m – —
TRENCH DEPTH – 0.5m
DISTANCE TO FENCE – 10m</td></tr>
<tr><td>200</td><td>
POLE – ○
EARTH ROD 10m DEEP – ●
RADIAL LENGTH(ℓ) = 15m – —
TRENCH DEPTH – 0.5m
DISTANCE TO FENCE – 10m</td><td>
POLE – ○
EARTH ROD 50m DEEP – ●
RADIAL LENGTH(ℓ) = 15m – —
TRENCH DEPTH – 0.5m
DISTANCE TO FENCE – 15m</td></tr>
<tr><td>300</td><td>
POLE – ○
EARTH ROD 40m DEEP – ●
RADIAL LENGTH(ℓ) = 20m – —
TRENCH DEPTH – 0.5m
DISTANCE TO FENCE – 20m</td><td>
POLE – ○
EARTH ROD 50m DEEP – ●
RADIAL LENGTH(ℓ) = 20m – —
TRENCH DEPTH – 0.5m
DISTANCE TO FENCE – 10m</td></tr>
<tr><td>500</td><td>
POLE – ○
EARTH ROD 60m DEEP – ●
RADIAL LENGTH(ℓ) = 20m – —
TRENCH DEPTH – 0.5m
DISTANCE TO FENCE – 30m</td><td>
POLE – ○
EARTH ROD 70m DEEP – ●
RADIAL LENGTH(ℓ) = 20m – —
TRENCH DEPTH – 0.5m
DISTANCE TO FENCE – 25m</td></tr>
</table>

5.12.2 MAXIMUM EARTH ELECTRODE RESISTANCE

The maximum resistance of the isolating transformer MV earth electrode to ensure safe step-and-touch potentials will be as follows:

Table 5.11 Isolating Transformer Earth Electrode Resistance

CAPACITY (kVA)	SYSTEM VOLTAGE (kV)	RATED CURRENT (A)	EARTH ELECTRODE RESISTANCE (Ω)
200	20	10	3,5
100	20	5	7

The earth electrodes as indicated in table 5.10, are designed to a GPR of 35V and will ensure safe step-and-touch potentials if the earth return current is limited to 10A under normal operating conditions. The risk of load currents as high as the maximum capacity of the isolating transformer (10A) will be unlikely, because statistics received from the reticulation planners in the Northern Cape region indicate that the diversity of load demands on existing SWER lines, as well as on single-phase and three-phase rural lines, is about 30% (load factor).

This might be a different situation when electrifying villages, and it is proposed that maximum demand metering is to be installed at the isolating transformer. This will give an indication to the area engineer if the capacity of the isolating transformer needs to be upgraded. This will also mean that the earth electrode resistance is to be decreased due to the higher load currents.

5.13 EARTHING OF THE DISTRIBUTION TRANSFORMER

Two earth electrodes are to be installed at the distribution transformer, namely, the MV earth electrode on the primary side (20kV) and the LV earth electrode on the secondary side (230V).

These electrodes are usually less expensive than the earth electrodes installed at the isolating transformer, due to the lower load currents.

The earth electrode configuration is mainly dependent on the soil type as explained in paragraph 5.7.

Soil types related to the Northern Cape region necessitate the need for different types of earth electrodes, such as electrodes to install in sand, clay, lime and rock.

The configurations decided on are a crowsfoot earth electrode (table 5.13), trench earth electrode (table 5.14) and deep-drilled earth electrode (table5.15).

5.13.1 EXISTING EARTHING PRACTICE AT DISTRIBUTION TRANSFORMERS

After a series of distribution transformer failures in the Northern Cape region, an investigation was done into the earthing philosophy used on existing SWER schemes with regard to the earthing of the MV surge arresters, transformer tank and MV and LV earth electrodes.

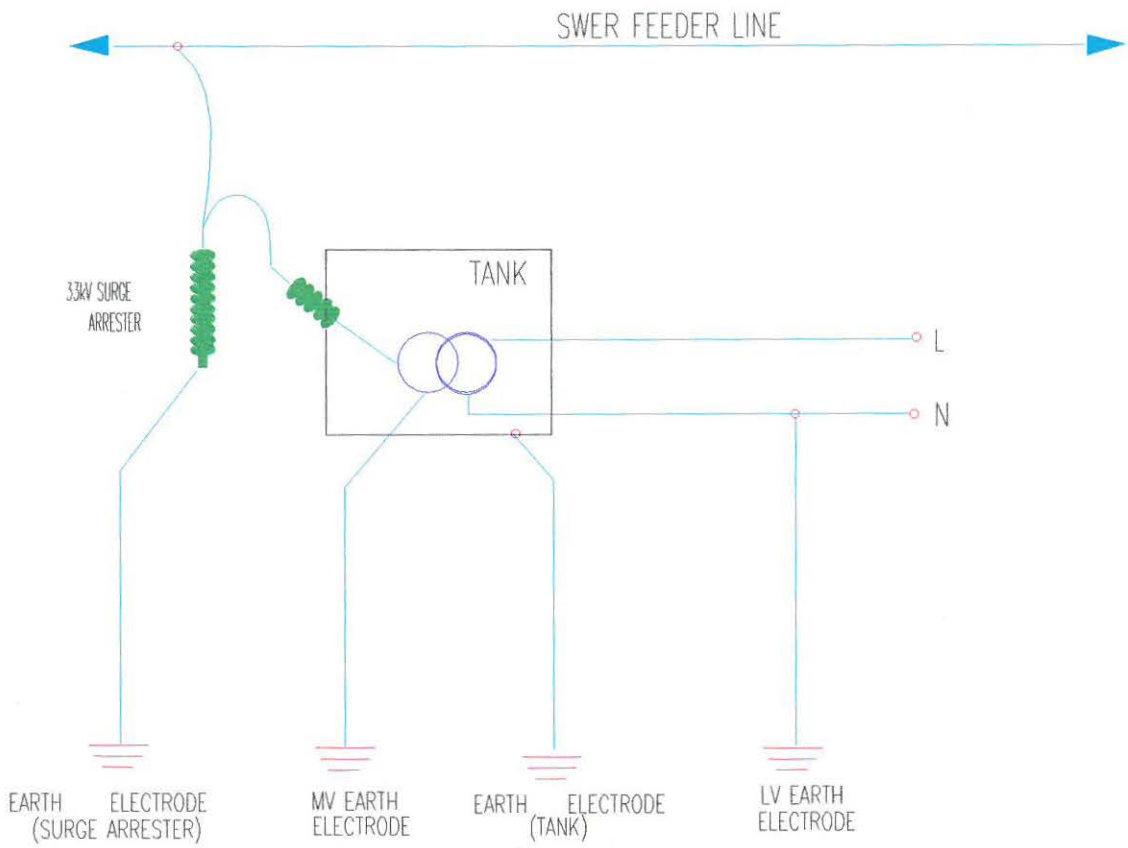


Fig. 5.6 Existing Earthing Practice at Distribution Transformer

The following earthing practice has been used in the Northern Cape region (see figure 5.6):

⇒ Separate earthing of the 33kV surge arrester

⇒ Separate earthing of the MV winding

⇒ Separate earthing of the LV winding

⇒ Separate earthing of the transformer tank

The author concluded that the present earthing philosophy must be terminated with immediate effect, due to the following reasons:

⇒ The costs involved (material and labour), because four separate earth electrodes are installed.

⇒ Identification of the earth electrodes is difficult, because all four earthing leads are in one PVC pipe.

⇒ A large area is taken up by the installation of the four electrodes.

⇒ It is difficult to preserve the 5m separation distance between the MV and LV earth electrodes. This resulted in the overlapping of the earth electrodes' equipotential curves.

⇒ The accuracy of the earth electrode resistance measurements is suspect due to the influence it has on one another.

⇒ Technically it is not sound engineering practice to separate the MV surge arresters and LV neutral from the transformer tank (see figure 5.7).

Refer to the example below.

Originally, all rural networks were installed with the high voltage hardware and surge arresters connected to one earth electrode, and the low voltage hardware, arresters (if fitted) and the neutral connected to a second separate electrode, as shown in figure 5.7.

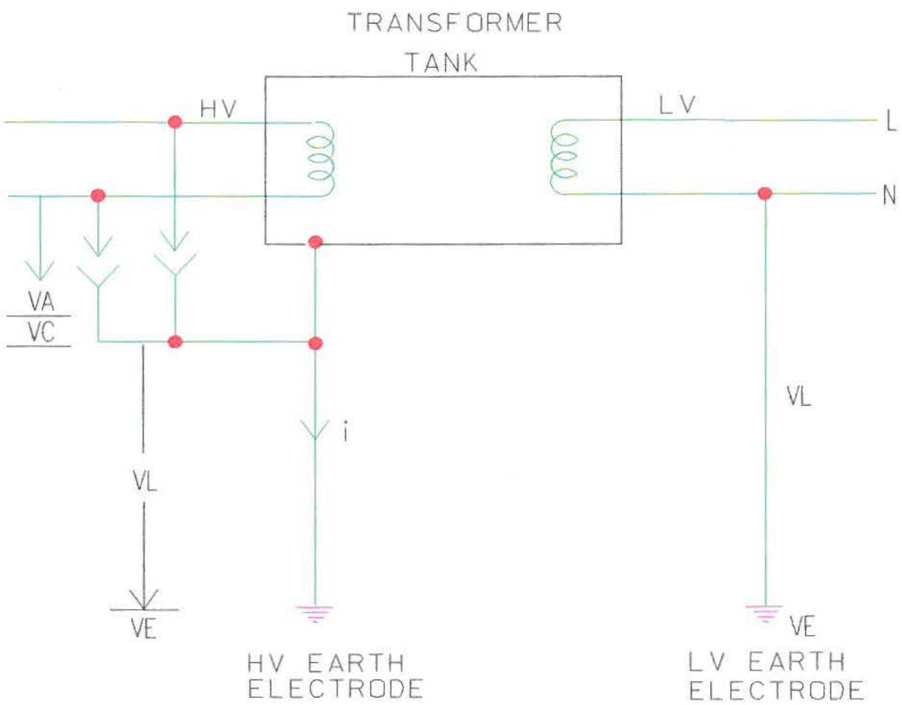


Fig. 5.7 Separate Earthing Installation

With this connection, the voltage between the primary winding and ground is not only the discharge voltage of the arrester (V_A), but also the impedance drop of the connecting lead between the arrester and the earth electrode (V_C), as well as the impedance drop of the earth electrode itself (V_E) and V_L the earth conductor.

The secondary or LV side of the transformer is almost at earth potential when the surge occurs, so the full discharge voltage exists between the primary and secondary windings of the transformer and between the secondary winding and the transformer tank, thus stressing the insulation.

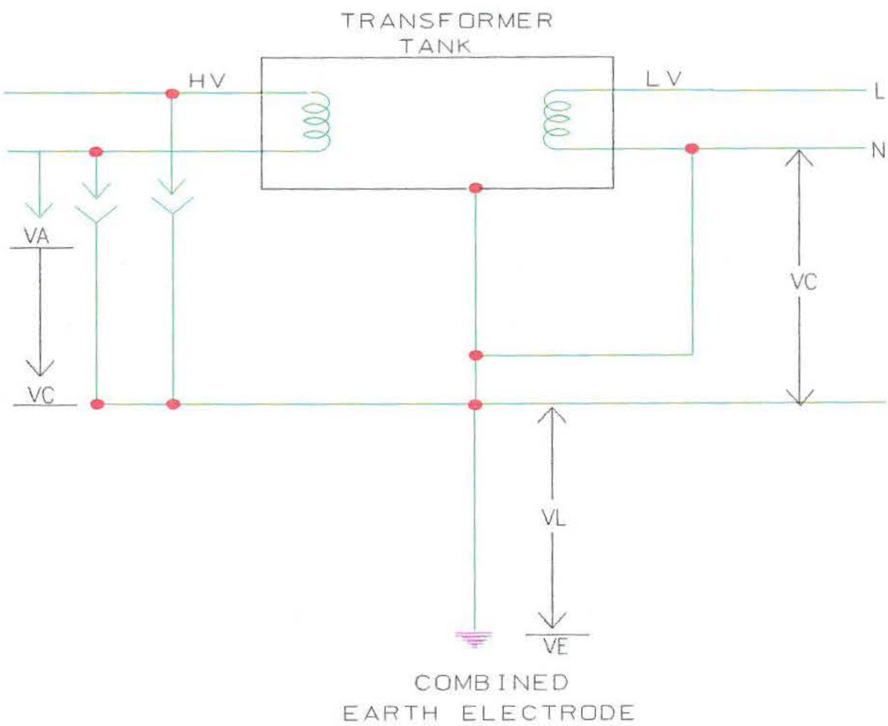


Fig. 5.8 Combined Earthing System

If the HV hardware and arresters are connected to the same earth as the LV windings on the pole, as in figure 5.8, then the potential difference between the two windings for the same discharge current will be much less.

It thus appears with reference to the above example that the separation of the earth connections each with its own electrode, contributed to the high failure rate of SWER distribution transformers in the Northern Cape region (20% failure rate over the past 5 years).

5.14 MV AND LV EARTH ELECTRODE CONFIGURATIONS

The MV and LV earth electrode configurations / layout to be installed, are based on the following practicalities found on site:

⇒ The crowsfoot earth electrode is recommended to be installed as a first option because of the advantages in table 5.12.

Table 5.12 Advantages and Disadvantages of Crowsfoot and Trench Earth Electrodes Under Transient Conditions (e.g. Lightning) [40, p.50]

ELECTRODE	ADVANTAGES	DISADVANTAGES
Vertical rods	Design simplicity. Can be extended to reach the water table in very high resistivity soils.	High surge impedance. Not easily installable where large rock formations are near the surface. Step voltage on earth surface can be excessive under high fault currents or during direct lightning strikes.
Horizontal buried conductors	Low surge impedance. Minimum surface potential gradient. Easy installation. Can achieve low resistance in areas where rock formations prevent the use of vertical rods. Can be combined with vertical rods to stabilise resistance fluctuations.	Subject to resistance fluctuations resulting from soil drying if vertical rods are not used. Subject to vandalism and theft.

