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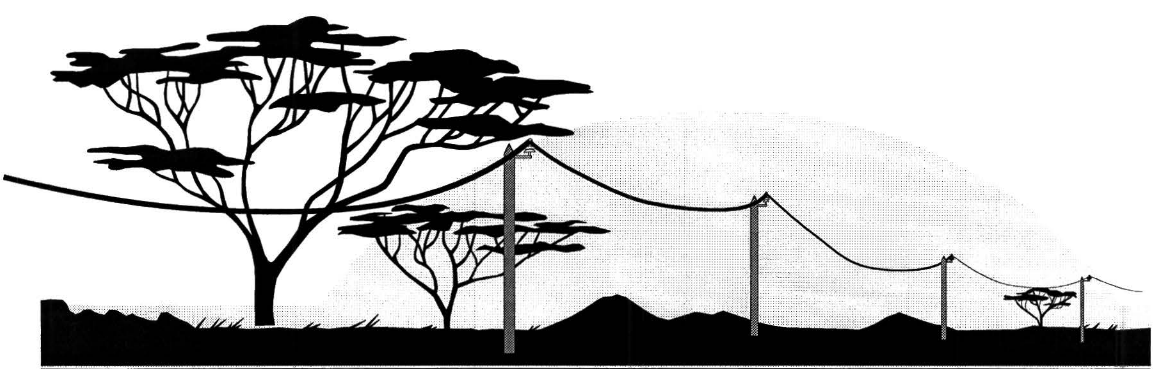
Albert Meijer, August 1995



Suitability of Single Wire Earth Return (SWER) systems for rural electrification in Tanzania

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PREFACE

I started my study of electro-technical engineering as poly-technical level (B.Sc.) because of my interest in technology. The content of the subjects was in my opinion focused on purely technological aspects and the relation to society did not receive attention in the courses.
After my graduation I had the opportunity to start the course of International Technological Development Sciences (M.Sc.) in Eindhoven. This course is among other things involved with in technology-transfer to developing countries. I choose this particular course because of my interest in developing issues as well as technology in relation to society. During this period I followed a course at the Utrecht University (UU), involving regional planning in developing countries. I became aware of the essential role of regional planning (decentralization) and development. This research assignment can be related to this subject in the form of rural development as a function of electrification.

The general goal of this study is to investigate the conditions which tolerate the implementation of a Single Wire Earth Return (SWER) distribution system for rural electrification in Tanzania. The justification for the investigation of the possibility is the fact that it could decrease the initial investment of an electrical network. Compared to the two other distribution systems for rural electrification utilised in Tanzania, Single-Phase Two Wire and Three-Phase Three Wire systems. The difference is one conductor in the first and two conductors in the second system. This is a simplification of reality, but the main idea for initiating this study. The SWER system has not been implemented in Tanzania before. In Canada it has been used successfully for rural electrification [1]. In Australia, still extensive SWER networks are in operation [5, 27]. In Africa an example of this distribution system can be found in Ghana [3].

The report has the following structure :
Chapter 1 comprises the theoretical framework. The goal, related research questions and the proposed methodology are presented. The structure of the report is that of the consecutive steps of the proposed methodology.
In chapter 2, an overview of the electricity infrastructure in Tanzania is presented. It is divided in Generation, Transmission and Distribution of electricity. For each of these subjects attention is given to figures and existing problems.
Chapter 3 and 4 are dedicated to the technical aspects of the study. In chapter 3, distribution systems are described in general. The main part, however, consists of the specific technical aspects of the Single Wire Earth Return (SWER) distribution system. In chapter 4 selection criteria related to the technical suitability of a pilot area are examined. These are divided into criteria at the National level and criteria at the Local or Regional level. To investigate the suitability at local level, some methods of investigation with their relevance are presented.
Chapter 5 and 6, are dedicated to socio-economic aspects related to the use of the distribution system. The role within rural development perspective, more specific, the contribution to the development goals of the Tanzanian government. Methods of investigation at the local (regional) level, consisting of a power market survey and measurements of technical nature (mentioned in chapter 4) , are presented. On the basis of the collected field data a preliminary grid design is then established.
In chapter 7, a comparison is made between three preliminary grid designs, the (1) Single Wire Earth Return distribution system compared with the conventional distribution systems, utilised in Tanzania, (2) Single-Phase Two Wire and (3) Three-Phase Three Wire. In this chapter I concentrate on the differences in the grid designs.
In chapter 8, an analysis of rural electrification projects, in the context of this study, is proposed. It is assumed that, in the project area, the technical and socio-economic conditions which indicate a secure operation of the SWER distribution system are met. To analyze the utilisation of the SWER system in rural electrification projects it should fulfill the concept of decreased initial investment costs, since that is the main justification. A criteria of financial nature. The analysis must give a decisive answer to the question if this distribution system (SWER) is preferable, in a particular situation, compared to the other two options. The analysis considers, furthermore, potential socio-economic benefits.