The above-mentioned recommendation is also in line with Eskom's Earthing Standard on conventional single-phase (2 wire) and three-phase networks [13].

⇒ The layout of the earth electrodes is such that it will only be installed to the one side of the pole (opposite directions). This is to preserve the minimum separation distance between the MV and LV earth electrodes as explained in paragraph 5.18.

⇒ The radials of the earth electrodes are limited by taking the practicalities found on site into consideration (e.g. fences).

Deep-drilled earth electrodes are only to be installed if the costs involved are feasible compared to the costs of moving the position of the distribution transformer to a site with more favourable resistivities or pickable soil.

5.14.1 STEPS TO DETERMINE THE REQUIRED MV EARTH ELECTRODE CONFIGURATION AT THE DISTRIBUTION TRANSFORMER

⇒ Determine whether the soil type on site will allow a crowsfoot, trench or deep-drilled type earth electrode to be installed (see tables 5.13 to 5.15).

⇒ Conduct soil resistivity tests at the exact position where the MV earth electrode is to be installed. Record the measurements on the form attached in Appendix C.

⇒ From the soil resistivity tests, determine the maximum resistivity ($\wp$max.) to a depth of 3,2m. From this value a corresponding column can be found.

⇒ Determine the average soil resistivity ($\wp$avg.) between a depth of 3,2m and 50m. From this value a corresponding row can be found.

⇒ Where the corresponding row intersects with the corresponding column, an earth electrode for the appropriate soil conditions can be found.

NOTE: When the soil becomes moist, continue to drill for 6 metres when installing deep-drill earth electrodes (stop drilling when water is encountered).

It will be necessary to do a specific earth electrode design if the soil resistivities as determined above are not within the limits of tables 5.13 to 5.15. The design costs must be compared to the costs of moving the installation position of the earth electrode or distribution transformers to a site with more favourable soil resistivities.

Table 5.13 Distribution Transformer MV Crowsfoot Earth Electrodes

EARTHING OF DISTRIBUTION TRANSFORMERS Soft soil / Crowsfoot earthing		ρ MAX TO A DEPTH OF 3.2m			
		200	500	800	1200
ρ AVERAGE BETWEEN A DEPTH OF 3.2m AND 50m	200	TRENCH DEPTH = 0.5m RADIAL LENGTH (ℓ) = 5m ROD LENGTH = 1.5m ROD SEPARATION DISTANCE = 5m NUMBER OF ROD = 4 NUMBER OF COPPER = 15m DISTANCE TO FENCE = 2m	TRENCH DEPTH = 0.5m RADIAL LENGTH (ℓ) = 10m ROD LENGTH = 1.5m ROD SEPARATION DISTANCE = 5m NUMBER OF ROD = 7 NUMBER OF COPPER = 30m DISTANCE TO FENCE = 2m	TRENCH DEPTH = 0.5m RADIAL LENGTH (ℓ) = 15m ROD LENGTH = 1.5m ROD SEPARATION DISTANCE = 7.5m NUMBER OF ROD = 7 NUMBER OF COPPER = 45m DISTANCE TO FENCE = 2m	TRENCH DEPTH = 0.5m RADIAL LENGTH (ℓ) = 22m ROD LENGTH = 1.5m ROD SEPARATION DISTANCE = 11m NUMBER OF ROD = 7 NUMBER OF COPPER = 66m DISTANCE TO FENCE = 2m
	500	TRENCH DEPTH = 0.5m RADIAL LENGTH (ℓ) = 5m ROD LENGTH = 1.5m ROD SEPARATION DISTANCE = 7m NUMBER OF ROD = 5 NUMBER OF COPPER = 15m DISTANCE TO FENCE = 2m	TRENCH DEPTH = 0.5m RADIAL LENGTH (ℓ) = 14m ROD LENGTH = 1.5m ROD SEPARATION DISTANCE = 7m NUMBER OF ROD = 7 NUMBER OF COPPER = 42m DISTANCE TO FENCE = 2m	TRENCH DEPTH = 0.5m RADIAL LENGTH (ℓ) = 16m ROD LENGTH = 3m ROD SEPARATION DISTANCE = 8m NUMBER OF ROD = 14 NUMBER OF COPPER = 48m DISTANCE TO FENCE = 2m	TRENCH DEPTH = 0.5m RADIAL LENGTH (ℓ) = 22m ROD LENGTH = 3m ROD SEPARATION DISTANCE = 11m NUMBER OF ROD = 14 NUMBER OF COPPER = 66m DISTANCE TO FENCE = 2m
	800	TRENCH DEPTH = 0.5m RADIAL LENGTH (ℓ) = 7m ROD LENGTH = 1.5m ROD SEPARATION DISTANCE = 7m NUMBER OF ROD = 5 NUMBER OF COPPER = 21m DISTANCE TO FENCE = 2m	TRENCH DEPTH = 0.5m RADIAL LENGTH (ℓ) = 16m ROD LENGTH = 1.5m ROD SEPARATION DISTANCE = 8m NUMBER OF ROD = 7 NUMBER OF COPPER = 48m DISTANCE TO FENCE = 2m	TRENCH DEPTH = 0.5m RADIAL LENGTH (ℓ) = 22m ROD LENGTH = 3m ROD SEPARATION DISTANCE = 11m NUMBER OF ROD = 14 NUMBER OF COPPER = 66m DISTANCE TO FENCE = 2m	TRENCH DEPTH = 0.5m RADIAL LENGTH (ℓ) = 22m ROD LENGTH = 3m ROD SEPARATION DISTANCE = 11m NUMBER OF ROD = 18 NUMBER OF COPPER = 66m DISTANCE TO FENCE = 2m
	1200	TRENCH DEPTH = 0.5m RADIAL LENGTH (ℓ) = 10m ROD LENGTH = 1.5m ROD SEPARATION DISTANCE = 10m NUMBER OF ROD = 4 NUMBER OF COPPER = 30m DISTANCE TO FENCE = 2m	TRENCH DEPTH = 0.5m RADIAL LENGTH (ℓ) = 22m ROD LENGTH = 1.5m ROD SEPARATION DISTANCE = 11m NUMBER OF ROD = 7 NUMBER OF COPPER = 66m DISTANCE TO FENCE = 2m	TRENCH DEPTH = 0.5m RADIAL LENGTH (ℓ) = 22m ROD LENGTH = 3m ROD SEPARATION DISTANCE = 11m NUMBER OF ROD = 18 NUMBER OF COPPER = 88m DISTANCE TO FENCE = 2m	DRILL

Table 5.14 Distribution Transformer MV Trench Earth Electrode

EARTHING OF DISTRIBUTION TRANSFORMERS					
Trench Earthing - Hard Soil (No Spikes)					
	ρ MAX TO A DEPTH OF 3.2m				
		200	500	800	1200
ρ AVERAGE BETWEEN A DEPTH OF 3.2m AND 50m	200	DEPTH = 0.5m RADIALS (ℓ) = 5m DISTANCE TO FENCE = 2m	DEPTH = 0.5m RADIALS (ℓ) = 15m DISTANCE TO FENCE = 2m	DEPTH = 0.5m RADIALS (ℓ) = 20m DISTANCE TO FENCE = 2m	DEPTH = 0.5m RADIALS (ℓ) = 25m DISTANCE TO FENCE = 2m
	500	DEPTH = 0.5m RADIALS (ℓ) = 7m DISTANCE TO FENCE = 2m	DEPTH = 0.5m RADIALS (ℓ) = 15m DISTANCE TO FENCE = 2m	60° DEPTH = 0.5m RADIALS (ℓ) = 20m DISTANCE TO FENCE = 2m	60° DEPTH = 0.5m RADIALS (ℓ) = 25m DISTANCE TO FENCE = 2m
	800	DEPTH = 0.5m RADIALS (ℓ) = 7m DISTANCE TO FENCE = 2m	DEPTH = 0.5m RADIALS (ℓ) = 20m DISTANCE TO FENCE = 2m	DEPTH = 0.5m RADIALS (ℓ) = 20m DISTANCE TO FENCE = 2m	DRILL
	1200	DEPTH = 0.5m RADIALS (ℓ) = 10m DISTANCE TO FENCE = 2m	60° DEPTH = 0.5m RADIALS (ℓ) = 20m DISTANCE TO FENCE = 2m	DRILL	DRILL

Table 5.15 Distribution Transformer MV Deep-Drilled Earth Electrodes

EARTHING OF DISTRIBUTION TRANSFORMERS					
Rocky Soil (Drill only)					
	Ø MAX TO A DEPTH OF 3.2m				
		200	500	800	1200
Ø AVERAGE BETWEEN A DEPTH OF 3.2m AND 5.0m	200	10m DISTANCE TO FENCE =10m	10m DISTANCE TO FENCE =10m	10m DISTANCE TO FENCE =10m	10m DISTANCE TO FENCE =10m
	500	15m DISTANCE TO FENCE =10m	15m DISTANCE TO FENCE =10m	20m DISTANCE TO FENCE =10m	20m DISTANCE TO FENCE =10m
	800	20m DISTANCE TO FENCE =10m	25m DISTANCE TO FENCE =10m	30m DISTANCE TO FENCE =10m	30m DISTANCE TO FENCE =10m
	1200	30m DISTANCE TO FENCE =10m	35m DISTANCE TO FENCE =10m	40m DISTANCE TO FENCE =10m	40m DISTANCE TO FENCE =10m

5.14.2 DISTRIBUTION TRANSFORMER MV EARTH ELECTRODE RESISTANCE

The maximum allowable MV earth electrode resistance at the distribution transformer is indicated in table 5.16.

Table 5.16 Distribution Transformer MV Earth Electrode Resistance

CAPACITY (kVA)	SYSTEM VOLTAGE (kV)	RATED CURRENT (A)	RESISTANCE (Ω)
16	20	0.8	43

The maximum earth electrode resistance as above will ensure safe step, touch and transfer potentials of less than 35 V under normal load conditions.

5.15 PRECAUTIONS REGARDING EARTH ELECTRODE INSTALLATIONS

To ensure a safe and reliable earth electrode installation, the following precautionary measurements must be adhered to during the installation of the earth electrodes at the isolating and distribution transformers. These factors are based on experience gained during the installation of the earth electrodes on the new Rooiwal SWER line.

5.15.1 ISOLATING TRANSFORMER

Earthing at the isolating transformers must consist of at least two deep-drilled earth electrodes to a minimum depth of 10m. This is to prevent drying out of the soil during drought seasons, thus preventing thermal runaway.

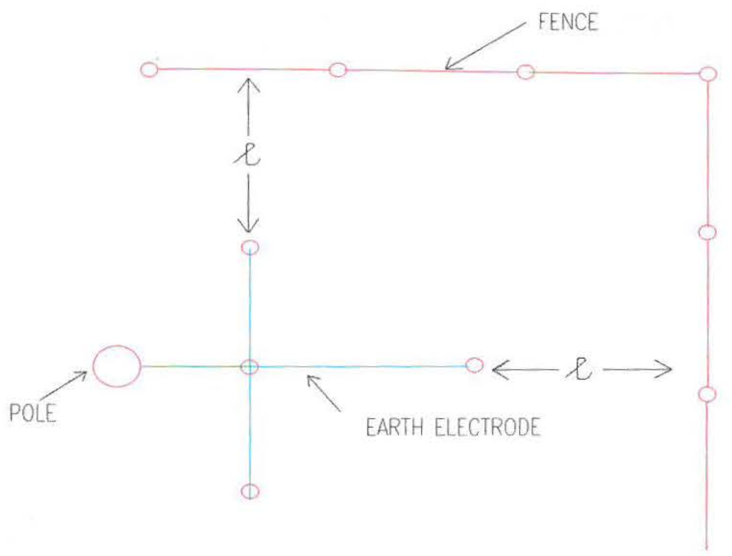
⇒ The deep-drilled earth electrodes must be so connected that in the event of losing one of the radials (e.g. theft), the deep-drilled earths are still connected to the transformer (see table 5.10).

⇒ The drilled holes must be backfilled with mitronite to ensure good contact with the earth and good conductivity during dry seasons.

⇒ The earth electrodes are not to be installed closer to a fence or any steel structure than the distances indicated for each electrode configuration in table 5.10. This will ensure safe touch potentials of less than 35 V under normal load conditions. During earth fault conditions (broken conductor), the SWER system will rely on the protection to clear the fault as in the case of conventional three-phase and single-phase networks.

5.15.2. DISTRIBUTION TRANSFORMER

⇒ The earth electrodes are not to be installed closer than 2m to any fence or steel structure. The author is of the opinion that the risk of dangerous transferred potentials to a remotely earthed fence under fault conditions will thereby be eliminated. The fence will be out of reach of a person standing in the vicinity of the earth electrode (see figure 5.9). The CDEGS programme also indicated that touch potentials within a radius of two metres of the designed earth electrodes (tables 5.13 to 5.15) were less than 35V.



ℓ = 2m (min)

Fig. 5.9. Minimum Distance of Distribution Transformer MV Earth Electrode to a Fence or Steel Structure

5.15.3 ISOLATING AND DISTRIBUTION TRANSFORMER

⇒ According to Eskom's Labelling Standard, a warning label must be installed on the pole, indicating the following:

- that the earthing lead is a continuous current-carrying conductor.
- the minimum radius from the pole wherein farming activities such as ploughing or fences are not allowed (Danger Zone).

⇒ The earth lead down the pole must be PVC insulated and protected by a 25mm dia. UV stable PVC pipe. (Steel pipe not allowed).

⇒ Ensure that an earthing conductor is installed between the two posts of a farm gate near the earth electrode installation to prevent electrical shocks to people opening the gates (According to Eskom Bloemfontein Standards, Drawing No D-FS-1 Rev.2, Appendix G).

⇒ The position of the earth electrodes must be clearly indicated on the spanning sheets. This will assist in locating the position of the electrode in the event of a failure of the earth electrode.

⇒ A radius of 5m around the pole must be clean of grass. This is to prevent damage to the PVC pipe protecting the insulation of the earthing lead down the pole during veld fires. The herbicides used must be in accordance with Eskom's recommended herbicide guides.

⇒ The earthing leads down the pole shall be a joint-free continuous conductor.

5.16 SWER EARTHING AND SAFETY IN VILLAGES

In order to ensure a safe SWER installation, the following earthing practice is suggested when electrifying villages. The earthing practice is based on information received from Dr H.J. Geldenhuys (New Technology Manager, Eskom Distribution Technology), and indicated in figure 5.10.

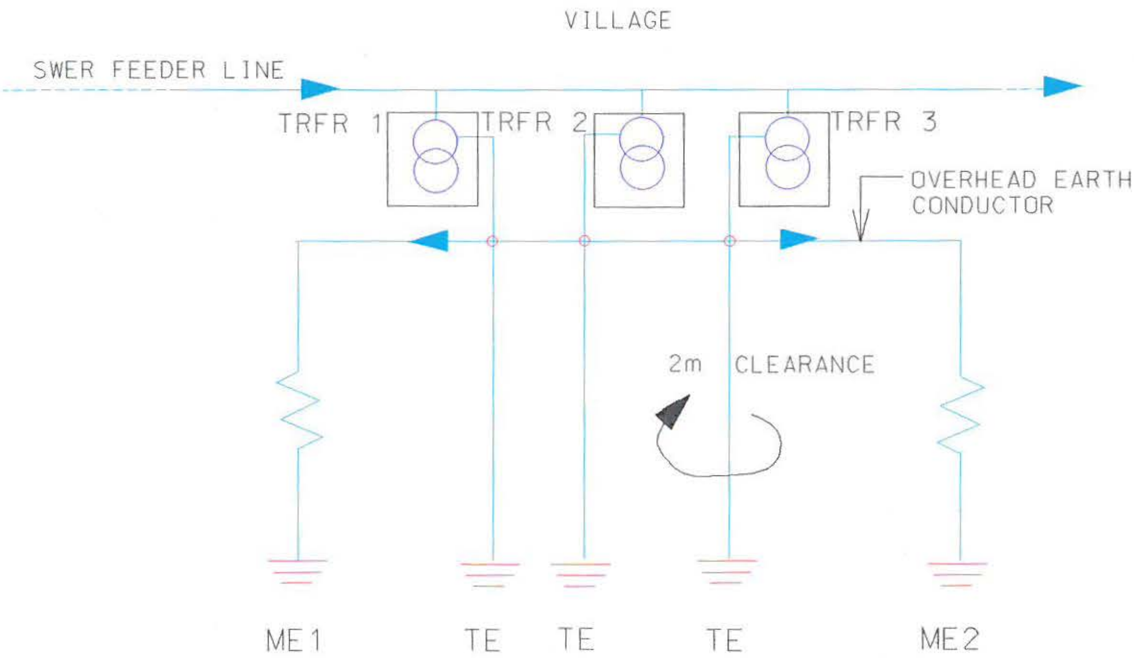


Fig. 5.10 Earthing via an Overhead Safety Conductor in a Village

⇒ The MV earthing bushings of the distribution transformers inside the village will be earthed via an overhead conductor connected to two main electrodes (ME1 and ME2) installed outside the village.

⇒ The earth electrodes must be designed to a maximum GPR of 35V. The designed earth electrodes in table 5.10 will be applicable to transformers with a total capacity of 200kVA.

⇒ The resistance of the two main electrodes (ME1 and ME2) should be in accordance with the values as indicated in table 5.11 when measured separately (Based on a capacity of 200kVA or 100kVA). This is to ensure that in the event of losing one of the earth electrodes due to damage or theft, the system will still be safe.

⇒ The two main electrodes (ME1 and ME2) have to be a minimum distance from any fence or steel structures as indicated in table 5.10.

⇒ According to Eskom's Labelling Standard, a warning label must be installed on the pole, indicating the following:

- the earthing lead is a continuous current-carrying conductor.
- the minimum radius from the pole wherein any fence or farming activities such as ploughing are not allowed.

⇒ The earthing leads down the poles must be PVC insulated and protected inside a 25mm dia. UV stable PVC pipe (Steel pipe not allowed).

⇒ Posts of farm gates in the area of the SWER line should be earthed in accordance with drawing D-FS-1 Rev.2, Appendix G. This is to prevent an electrical shock to a person opening the gate due to induced voltages and stray currents.

⇒ A clearance of 2m around the earth electrodes installed inside the village to any fence or steel structure as explained in paragraph 5.15.2, should be maintained.

⇒ The transformer pole earths (TE) installed inside the village is simply butt wrapped wire around the bottom of the pole (insulated above ground level). This is to avoid step-and-touch potential problems.

⇒ In villages where the risk of copper theft is high, special attention should be given to the installation of the earth electrodes (see paragraph 5.23).

⇒ The overhead earth wire inside the village must be installed underneath the MV SWER conductor. This will ensure a good contact between the MV conductor if broken and earth thereby blowing the fuse installed at the isolating transformer.

5.16.1. CRITICISM RELATED TO THE PROPOSED EARTHING PRACTICE FOR VILLAGES

The following points must be kept in mind when electrifying villages:

⇒ The main earth electrodes installed outside the villages to prevent step-and-touch potentials due to fences may only be a temporary solution because of the expansion of the village.

⇒ The possibility of copper theft (earth electrodes) are more likely and could result in injury due to the continuous load currents.

⇒ A broken overhead earth return conductor will not operate the protection and could result in fatal accidents.

The above difficulties must be evaluated on a pilot project before being accepted as a standard.

5.17 LV EARTHING AT THE DISTRIBUTION TRANSFORMER

Earthing on the LV side of the distribution transformer will be in accordance with the Eskom Distribution Standard [13]. The LV neutral of the distribution transformer shall be earthed in accordance with the TN-C-S earthing system as described in NRS 016.

This practice of earthing involves the following (see figure 5.11):

⇒ The supply is earthed at the source and the protective earth and neutral (PEN) conductor is combined.

⇒ The combined (PEN) conductor is earthed only at the transformer.

⇒ The PEN conductor is connected to the consumer's main earthing terminal via the service cable.

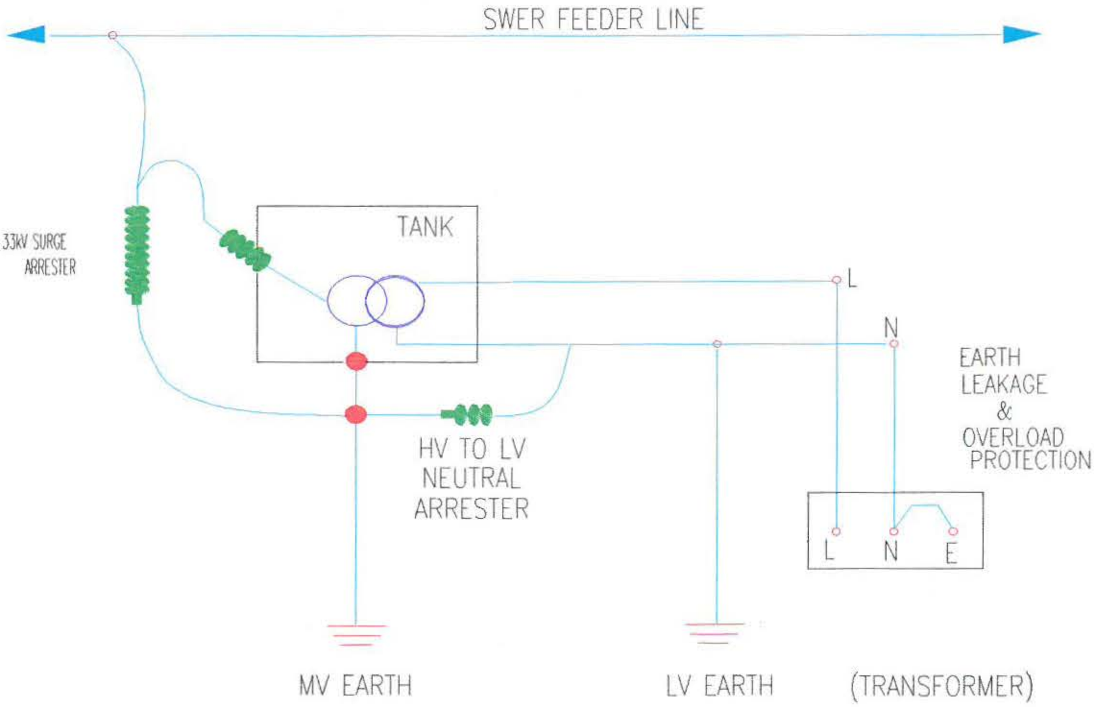


Fig. 5.11 Earthing Arrangement between MV and LV Earth Electrodes at the Distribution Transformer

5.17.1 LV EARTH ELECTRODE RESISTANCE

The overall resistance to earth of the LV electrode installed on the secondary side of the distribution transformer shall be such as to ensure that the protection at the isolating transformer will operate in the event of a breakdown between the MV and LV windings of the transformer. Based on the above-mentioned theory the maximum LV earth electrode resistance (R_{LV}) will be calculated on the following assumptions:

⇒ SWER voltage (V)	20 kV (phase to ground)
⇒ Load current (I_L)	10 A
⇒ Isolating transformer earth electrode resistance (R_I)	3.5 ohm
⇒ Distribution transformer MV earth electrode resistance (R_D)	43 ohm
⇒ Isolating transformer rating	200 kVA
⇒ Distribution transformer rating	16 kVA
⇒ Fuse rating installed at the isolating transformer	5 A (assume that the fuse will operate at twice the fuse current rating -10A).

The maximum earth electrode resistance (R total) is calculated as follows:
(The resistance of the conductor was not taken into consideration).

$$R\ total = (R_{LV} + R_I)$$

$$R_{LV} + R_I = V / I_L$$

$$R_{LV} = (20000 / 10) - 3.5$$
$$\approx 2000\ ohm$$

Applying a safety factor of 4 will ensure acceptable protection under:

⇒ Seasonal variations in soil resistivity.

⇒ Variations in the effectiveness of the MV electrode installed at the isolating transformer.

To conclude, the maximum resistance of the LV earth electrode installed at the distribution transformer will be as follows:

Table 5.17 LV Earth Electrode Resistance

PROTECTION AT THE SWER ISOLATION TRANSFORMER	4 TIMES THE PROTECTION CURRENT	LV EARTH RESISTANCE
5A trip coil auto recloser	* 40A (10A x 4)	500Ω
5k fuse	* 40A (10A x 4)	500Ω

* Assume that the recloser or fuse will operate at twice the trip-coil or fuse rating current.

NOTE: The LV earth electrode resistance is only applicable to a 5A k-type fuse which will allow a maximum current of approximately 10A.

5.17.2 LV EARTH ELECTRODE SELECTION

The earth electrode configuration to be installed must be in accordance with Eskom's Distribution Standard, tables 3 and 3a [13].

The electrical criterion used for the selection of an appropriate earth electrode is the measured soil resistivity value in ohm metre at a depth of 0.5m to 2m below ground level. This depth is important, as the soil close to the electrode has the greatest effect on its final resistance value.

5.18 SEPARATION OF MV AND LV EARTH ELECTRODES

The Eskom Standard regarding conventional lines on the above is that the MV and LV earth electrodes may be interconnected, provided that the earth electrode resistance of the combined system is less than one ohm [13, p.6]. If not, the minimum separation distance between MV and LV earth electrodes is to be 5m. In the case of SWER, the practice of combining the MV and LV earth electrodes **will not be allowed** due to a continuous current in the MV earth electrode. It is therefore essential that the MV and LV earth electrodes are separated. Studies conducted by using the CDEGS programme indicated that the existing separation distance of 5m will also be applicable to SWER networks. This practice will prevent high voltages under fault conditions from being transferred to the LV side [28].

The minimum separation distance of 5m may be achieved as follows:

⇒ Earth the LV neutral one span away from the distribution transformer.

⇒ Install PVC insulated earthing leads below ground level to preserve the 5m minimum separation distance between MV and LV earth electrodes on the same structure.

The requirement of the MV and LV earth electrodes to be separated puts the transformer under risk of impulse surges, as explained in paragraph 5.13.1. To avoid this danger and the transfer of high voltage gradients to the customer's installation, a maximum over voltage (MOV) surge arrester, rated 6kV (20kV SWER voltage) must be installed between the neutral on the LV side and the tank of the transformer as indicated in figure 5.11 [17].

To conclude, the existing SWER earthing practice at the SWER distribution transformer as explained in paragraph 5.13.1 will now be changed as follows:

The MV surge arresters, transformer tank and the earthing bushing on the primary side of the distribution transformer will be earthed via the same earth electrode with a maximum resistance of 43 ohm. The LV earth electrode installed will be separated from the MV earth electrode by a minimum separation distance of 5m and have a maximum resistance of 500 ohm.

The above analysis indicates that the earthing practice as described above will ensure a safe and cost-effective SWER installation.

5.19 MEASUREMENT OF THE RESISTANCE OF AN EARTH ELECTRODE

The calculated resistance of a given electrode system is based upon many approximations such as the assumption concerning the homogeneity of the soil, which is rarely homogeneous. It is thus necessary to measure the resistance of the earth electrode to true earth in order to ascertain that the following design objectives have been attained:

⇒ verify the adequacy of a new earthing system

⇒ detect changes in an existing earthing system

⇒ check on the accuracy of the design parameters and calculations

The best and most accurate technique for measuring the resistance of a relatively small earth electrode is the 61,8 % method as explained in Appendix F. This method is used on existing SWER lines as well as on conventional three-phase and single-phase networks. Another method used by Eskom is the Slope method. This method is suggested when measuring large earthing systems such as those of main power substations [13, p.26].

5.19.1 IMPORTANT FACTORS TO CONSIDER BEFORE MEASURING THE RESISTANCE OF AN ELECTRODE

The methods used by maintenance personnel and contractors when measuring earth electrode resistances were found not to be according to Eskom Standards. This appears to be due to a lack of training and / or experience.

Investigations during field trials on the Rooiwal SWER scheme, indicated that the following factors have an influence on the resistance readings of the earth electrode, and thus need to be taken into consideration when conducting measurements. The factors below must be read in collaboration with Appendix F.