In the conclusion and recommendations a summary is given with respect to the suitability of the SWER distribution system in Tanzania for rural electrification. The major conditions which could indicate secure operation are given. The recommendations, in this study, relate to technical aspects of the SWER system. Some technical modifications, to provide for adverse consequences of the system, will be expressed.

I like to thank the following people for their support and contribution in the realization of this study, Mr. Masawe, Mr. Kingu and Charles for their assistance and all other personnel of TANESCO who made this study possible, P.E. Lapperre, R.E. Lapperre, A.M.C. Lemmens and J.W Wetzer for their comments, suggestions and time. Personnel of the student home where I stayed for half a year. Mireille Reyme, Petra de Jongh and my Mother for their support and assistance.

APPENDIX

A) TECHNICAL

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Abbreviations used in this report

a	-	radius of rod
A	-	area
A	-	Ampere
AA	-	All Aluminium Conductors
AAC	-	Aluminium alloy conductors
AC	-	alternating current
ACSR	-	Aluminium Clad Steel Reinforced conductor
b	-	radius of ring
β	-	angle of rod with soil surface
CaO	-	lime
°C	-	degrees celcius
CCM	-	Chama Cha Mapinduzi, the present ruling political party in Tanzania
D_e	-	equivalent depth of return of earth current
d	-	geometric mean radius of the overhead condutor
DC	-	direct current
δ	-	skin depth
GPR	-	Ground Potential Rise
G_1, G_2	-	earthing grid
h	-	height of conductor above soil surface
Hz	-	cycles per second
I	-	current
I_a	-	current through the accidental circuit
I_B	-	body current
ITDS	-	International Techcnological Development Sciences
J	-	current density
j	-	imaginary unit [=$\sqrt{(-1)}$];
kHz	-	10^3 cycles per second
km	-	kiliometre
kr	-	reflection coefficient
k	-	$\sqrt{\omega\mu\sigma}$;
K_0	-	modified Bessel function of the second kind, zero order.
K_2O	-	potash
kV	-	kilo volt
KVA	-	Kilo Volt Ampere
l	-	length *l*
ln	-	natural logarithm
LV	-	Low Voltage
m	-	metre
mA	-	milli Ampere (10^{-3} A)
MES	-	Modified European System
MgO	-	magnesia
MV	-	Medium Voltage
MW	-	Mega Watt (10^6 watt)
MWh	-	Mega Watt hour
NAS	-	North American System
Na_2O	-	soda)
θ_{rise}	-	temperature rise
$\theta_{ambient}$	-	ambient tempearture
Ω	-	ohm
Ω.*m*	-	ohm per meter
r	-	radius
R	-	resistance
R_{eq}	-	equivalent resistance
R_b	-	body resistance

R_a	-	total effective resistance of the accidental circuit
ρ	-	resistivity
S_b	-	empirical constant related to the electric shock tolerated by a certain percent of a given population.
sec.	-	second
SWER	-	Single Wire Earth Return
TES	-	Traditional European System
TANESCO	-	Tanzania Electric Supply Company Ltd.
t_s	-	duration of the current exposure in seconds;
τ	-	time constatnt
TWh	-	Terra Watt hour
U	-	voltage
V	-	potential
V_{step}	-	step voltage
V_{eq}	-	equivalent voltage source
ω	-	angular frequency
y	-	lenght from rod to soil surface
γ	-	specific heat (*Ws/m^3 °C*)
λ	-	heat conductivity being (*W/m°C*)
μ	-	permeability in vacuum
σ	-	conductivity
π	-	pi (3.14)
ϕ	-	angular coordinate

1 THEORETICAL FRAMEWORK

1.1 PROBLEM SETTING

Energy situation in Tanzania
Energy sources in Tanzania can be divided into three main sources, **bio-mass** fuels, **petroleum products** and **hydro-power**. Bio-mass constitutes 92%, petroleum 7% and hydro power 1% of the energy use [5]. Bio-mass can be divided into fire-wood, charcoal, crop residues and dung. The petroleum fuels are imported as crude oil and refined in Tanzania. There are, however, large reserves of the natural resources gas and coal. Plans have already been made to utilize these resources for electricity generation in the near future.
The World energy demand is forecast to grow at a rate of 2 percent per annum in the 1989- 200 period. Developing countries are expected to register higher energy demand rate, reflecting their low base rates. The African region is expected to exhibit a growth rate of 3.5 %. In Tanzania, where the largest amount of the energy demand consists of **bio-mass**, it will further increase the pressure on forest land. The sources of firewood supply in and around the villages have diminished to a great extent already. In some regions such as Shinyanga, Mwanza or parts of Arusha and Singida where wood is very scarce, the use of dung or farm residues remain the only means of the people to sustain life.

The electricity is generated by hydro-power stations and diesel generators. The main hydro-power station is located at Kidatu. The hydro-power stations feed the national-grid while the diesel generators are used for local grids in areas where no access to national-grid electricity is available. An exception are some large diesel generators connected to the national grid which are utilized in periods of peak demand.
The national grid connects the main urban centres in Tanzania with spur lines to a number of rural areas along the main transmission lines. As a result of the large distances between the load centres themselves and the generating stations, there are more than average transmission losses.
The consumption pattern divided by sector is roughly the following: the industrial sector consumes 52%, residential consumers account for 26% and the remaining public sector and services account for 22% of the total electricity consumption [5]. One remark should be made in this context, around 50% of all generated electric power is consumed in the Dar es Salaam region.

Rural electrification
The rural electrification is defined as the supply of electricity to district townships, other small townships, villages, development centres, settlements, agro-based industries and other small industries outside the towns. The power demand in these areas varies from a few hundred kW to a few MW.
As the majority of the Tanzanians live in the rural areas and biomass is the main energy source which causes, among others, deforestation it is important to promote the use of non-traditional fuels. Electricity from indigenous sources as hydroelectric power or solar energy are alternatives that could help to prevent a possible energy crises in the country. An other option for supplying the remote areas with electricity is by connection to the national grid.
Until now all regional and 69 district headquarters are electrified. It is intended to electrify the remaining 34 headquarters up to the year 2005. Emphasis will be put on districts with agro-based industries with use of, as much as possible, indigenous resources. Ultimately the rural electrification programme's objective is to electrify all 8000 villages in Tanzania [16].

Goal definition
With respect to the connection of rural areas to the national electricity grid, the present distribution system is composed as follows :

- **three wire three-phase system;**
- **two wire single-phase system;**

The electrified rural areas, not connected to the national grid, utilize diesel power plants. The equipment and fuel for the diesel power plants has to be imported. This puts pressure on the limited reserves of

foreign currency. The fact that the fuel and spare parts have to be imported implies that it affects the performance of the diesel power plants during their entire operational time. Distribution systems connected to the national electricity grid could be more suitable in this context. Another problem in the rural electrification program is insufficient financial support.
The application of more appropriate technologies, meaning less investment costs, limited dependence of foreign exchange and local production of inputs could be a way to achieve a more efficient electricity supply. A contribution in this perspective can be a technology with limited capital investment requirements.
Bearing this in mind a single wire single-phase distribution system can be considered. This method uses only one line or cable to supply electric-power to an area, which means a reduction of one wire in relation with the two wire single-phase system and three wires in relation with the three-phase system(3 phases and 1 neutral). It can result in a considerable reduction of investments costs.
The selection of the research goal is based on a direct request of TANESCO, in the framework of the course International Technological Development Sciences at the University of Eindhoven and my personal interest in rural development. The goal is formulated as follows :

To develop an instrument to investigate the viability of a single-wire single-phase distribution system for rural electrification in Tanzania and, to asses the possible social and economical benefits in a pilot area

1.2 RESEARCH QUESTIONS

A : Technological aspects

1. Is the single wire earth return distribution system technically viable for rural electrification in Tanzania ?

   To make a judgement about the technical viability the following sub-questions have to be asked :

   1.1 What are the specific features of the distribution system ?
   1.2 What are the climatological/geographical and geophysical conditions ?
   1.2 How do the environmental conditions, in which the technology operates, effect the performance of the distribution system ?
   1.3 What are the possibilities to alter the environment in order to make it suitable for the distribution system considered ?
   1.4 What are the consequences of three-phase loads on the technical viability of this system ?
   1.5 What is the maximum power to be distributed ?
   1.6 Which electrical equipment, e.g. transformers, switch-gear, cable/line sizes, is required ?