⇒ The auxiliary probes (P2 and C2) are to be positioned far enough from the earth electrode under test. This is to prevent the equipotentials of the electrode under test from overlapping with the test probes, thereby influencing the resistance readings.

An additional guide to accurate resistance measurements is the relationship between the distance (X) to the current probe (C2), and the radials of the earth electrode under test. The minimum requirement is that the distance between the electrode under test and the current probe (C2) must be at least five times more than the radial length of the trench earth or the depth of the electrode, which ever is the greatest.

⇒ The minimum distance between the electrode under test and the auxiliary current probe (C2) must be 100m.

⇒ Watering of the potential and current probes (P2 and C2) to reduce the earth resistance may be necessary in areas where the soil resistivities are high and the current injected is measured to be less than 5mA.

The 61,8 % method was applied on the Rooiwal SWER line and found to be efficient as a good correlation between the calculated resistance values, and the field measurements were achieved.

The author therefore recommends that the 61,8 % method be used when measuring the resistance of SWER earth electrodes.

5.20 ELECTRODE ENHANCEMENT

In certain high earth resistivity areas, the use of chemicals such as magnesium sulphate, copper sulphate, calcium chloride and sodium chloride may lead to a significant decrease in local soil resistivity [30]. The selection of chemicals depends largely upon cost, availability and susceptibility to corrosion.

Mitronite was used to a great extent with huge costs involved on SWER schemes in the Northern Cape region. The standard practice was to use mitronite on all SWER electrodes installed in the Northern Cape region.

Mitronite was used on one of the distribution transformer earth electrodes installed on the Rooiwal SWER scheme. This electrode was installed in sandy soil with a top layer soil resistivity of 500 ohm metre (depth < 3,2m) and a bottom layer soil resistivity of 200 ohm metre. The resistance of this earth electrode installed was 55% less than that of another earth electrode installed in the same soil conditions, but 67% more expensive. This result corresponds with tests done by the Australians, who claim that a decrease of 50% can be obtained by extensive chemical treatment, but a reduction of 20% is more likely appropriate [6, p.9]. Earth electrodes treated with chemicals should be monitored over a period of a few years in order to determine the reliability and success thereof.

Different types of conductive concrete are now under investigation by TRI to determine the situations that necessitate the use of conductive concrete, the type of conductive concrete to be used and how the conductive concrete should be mixed and applied.

The author recommends that mitronite will only be used at isolating transformer earth electrode installations as a safety precaution to ensure a good contact between the electrode and earth, to enlarge the physical size of the electrode, to extract moist from the soil reducing the resistivity and to ascertain a durable earth electrode installation under seasonal variations.

Conductive concrete may be used at distribution transformer earth electrodes only when the costs involved are less than to move the complete transformer structure to a lower soil resistivity area.

5.21 EARTHING MATERIALS

To ensure a durable and cost-effective earth electrode installation, different comparisons were done between bare solid copper rod, flat copper strap and stranded copper based on costs, contact area to earth and the practical installation of the electrode. Materials installed on existing SWER lines are 50 x 3,15mm flat copper strap for deep-drilled earth electrodes and 10mm dia. solid CU rod for trench earth electrodes.

The author decided to investigate other materials such as 10mm dia. bare stranded copper, 16mm dia. bare stranded copper and 16mm dia. solid copper rod based on material costs and contact area (see Appendix E). Calculations indicate that savings of 87% were achieved by using 10mm dia. bare stranded copper instead of 10mm dia. bare solid copper for trench earth electrodes, and 60% by using 10mm dia. bare solid copper rod instead of 50x3,15mm flat copper strap at isolating transformer earth electrodes.

Based on the above, the author recommends the following earthing practice regarding materials to be used for SWER earth electrodes in the Northern Cape region:

5.21.1 ISOLATING TRANSFORMER MV EARTH ELECTRODE

The deep-drilled earth electrodes, as well as the radials interconnecting the drilled electrodes with the earthing leads down the pole, must consist of 10mm dia. bare solid copper rod (see figure 5.12). The earthing leads down the pole will be minimum 16mm² PVC insulated stranded copper wire, or as determined by the fault currents.

Fig. 5.12 Earthing Materials at Isolating Transformer

Underground connections will be done with at least two phosphor bronze earthing clamps per connection.

5.21.2 DISTRIBUTION TRANSFORMER EARTH ELECTRODES

Field experience gained on the Rooiwal SWER scheme shows that the following materials should be used for a crowsfoot, trench or deep-drilled earth electrode for both MV and LV earth electrodes:

⇒ **Crowsfoot Type Earth Electrode**

The spikes installed will be 1,5m x 16mm dia. copper clad earth spikes and the material used to interconnect the earth spikes will be 10mm dia. bare stranded copper wire (see figure 5.13). To extend the length of the earth spike to 3m, an earth spike coupler must be used. The stranded copper radials are to be connected to the earth spike by using two phosphor bronze earthing clamps.

The earthing lead down the pole must be a minimum 16mm² PVC insulated copper wire, or as determined by the fault currents.

Fig. 5.13 Materials at Distribution Transformer Crowsfoot Earth Electrode

⇒ **Trench Type Earth Electrode**

The trench earthing conductors will consist of 10mm dia. bare stranded copper wire. The earth lead down the pole will be16mm² PVC insulated copper wire and all connections underground will be made with double phosphor bronze earthing clamps.

Fig. 5.14 Materials at Distribution Transformer Trench Earth Electrode

⇒ **Deep-drilled Earth Electrodes**

Deep-drilled earth electrodes will consist of 10mm dia. bare solid copper rod. The earthing lead down the pole is connected to the solid copper rod by means of two phosphor bronze earthing clamps

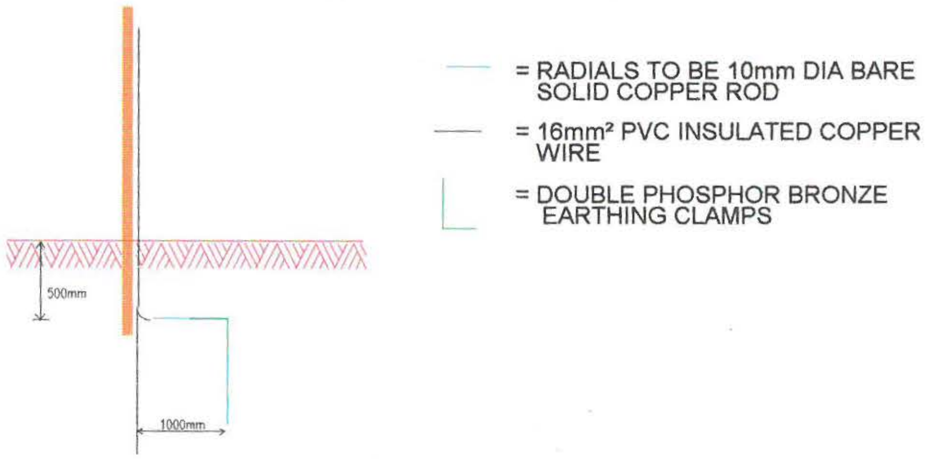


Fig. 5.15 Materials at Distribution Transformer Deep-drilled Electrode

5.22 PRECAUTIONARY MEASUREMENTS WHEN INSTALLING THE EARTH ELECTRODE

The two main problems experienced during the installation of the Rooiwal earth electrodes were that the stranded copper wires were damaged when connected to the earth spikes before driven into the soil with a hammer. Another problem experienced is that the earthing clamps become loose when connected to the earth spikes before driven into the soil.

The earth spikes must therefore be driven into the soil until ± 100mm of the spike is above the ground level inside the 500mm trench before the stranded copper wire is connected to the earth spike by means of phosphor bronze earthing clamps.

5.23 PRECAUTIONARY MEASUREMENTS AGAINST THEFT OF EARTH ELECTRODES

If there is a high risk of copper theft in the area where the SWER earth electrodes are to be installed, it is suggested that the trenches of the earth electrodes should be backfilled with ordinary concrete (± 300mm x 300mm). Investigations into theft of copper inside townships indicate that only the copper earthing leads down the poles are stolen, and it is therefore suggested to use concrete poles with a PVC conduit pipe inside the pole. The earthing lead must go through the PVC conduit inside the pole, thereby preventing the theft thereof.

5.24 MAINTENANCE OF EARTH ELECTRODE INSTALLATIONS

The periodic checking and resistance measurement of the earth electrodes are very important to ensure a safe and reliable SWER system.

Earth electrode resistance measurements should take place every six months (preferably during dry and winter seasons) during the first two years after installation in order to determine the effects of seasonal variations etc. on the resistance of the installed earth electrodes. These measurements must be recorded and filed for future reference, if required.

The following are to be observed and recorded during the inspection of the earth electrode installation:

⇒ Check for any visual damage to the earth electrode installation due to vandalism or farming activities.

⇒ Check for any damages to the insulation of the earthing leads down the pole due to veld fires.

⇒ Check if the area around the pole (± radius of 5m) is clean of grass to prevent damage to the insulation of the earthing leads due to veld fires. Herbicides used must be in accordance with Eskom's specifications.

If the recorded values of the earth electrode installations indicate no drastic variations during the two-year period, and the resistances of the earth electrodes are within the prescribed limits, the installations may be checked once a year.

The involvement of the farmers or communities living in the area of the SWER scheme could be of great assistance to the maintanance team when hazardous conditions such as damaged conductors, earths, surge arresters, etc. are reported.

Their involvement could assist in the reduction of maintenance costs and ensure a good and safe quality of supply.

CHAPTER SIX

DISCUSSION AND CONCLUSIONS

6.1 SIMILAR RESEARCH

As far as can be determined, no similar research, either regarding background or scope has been published or referred to in South Africa. The cost saving and safety aspects due to the increase of the GPR has not been investigated previously, nor has the basic design of SWER earth electrodes been examined in such detail.

6.2 DIRECT RESULTS

When one considers all the analyses and recommendations made during this study, a couple of important aspects are found throughout the thesis, namely:

⇒ No previous analyses were made on increasing the ground potential rise (GPR) limit of 20V and the effects thereof on step, touch and transferred potentials.

⇒ The increase of the GPR limit to 35V resulted in tremendous cost savings without sacrificing safety. This is evident from the savings achieved on the Rooiwal SWER scheme.

Savings of 87 % (R167 352,00) were achieved by the installation of the earth electrodes forming part of this thesis. This excludes the costs of conductive concrete (Mitronite @ R30 000,00) that was used as a standard on all SWER earth electrode installations in the Northern Cape region.

⇒ Never in any of the previous designs of SWER earth electrodes were proper analyses carried out on the soil resistivity results, especially regarding the effects of the underground water table, which played a tremendous role in reducing costs in high top layer soil resistivity areas.

⇒ The influence of the terrain, e.g. rock or sand, determines the type and configuration of the earth electrode to be installed. In the past this was not taken into consideration and it resulted in practical problems with regard to the installation of overdesigned earth electrodes.

⇒ This study also compiled information on SWER schemes that was not easy accessible, into one document, which makes it easy for future use.

⇒ The relationship and correlation between the theoretical design and practical installations were tested on the Rooiwal SWER scheme. Practical problems experienced were investigated, and the necessary alterations were done on the recommended earth electrode designs.

⇒ Standard materials were used on all the earth electrodes designed. This is in line with Eskom's standardisation process.

⇒ A point worth mentioning is the connection of the trench earth electrodes to the earth spikes (crowsfoot earth electrodes) or one another. Brazing and gas welding are not recommended but rather the use of phosphor bronze clamps. This was a direct result of field tests carried out on the Rooiwal SWER scheme.

6.3 INDIRECT RESULTS

The principles of SWER are not widely known, and therefore overdesigning due to a conservative approach especially w.r.t. earthing resulted in expensive SWER schemes. This problem is now addressed as part of this thesis. All the earth electrodes designed in this thesis were done by using a specialised software package called CDEGS. The author is of the opinion that without the CDEGS package the earth electrodes designed would not have been possible.

6.4. FURTHER RESEARCH

The protection of SWER schemes remain a concern to the Field Services Managers, as no earth fault protection exists. Further studies should be carried out on the detection of a grounded conductor, thereby limiting overhead conductor failures, and improving safety.

6.5 CONCLUSION

For the first time in history of Eskom, SWER earth electrodes are designed by taking the essential factors as described in Chapter 5 into consideration. A scientific approach was taken to the design of feasible earth electrodes for application in the Northern Cape region. The theoretically designed electrodes were installed and measurements were taken to verify the designs. These sets of electrodes make it possible for standardisation and easy reference to determine the type of electrode required.

It will now also be possible to compare the SWER technology with other technologies such as conventional single-phase and three-phase systems, thereby ensuring the most cost-effective installation. This will help Eskom to achieve their commitment towards the Reconstruction and Development Programme of connecting 1,75 million households by the year 1999. (300 000 connections per year).

APPENDIX A

CALCULATION OF GROUND POTENTIAL RISE, STEP, TOUCH AND TRANSFERRED POTENTIALS

1. GROUND POTENTIAL RISE

Fig. A1 presents a means of estimating, within an order of magnitude, the earth electrode resistance and therefore the GPR of an earth electrode buried in uniform soil. The formulae presented are exact for hemispherical electrodes [3, p. 337].

$$R_e = \frac{\wp}{2\pi r_e}$$

Where : $\wp$ = resistivity of soil (ohm metre)

r_e = radius of the hemisphere (in metre)

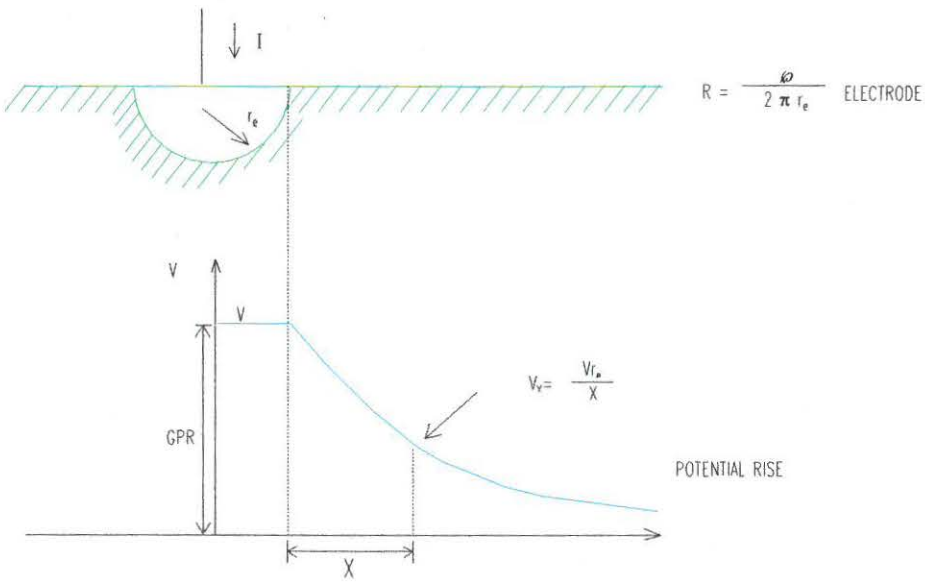


Fig. A1 Resistance and Potential Rise of an Equivalent Hemisphere [3, p. 335]

When a current (I) is injected into the ground, the GPR of the electrode will be:

$$V = \frac{\wp I}{2\pi r_e} \qquad [3, p.336]$$

and the GPR at a distance Vx around the electrode is

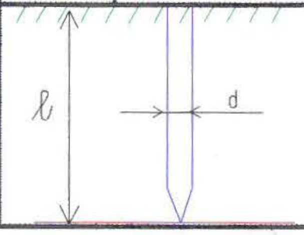
$$V_x = \frac{\wp I}{2\pi x}$$

I = Injected current

x = Distance from the axis of hemisphere ($x > r_e$)

Table A1 can be used to calculate the earth resistance R_e and the radius r_e of an equivalent hemisphere for driven rods [3, p.337].

Table A1 Formulae for the Earth Resistance R_e and radius r_e of an Equivalent Hemisphere [3, p.337]

Electrode		Earth resistance Re	Radius of equivalent hemisphere r_e
Type	Shape and Size		
Driven Rod		$\frac{\wp}{2\pi \ell}\left[\ln \frac{8\ell}{d} - 1\right]$	$\frac{\ell}{\ln \frac{8\ell}{d} - 1}$

For clarification purposes an explanation of step, touch and transferred potentials is given in paragraph 2, 3 and 4.

2. STEP POTENTIALS

A step potential is the difference in surface potential experienced by a person bridging a distance of 1m with his feet without coming in contact with any other earthed object. Step voltages are usually not a problem if touch voltages are within safe limits. The human being can also tolerate higher step voltages than touch voltages due to the higher surface resistance contact.

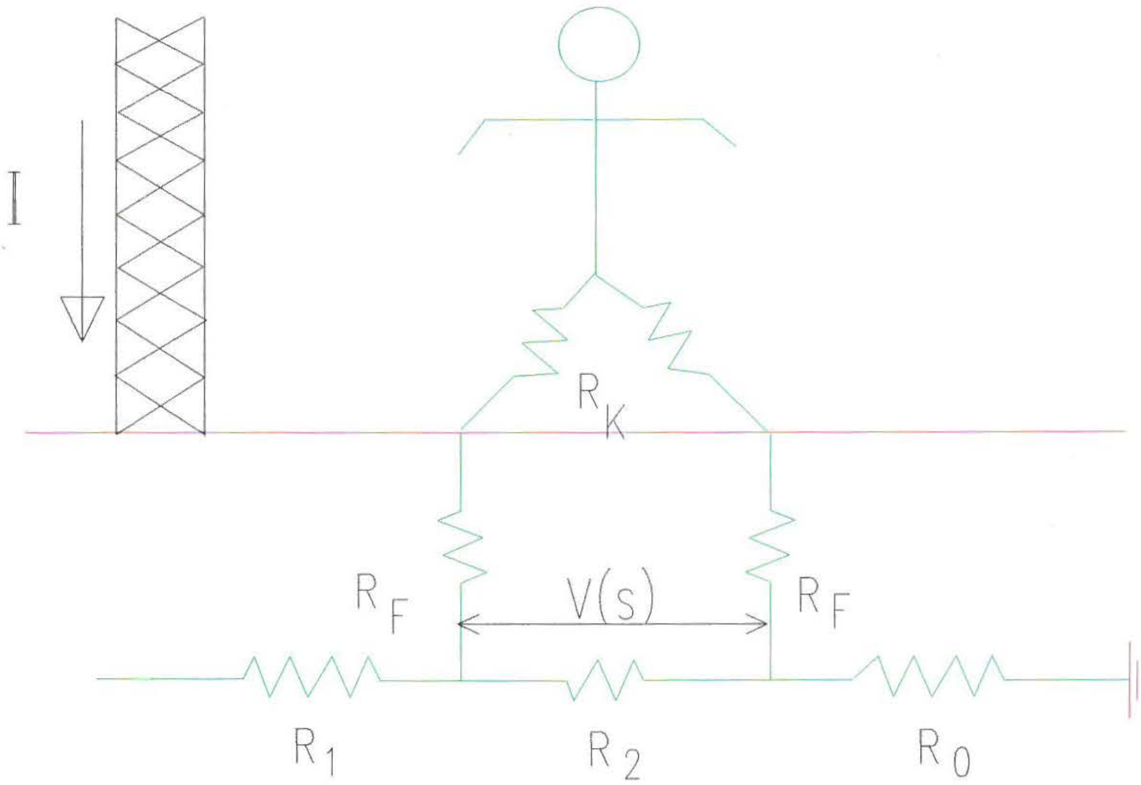


Fig. A2 Step Potentials

The limit of a safe Step Potential can be determined by [45, p.6]:

$$V(s) = Ik\,(R_k + 2R_F)$$

$$= \frac{0{,}116}{\sqrt{t}}\,(1\,000 + 6\rho s)$$

$$= \frac{116 + 0{,}7\,\rho s}{\sqrt{t}}$$

Ik = Body current limit = $\frac{0{,}116}{\sqrt{t}}$ for 0,03 sec < t < 3 sec

R_k = Body resistance ≈ 1 000 ohms

R_F = Resistance under feet ≈ 3 $\wp s$

$\wp s$ = Surface layer resistivity in ohm metre

3. TOUCH POTENTIALS

A touch potential is the potential difference between the ground potential rise and the surface potential at the point where a person is standing, while at the same time touching an earthed structure.

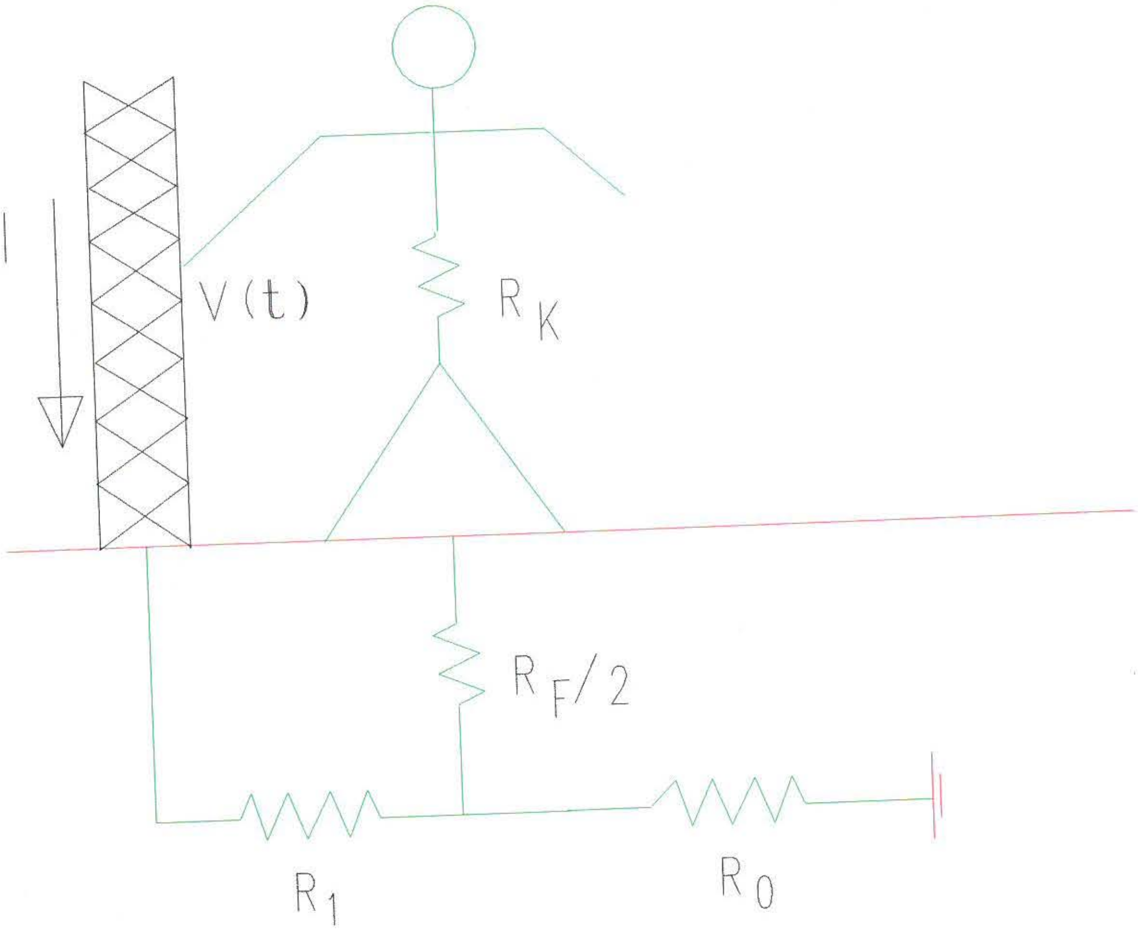


Fig. A3 Touch Potentials

Limit of safe Touch Potential V(t) $= I_k (R_k + 0{,}5R_F)$ [45, p.7]

$$= \frac{0{,}116}{\sqrt{t}} (1000 + 1{,}5 \wp s)$$

$$= \frac{116 + 0{,}17 \wp s}{\sqrt{t}}$$

4. TRANSFERRED POTENTIALS

A transferred potential is a case of the touch voltage at a remote area, where voltage may be approaching the full ground potential rise of an earth electrode.

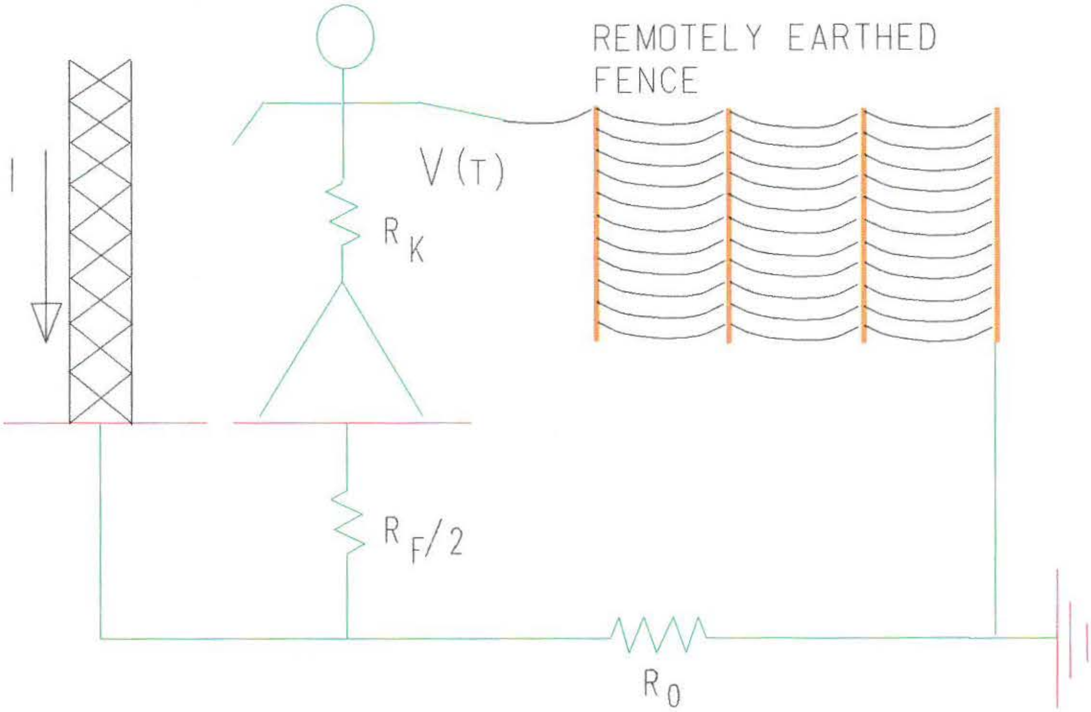


Fig. A4 Transferred Potentials

Transfer potential limit $V_{(T)}$ = $\dfrac{I_k (R_k + 0.5 R_f)}{\dfrac{116 + 0.17 \rho_s}{\sqrt{t}}}$ [45, p.8]

APPENDIX B

TEST RESULTS ON ROOIPOORT SWER LINE

The concern regarding dangerous transferred potentials to a remote earth when increasing the GPR was investigated by doing measurements on an existing SWER line (Rooipoort) in the Northern Cape region.

Tests completed include the following:

⇒ Measurement of load current.

⇒ Measurement of GPR under normal load conditions.

⇒ Calculations of earth electrode resistance at isolating transformer.

⇒ Measurements of transferred potentials to a fence regularly earthed via metal droppers.

⇒ Measurement of transferred potentials to a fence only earthed at a remote point.