B : Socio-economic aspects

2 Is there a need for electricity and can it contribute to the development of the pilot area.

2.1	What will be the power-consumption and which potential benefits - social and economical - can be expected from domestic electrification ?
2.2	What will be the power-consumption and which potential benefits - social and economical - can be expected from industrial, agricultural and service sectors electrification ?
2.3	Which economic activities are present in the specific area ?
2.4	How accessible is the area with respect to roads and national grid ?
2.5	Which infrastructural facilities are present and at which level ?
2.6	What is the demographic situation ?
2.7	Are there regional development plans and what do they include ?

1.3 METHODOLOGY

My contribution is an instrument to investigate, in a structural and methodological way, the technical viability of a single-phase distribution system in the rural areas of Tanzania, and to asses the possible social and economical benefits of electrification in a pilot area. The methodology applied for this exercise is reviewed in the following paragraphs.

Technological context :
The technical data associated with the system are collected through a literature research. Data with respect to environmental conditions are collected either by the analysis of existing documents or in the field.

Environmental characteristics (***conditions related to soil-suitability***) **:**
- annual rainfall;
- length of the seasons;
- altitude;
- soil moisture regimes;
- type of soils;

Conductivity : Measurement of the soil-conductivity by injection of a known current into the Soil and measurement of the resulting potential difference.

Additional information, like vegetation, will also be collected.

Social context :
To select a rural area where the distribution system could be introduced, a comparison of several areas of interest is worked out, after which a decision about areas is made. The following characteristics apply :

Economical characteristics (***estimate of expected load-types [single versus three-phase]***)**:**
- agriculture;
- industry;
- services, commerce.

Accessibility (***potential development perspective***) **:**
- distance to major cities;
- distance from existing grid;
- state of the roads.

Infrastructure (***potential development perspective***) **:**
- water supply;
- schools;
- health care;
- credit access;
- etc...

Demographic aspects (***related to the limited capacity of the line***) **:**
- population;
- growth rate.

Regional development plans (***to put it in an integrated development perspective***)

To asses the need of electricity a power market survey is conducted. This consists of two questionnaires, one for the domestic consumers and one for the commercial, industrial, institutional and agricultural consumers.

Assessment of the load will be performed by comparing different load forecasting methods to reach a value. If the load-growth is estimated and the maximum load calculated, the specifications of the necessary equipment can be determined.

Household survey : The objective of this survey is to get a picture of the present energy use pattern as well as the socio-economic situation in the area. The following aspects are included:
- general information on the household;
- economic activities;
- energy use pattern;
- housing conditions;
- accessibility;
- opinion on electricity/potential use.

Commercial, Industrial, Institutional, and Farmer survey : in this survey the following characteristics are included :
- general overview of the establishment;
- energy use pattern;
- housing conditions;
- production;
- accessibility;
- transport status;
- opinion of electricity;
- potential use/experience.

The areas selected where, however, not in agreement with the ideas of my supervisor at TANESCO. Two other areas where selected for me. One township was even supplied with electricity. Because I used an instrument of TANESCO for the conductivity measurements an employee accompanied me during the fieldwork. I only could interview a limited number of people as result of the time that was at my disposal.