1. MEASUREMENT OF LOAD CURRENT

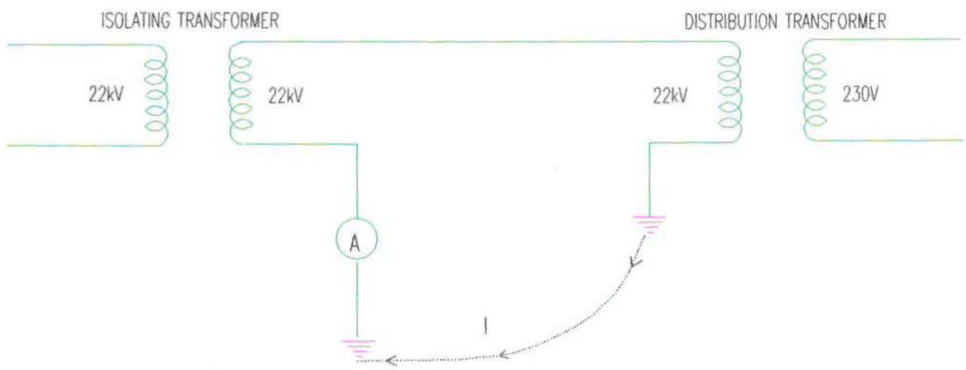


Fig.B1 Load Current Measurement

The return currents to the isolating transformer earth electrode were measured with a clip-on CT (current transformer). The magnitude of the load current (I) measured was: I = 1.2A.

2. MEASUREMENT OF GPR AT THE EARTH ELECTRODE

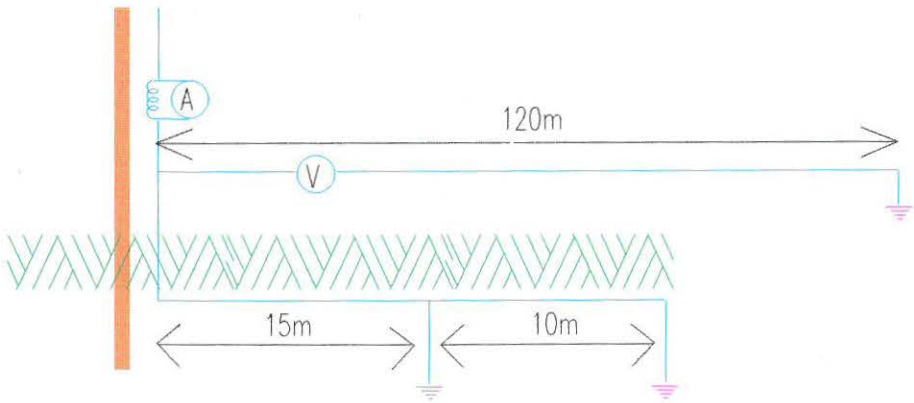


Fig. B2 Measurement of Ground Potential Rise

The GPR measured was as follows:

I = 1.2A
V(GPR) = 4.88V

3. EARTH ELECTRODE RESISTANCE

The earth electrode resistance was calculated as follows:

$$R \text{ electrode} = \frac{V(GPR)}{I} = \frac{4.88V}{1.2A} = 4.07\Omega$$

Although the GPR is only 4.88V, dangerous step, touch and transferred potentials will occur during full load currents.

$$\begin{aligned} V\,(GPR) &= I \times R \text{ electrode} \\ &= 10 \times 4.07 \\ &= 40.7V \end{aligned}$$

This earth electrode resistance needs to be improved to prevent electrical shock during full load conditions. The maximum earth electrode resistance allowed is 3.5 ohm.

4. TRANSFERRED POTENTIALS TO A FENCE REGULARLY EARTHED VIA METAL DROPPERS

The earth electrodes of the isolating transformer were installed ± 50m to the nearest fence. Touch potentials measured on the fence were as follows:

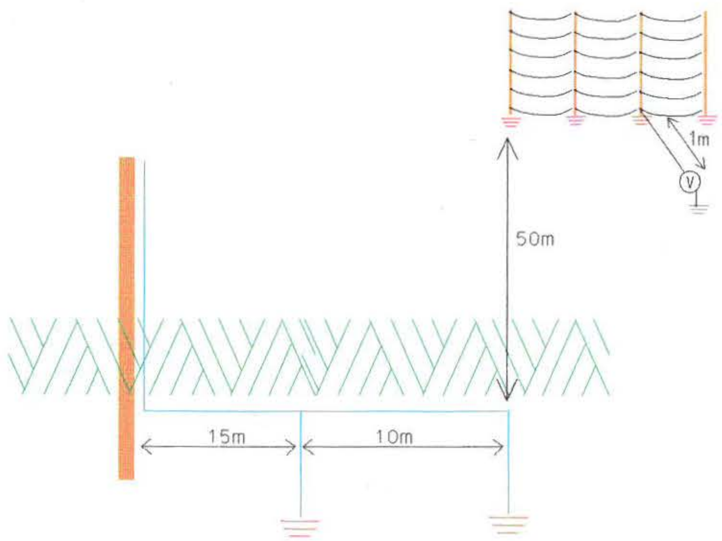


Fig. B3 Step Potential Measurement

$V = 530mV$

From the above it is clear that transferred potentials to a fence that is regularly earthed and installed some distance from the earth electrode will not cause any problems.

5. TRANSFERRED POTENTIALS TO A FENCE THAT IS ONLY EARTHED AT A REMOTE POINT

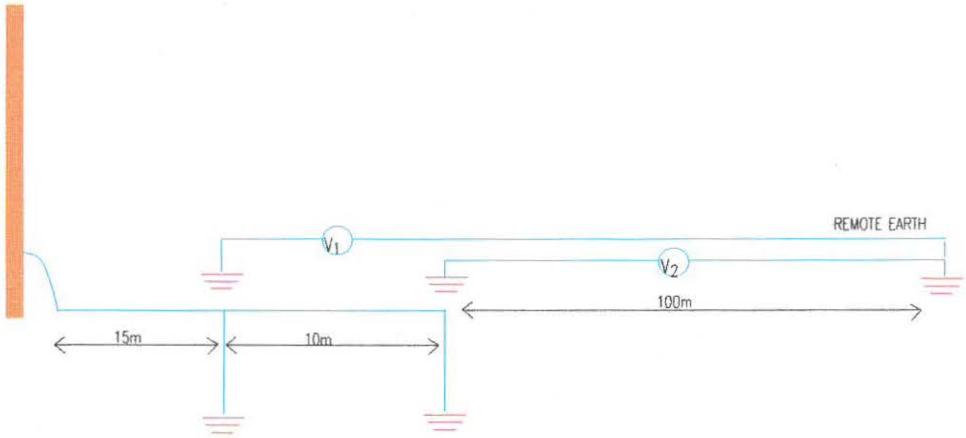


Fig. B4 Transferred Potential Measurement

$V_1 = 3.74V$

$V_2 = 3.64V$

The results indicated that the transferred potentials measured to a remote earth electrode ($V_1 = 3.74V$, $V_2 = 3.64V$) are almost as high as the GPR ($V_{GPR} = 4.07V$). It is thus very important to limit the GPR to ensure safe step, touch and transferred potentials.

APPENDIX C

WENNER METHOD OF MEASURING SOIL RESISTIVITY

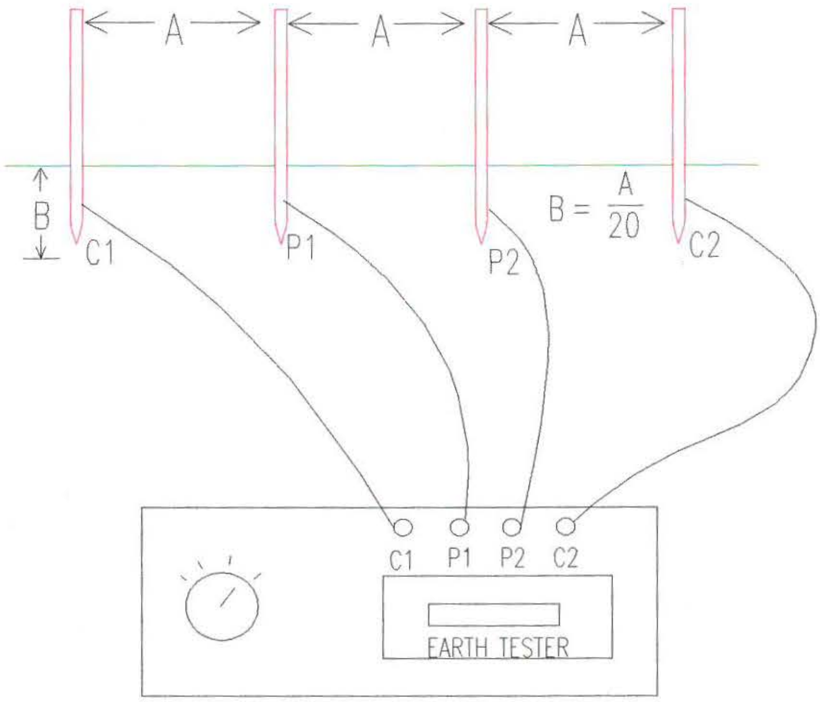


Fig. C1 Wenner Method of Measuring Soil Resistivity

Four probes are driven into the earth along a straight line, at equal distances (A) apart, driven to a depth (B). The voltage between the two inner (potential) probes is then measured and divided by the current between the two outer current probes to give a value of mutual resistance (R). The resistivity is then:

$$\wp = \frac{4 \pi A R}{1 + \frac{2A}{\sqrt{A^2 + 4B^2}} - \frac{A}{\sqrt{A^2 + B^2}}}$$

Where $\wp$ = resistivity of soil in ohm metre

R = resistance in ohms resulting from dividing the voltage between the potential probes by the current flowing between the current probes.

A = distance between adjacent probes in metre

B = depth of the probes in metre

If (B) is small compared to (A), as is the case of probes penetrating the ground for a short distance only, the above equation can be reduced to:

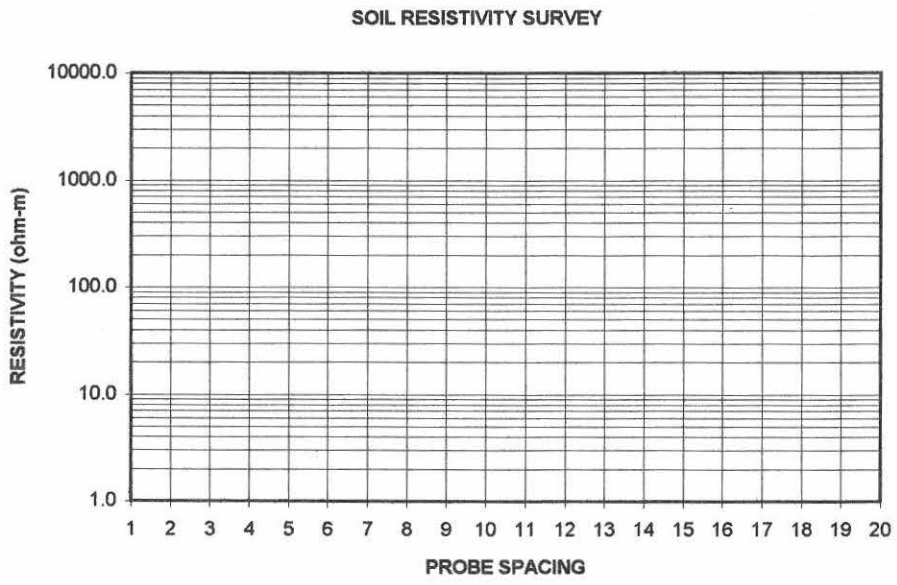
$$\wp = 2 \pi A R$$

SOIL RESISTIVITY SURVEY PLACE:____________________

SURVEY DATE: __________ RESPONSIBLE PERSON: ______________

TABLE C1 SOIL RESISTIVITY SURVEY FORM

PROBE SPACING $A\ (m)$	DEPTH $D = 0.8*A(m)$	TESTER READING (ohm)	GEOMETRIC FACTOR (K) $K = 2*\Pi*A$	RESISTIVITY (ohm-m)
1	0.8		6.28	0.0
2	1.6		12.57	0.0
3	2.4		18.85	0.0
4	3.2		25.13	0.0
5	4		31.42	0.0
6	4.8		37.70	0.0
7	5.6		43.98	0.0
8	6.4		50.27	0.0
9	7.2		56.55	0.0
10	8		62.83	0.0
11	8.8		69.12	0.0
12	9.6		75.40	0.0
13	10.4		81.68	0.0
14	11.2		87.96	0.0
15	12		94.25	0.0
16	12.8		100.53	
17	13.6		106.81	
18	14.4		113.10	
19	15.2		119.38	
20	16		125.66	



SOIL TYPE:____________________

WATER TABLE:__________________

RAINFALL STATISTICS:______________

APPENDIX D

VOLTAGE PROFILES AROUND AN ISOLATING TRANSFORMER EARTH ELECTRODE

An example of the potential profiles and the magnitudes of the step-and-touch potentials around an earth electrode installed in uniform soil of 500 ohm metre is indicated below. The load current was taken as 10A with a maximum earth electrode resistance of 3,5 ohm and a GPR of 35 V.

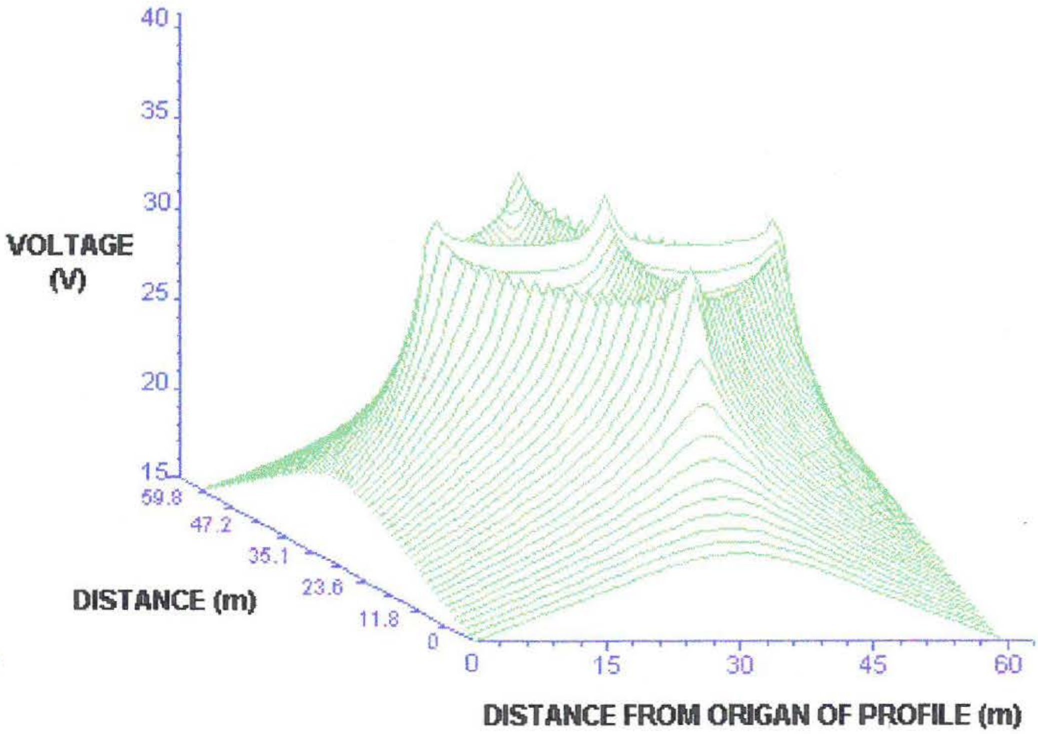


Fig. D1 3-D plot of voltages around an Isolating Transformer earth electrode

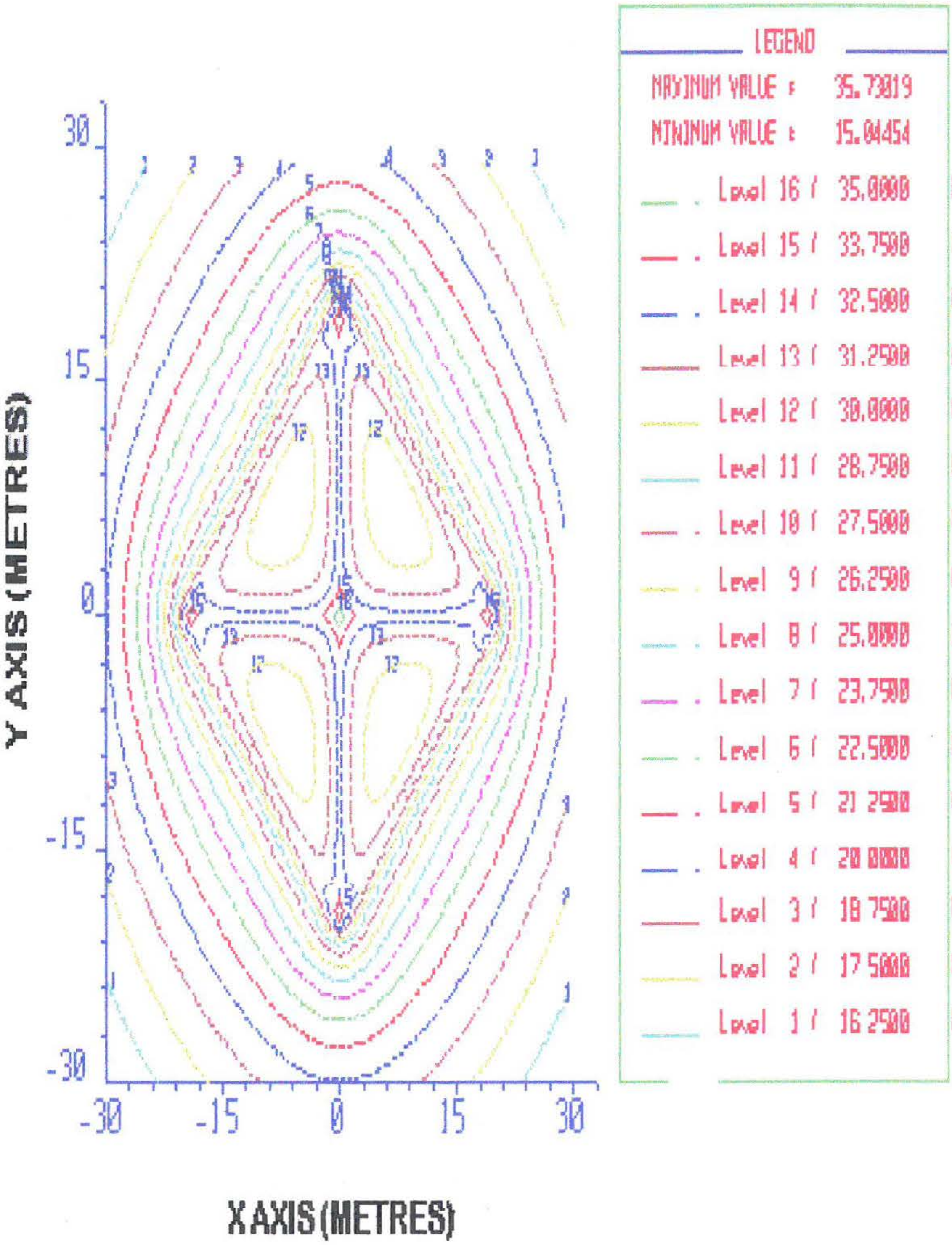


Fig. D2 Potential Profile around an Isolating Transformer earth electrode

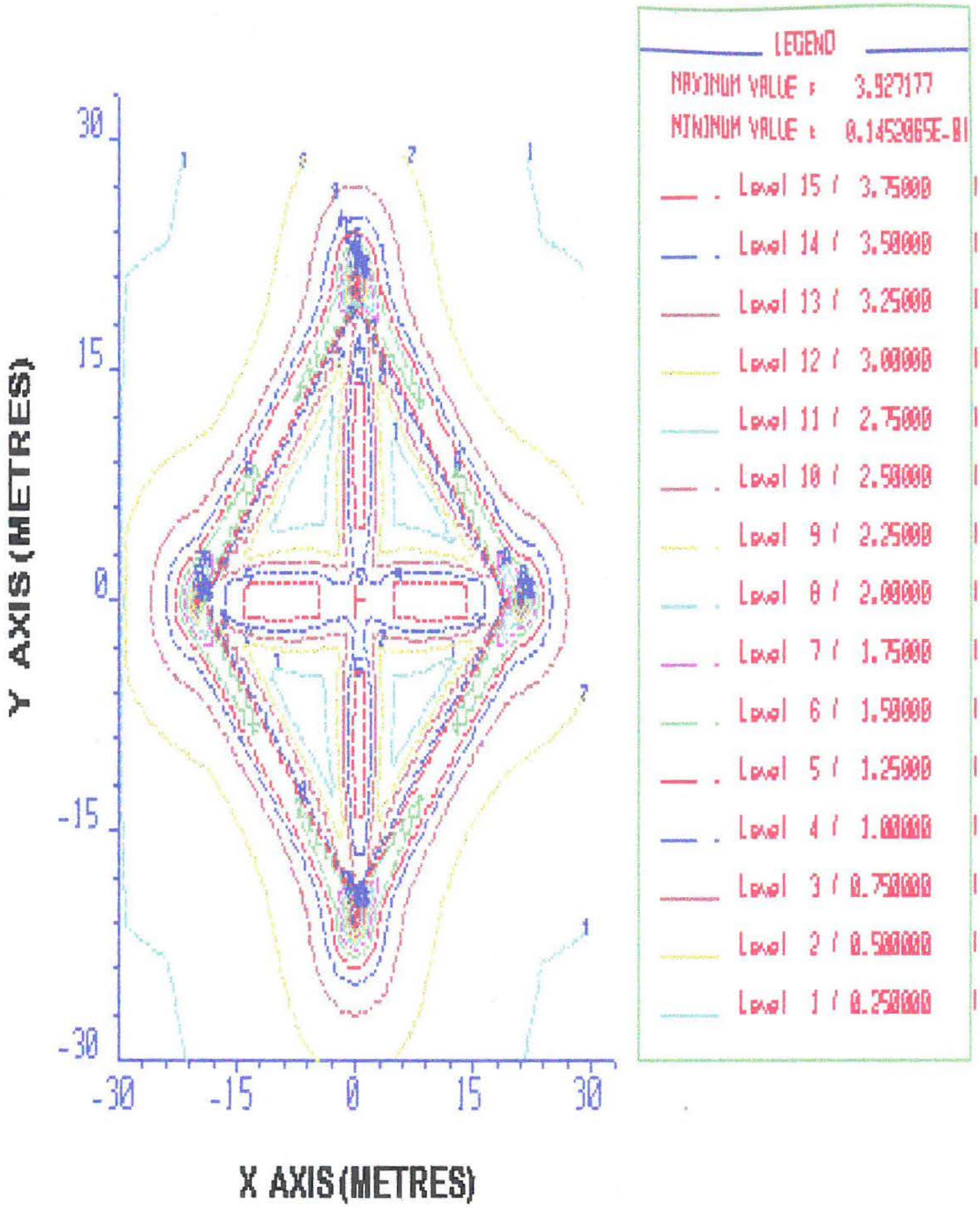


Fig. D3 Step Potential Magnitudes around an Isolating Transformer earth electrode

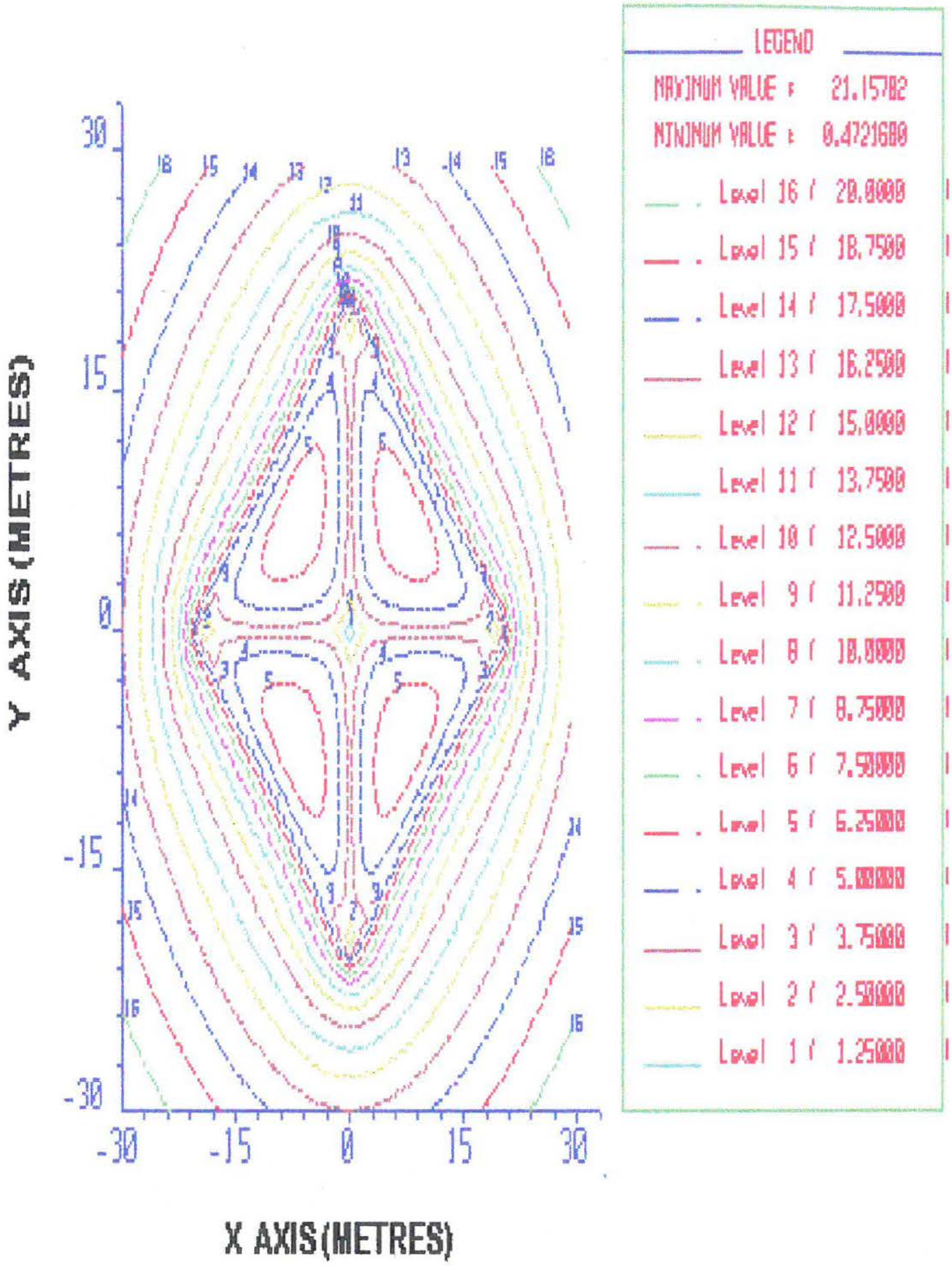


Fig. D4 Touch Potential Magnitudes around an Isolating Transformer earth electrode

APPENDIX E

EARTHING MATERIALS INVESTIGATED

Table E1 Earthing Material Costs

MATERIAL	COST/METRE
10mm dia. solid Cu rod	R11,20
10mm dia. stranded Cu	R1,39
16mm dia. solid Cu rod	R28,64
16mm dia. stranded Cu	R2,24
50 x 3,15 flat Cu strap	R28,41

The 10 mm dia. bare stranded copper can be used for the same earth contact area of the 10mm dia. solid copper rod currently in use for earth trenching, and it proved to be 87% less expensive.

Another cost comparison was done on a deep-drilled earth electrode, to a depth of 80m, in uniform soil with a resistivity of 1 200 ohm metre, and indicated the following:

The resistance reading of the 10mm dia. solid copper rod was 23,98 ohm compared to the 21,066 ohm of the 50 x 3,15mm flat copper strap. Material costs were R896,00 (R11,20 x 80m) for the 10mm dia. solid copper rod and R2 272,80 (R28,41 x 80m) for the 50 x 3,15mm flat copper strap. (60 % more expensive for a resistance difference of only 12 %). It is thus clear that the use of flat copper strap is not worth the costs involved compared with the 10mm dia. bare solid copper rod.