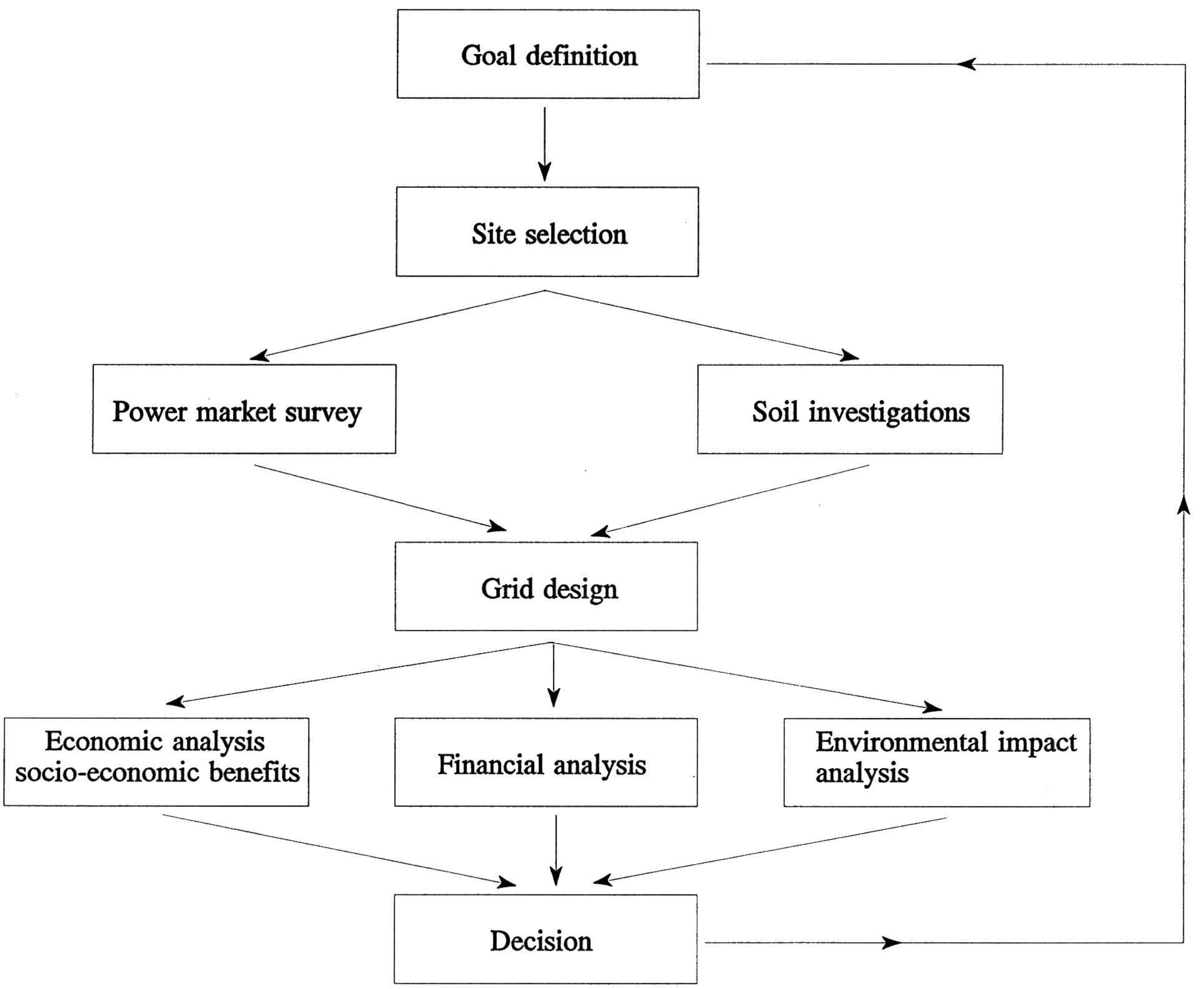
Socio-economic benefits are characterized in quantitative and qualitative terms, the degree of the expected benefits are related to, for example, the socio-economic structure of the area and supplementary incentives to stimulate the use of electricity.

- **Household benefits :** cheaper and better lighting, more time for studying and working after dark, making household labour easier, quality of live improvement.
- **Industrial, commerce and agricultural benefits** : possible replacement of energy source cheaper form, higher productivity, longer opening hours, water supply, irrigation, higher quality of products

Preparation of the data : To answer the question wether this technology is applicable in Tanzania for rural electrification, the data will be used for a grid design. Three options will be analyzed: (1) SWER(Single-Wire Earth Return) distribution system, (2) single-phase two-wire distribution system, and (3) conventional three-phase distribution system.

Analysis : The SWER(Single-Wire Earth Return) distribution system will be compared with the two other distribution systems to come to a conclusion about the viability of this technology. The analysis will be based on financial, technical, socio-economical and environmental aspects.

Theoretical model :



1)	**Problem setting**	(rural electrification in Tanzania)
2)	**Goal definition**	(research goal)
3)	**Site selection**	(the area of investigation)
3)	**Data-collection**	(case-study => interviews, observations, documents)
4)	**Preparation for analysis**	(load forecast, grid design, potential benefits)
5)	**Analysis**	(socio-economic, financial and environmental aspects)
6)	**Decision**	(eventual conclusion on the viability of the SWER distribution system)

2 ELECTRICITY INFRASTRUCTURE IN TANZANIA

2.1 GENERATION

Electricity in Tanzania is generated by two types (1) hydro-electric power which contributes for 75% in the total demand and (2) thermal plants (diesel) that produces the rest. The capacity, in production, of the interconnected and isolated systems in 1991 was as follows [17] :

Table 2.1 : National grid and isolated system (1991):

National grid (production interconnected system 1991)				Isolated system (production 1991)			
Station	Capacity (MW)	Electricity generated (TWh)	Capacity util. (%)	Station	Capacity (MW)	Electricity generated (TWh)	Capacity util. (%)
Kidatu (Morogoro)	200.0	978.6	55.9	Liwale	0.1	0.1	11.4
Mtera	80.0	501.6	71.6	Bukoba	4.5	10.6	26.9
Hale (Tanga)	21.0	111.4	60.6	Chamwino	0.4	0.3	8.6
Pangani falls	17.5	75.2	49.1	Babati (Arusha)	2.0	1.3	7.4
Nyumba ya Mungu (Moshi)	8.0	55.0	78.5	Kigoma	4.1	8.7	24.2
Arusha-Thermal	3.7	6.6	20.4	Kilwa/Masoko	0.7	0.6	9.8
DSM-Thermal (Ubungo)	49.4	4.3	1.0	Kondoa	2.4	0.8	3.8
Dodoma (Zuzu)	5.1	0.5	1.1	Lindi	1.4	5.3	43.2
Iringa/Tosamaganga	12.0	3.8	3.6	Mafia	2.0	0.8	4.6
Mbeya/Iyunga	13.9	5.5	4.5	Mpwapwa	1.0	2.3	26.3
Musoma	7.4	0.1	0.2	Mtwara	4.4	7.7	20.0
Mwanza/Nyakato	28.0	6.0	2.4	Njombe	1.9	3.9	23.4
Mwanza/South	4.5	0.2	0.5	Songea	2.6	11.1	48.7
Tabora	7.4	1.6	2.5	Sumbawanga	2.1	7.0	38.1
				Tukuyu/Mwakaleli	1.7	5.0	33.6
				Ikwiriri	1.0	0.1	1.1
				Masasi	4.5	7.4	18.8
TOTAL	451,1	1750,4	44,3	TOTAL	38.2	73.0	2.2

Grid and Isolated system	Capacity (MW)	Electricity generated (TWh)	Capacity utilisation (%)
TOTAL	489.3	1823.4	42.5

Problems in capacity utilisation

While the major part of the electricity is generated by hydropower plants it is for a large part depending on water levels in the river basins. In 1994 electricity was rationed as result of the low level of the basins due to two factors, in the first place more water was utilised for irrigation and in the second place, seasonal rainfall was less than average. The age of the generator-sets, which effects the efficiency to a significant extent, is another problem.

2.2 TRANSMISSION

The transmission system consists of an interconnected grid between the major urban centres in Tanzania. The transmission is performed by lines with voltage levels of 220 kV and 132 kV. In figure 2.1 a graphical view of the system is shown.