APPENDIX F

EARTH ELECTRODE RESISTANCE MEASUREMENT (61,8% METHOD)

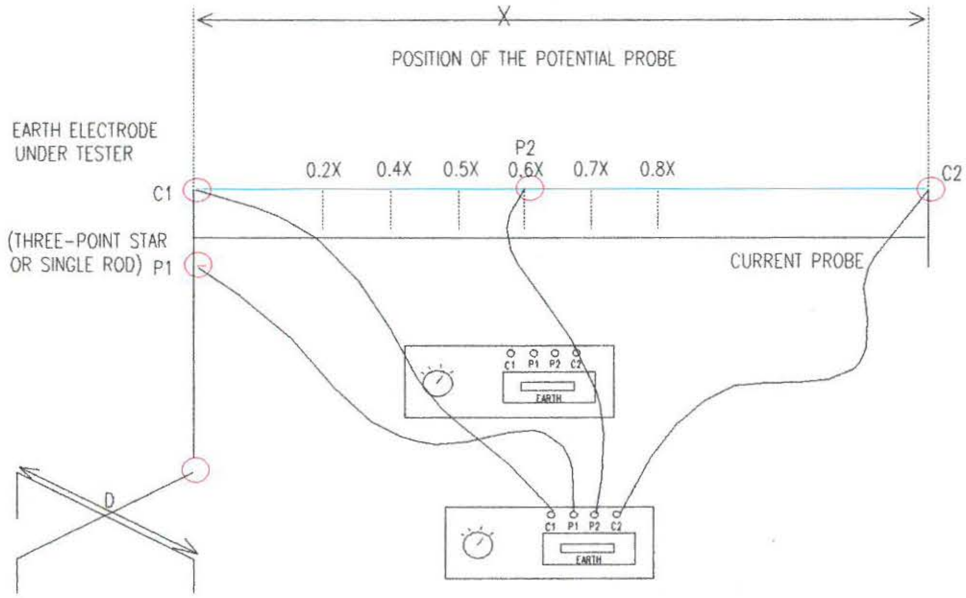


Fig. F1 Earth Electrode Resistance measurement (61,8% method)

The 61,8% method for measuring the resistance of a SWER earth electrode is described below [13, p.25].

⇒ Identify the earth electrode to be tested. Establish the physical layout of the earthing system and type of electrodes installed, for example in figure F1 the earth electrode is a combination of horizontal (trench) electrodes and vertical rods.

⇒ Disconnect the earth electrode from the earthed equipment, preferably at the point where the wire from the equipment connects to the earth electrode.

⇒ Identify the position of the current probe C2. Measurement should be taken away from the line of any known trench earth, metallic pipe or underground cables. **The distance between the electrode under test and the current probe (C2) should**

be five times the length of the longest earth rod or longest horizontal radial length of the earthing system, but not less than 50m. For standardisation purposes it is proposed that a distance of 100m be used.

⇒ Set the potential probe (P2) in line with the tested electrode at a distance equal to 0,618 of the distance to the current probe (x). Water the area around the current probe (C2) to reduce its resistance, thus reducing its influence on the measurement.

⇒ Connect the earth tester terminals (C1) and (P1) to the tested electrode, terminal (P2) to the potential probes (P2) and the terminal (C2) to the current probe (C2). Operate the earth tester and obtain the resistance reading.

⇒ Repeat the measurements for potential electrode set-up at the distances shown in the illustration, i.e. 0.2, 0.4, 0.5, 0.6, 0.7 and 0.8 of the distance to the current probe (C2). An exact measurement can be obtained at a distance of 61.8% of x (see figure F1).

⇒ The values obtained by measurement at the six positions (R_1 to R_6) should be recorded in table F1.

⇒ The resistance of the electrode under test is equal to the value obtained from the measurement and corresponding to the distance of 61,8% of x (See figure F1).

Table F1 Earth electrode resistance measurement results

Definition	Position	Distance m	Resistance Measured
X	Probe C2		
R_1	Probe P2 at 0,2x		
R_2	Probe P2 at 0,4x		
R_3	Probe P2 at 0,5x		
R_4	Probe P2 at 0,6x		
R_5	Probe P2 at 0,618x		
R_6	Probe P2 at 0,8x		

APPENDIX G

EARTHING OF GATES

The earthing practice with reference to farm gates in the vicinity of SWER earth electrodes is indicated below:

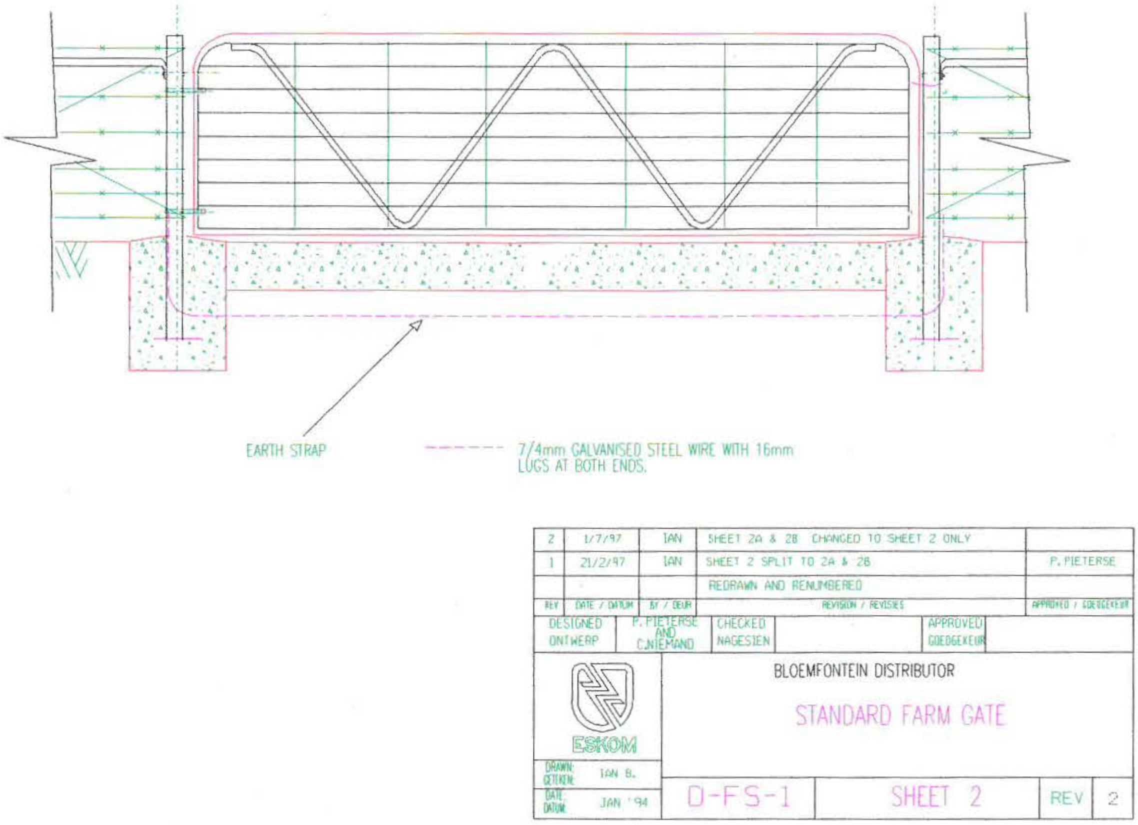


Fig. G1 Earthing of Farm Gates

REFERENCES

1. An Insulated Wire Distribution System (Shield Wire Scheme). Johannesburg: Eskom Megawatt Park.

2. Britten, A.C. Single-wire Earth Return Systems in Eskom, Draft Version 1. Johannesburg: Eskom Technology Research and Investigation Group, July 1996.

3. C.C.I.T.T. Chapter 5, Calculation of Conductive Coupling, Vol. 11.

4. Cass, J. Paper presented on SWER Earthing Methods. Australian Visit: Rockhampton, 1997.

5. Circuit Breaker Industries LDT. Circuit Breaker Application and Selection. Johannesburg.

6. Code of Practice, Protective Earthing. New South Wales, June 1975.

7. Code of Practice for Mitigation of Hazardous Voltages Induced into Telecommunication Lines, Issue 2. 1978.

8. Cohen, V. Application Guide for the Protection of LV Distribution Systems. Circuit Breaker Industries. Johannesburg, 1997.

9. Coulter, B. Low Cost Distribution for Rural Electrification in Australia Single-wire Return (SWER) Systems. Paper presented at the World Bank Electric Power Design Workshop, Washington,DC. Australia: Victoria, May 1993.

10. Dowsett, A.D. Single-wire Transmission. Australia: Queensland, 29 April 1954.

11. Drew, N.P. Single-wire Earth Return Distribution Systems - Economical Rural Electrification. Distribution Engineering Department. State Electricity Commission of Victoria. Australia: Brisbane, October 1988.

12. Effects of Current on Human Beings and Livestock. IEC 479 - 1, Third Edition. 1994-09.

13. Eskom Distribution Standard, Part 2, Earthing. Johannesburg: Eskom Distribution Technology, 1994.

14. Eskom Electrification Standard, Part 8A. Johannesburg: Eskom Distribution Technology, 1992.

15. Eskom Distribution Standard, Part 4, Meduim Voltage Reticulation. Johannesburg: Eskom Distribution Technology, 1997.

16. Eskom Transmission Engineering. Single-wire Earth Return. Johannesburg: Eskom, 1990.

17. Geldenhuys, H. J. Paper presented on Step-and-Touch Potentials around a SWER Electrode, and SWER Earthing in Villages. Bloemfontein: Eskom , May 1997.

18. Geldenhuys, H.J. The Role of Earthing, Chapter 5. Pretoria: CSIR, 1992.

19. Harvey, J.L.W. Single-wire Earth Return High Voltage Distribution for Victorian Rural Areas. Electrical & Mechanical Engineering Transactions. Australia, May 1959.

20. High Voltage Earth Return Distribution for Rural Areas, Fourth Edition. The Electricity Authority of New South Wales. Australia, June 1978.

21. High Voltage Earth Return Distribution for Rural Areas, Third Edition. The Electricity Authority of New South Wales. Australia, April 1968.

22. Hoffmann, B.B. Rural Industry Technology in Developed and Developing Countries, Single-wire Earth Return Development in Queensland. The Electricity Authority of Capriconia. Australia: Rockhampton, May 1988.

23. IEEE. Guide for Safety in AC Substation Grounding. Catalog Number 86-081063. March 1985.

24. Le Roux, J.L. Criteria for the Selection of Power Cables. Pretoria: Eskom Northern Division, May 1996.

25. Leyland, B. W. A Low Cost Rural Distribution System Using Single-wire Earth Return. New Zealand: Auckland, 1987.

26. Leyland, B.W. Earth Return Applied to High Voltage Systems. New Zealand: Auckland, 8 February 1965.

27. Macintosh , W.A. The Limits of the Single-wire Earth Return System of High Voltge Distribution, as Affected by Telecommunication Co-ordination Problems. Electrical Engineering Transactions. Australia, March 1966.

28. Moore, R.J.C. Separation between Distribution Transformer High Voltage and Low Voltage Earth Electrodes.Technical no. 123/2/161 Johannesburg: Eskom Technology Research and Investigation Group, March 1982.

29. Moore, R.J.C. The Seasonal Variation of Earth Mat Resistances. Report no.123/2/98.1. Johannesburg: Eskom Technology Research and Investigation Group, December 1977.

30. Moore, R.J.C. The use of Electrically Conductive Concrete as an Earthing Medium. Technical note 123/3/69. Johannesburg: Eskom Technology Research and Investigation Group, January 1981.

31. National Electricity Regulator. Lighting up South Africa. Progress Report on Electrification. 1995.

32. Paper Received from H. J. Geldenhuys on how to determine the temperature rise of the soil at the surface of an earth electrode. Johannesburg: Eskom Distribution Technology.

33. Parkash, O.M. Reduction of Power Losses in Transmission and Distribution for Rural Electrification by Use of Single-wire Earth Return System. Institute of Armament Technology. Poona, June 1984.

34. Patni, P.K. Design of Single-phase High Voltage Line Using Earth as a Return Conductor. Journal of Mines, Metals & Fuels. Madhya, February 1979.

35. Power System Grounding, Electromagnetic Fields & Interference Analyses, Vol.1. A Short Intensive Engineering Course Designed & Presented by SES. Johannesburg, November 1994.

36. Protection against Electric Shock, Common Aspects for Installation and Equipment. IEC-1140 1992-06.

37. Research Directorate of Karnataka Electricity Board. Single-wire Earth Return System. Technical Report no. 11, Kasturba Gandhi Marg, New Delhi - 110001. New Delhi: Bangalore, June 1977.

38. Robertson, E. Rural Electrification by Means of High Voltage Earth Return Power Lines. Electrical Engineering Transactions Institution of Engineers. Australia: New South Wales, March 1965.

39. SABS 0198 The Selection, Handling and Installation of Electric Power Cables of Rating not exceeding 33kV, Part V. Determination of Thermal and Electric Resistivity of Soil. Published by The Council of the South African Bureau of Standards. South Africa, 1988.

40. SABS 0199 The Design and Installation of an Earth Electrode. Published by The Council of the South African Bureau of Standards. South Africa, 1985.

41. Scorer, J.S. Electrification of Properties in Remote Areas. Murrumbidgee County Council Report. Australia: New South Wales.

42. Sikder, S.R. & Ganguly, B. Single-phase Ground Return H.V. System for Irrigation Schemes. Vol. 51. West Bengal: Calcutta, October 1970.

43. Smith, H. Earthing. Paper presented at the University of Pretoria. Johannesburg: Technology Consulting Services, 1995.

44. Taylor, J. Service Experience with Single-wire Earth Return Distribution Systems in Central Queensland. Presented at the 7th Annual CEPSI Conference. Australia: Brisbane, October 1988.

45. Van Der Merwe, W.C. A Guide for the Design of a Substation Earthing System. Johannesburg: Eskom Megawatt Park, August 1995.

46. Whyte, G.A. The Use of Galvanized Mild Steel as a Replacement for Copper Earth Tails in Substation Earthing Applications. Johannesburg: Eskom Distribution Technology, October 1992.