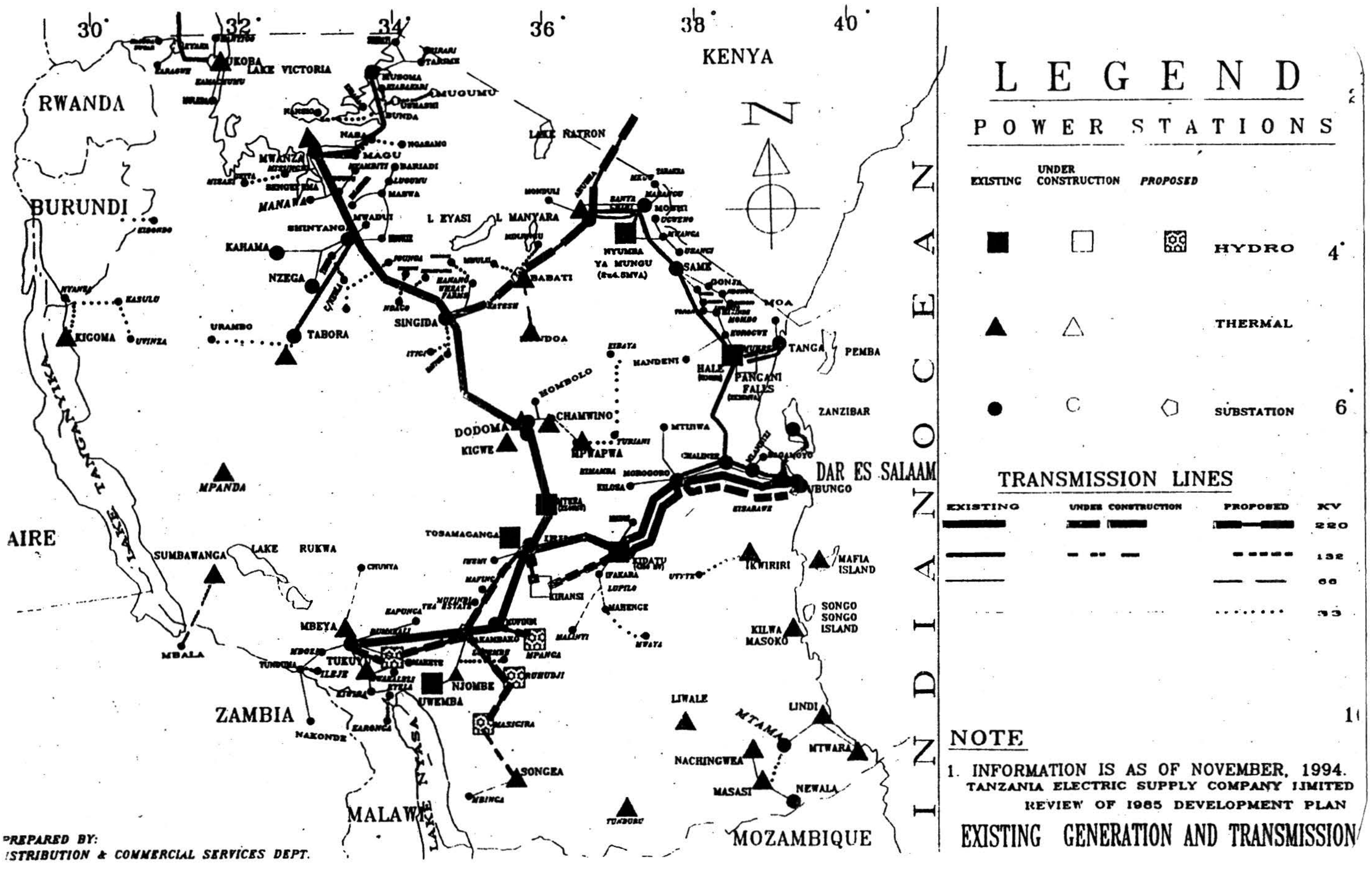


Figure 2.1 : Generation and transmission system of Tanzania

Table 2.2 Interconnected transmission system lines :

Voltage(kV)	Circuit	Routing	Line length(km)
220	1	Kidatu - Morogoro - Ubungo	300
220	1	Kidatu - Iringa - Mufindi - Mbeya	500
220	1	Iringa - Dodoma - Singida	454
132	1	Ubungo - Chalinze - Morogoro	179
132	1	Chalinze - Hale - Same - Arusha	563
132	1	Hale - Tanga	60
132	1	Ubungo - Zanzibar	41
220	1	Singida - Shinyanga - Mwanza	360
132	1	Mwanza - Musoma	210
132	1	Shinyanga - Tabora	200
132	1	Shinyanga - Kahama	100
132	1	Shinyanga - Nzega	77

2.3 DISTRIBUTION AND CONSUMPTION

The distribution networks in the rural areas operate at 66 kV, 33 kV and 11 kV. Both grid supplied and diesel supplied networks use these voltage levels. The system with 3-phase 3-wires is used.
Table 2.4 and table 2.5 [17] give some data about the consumption of electricity in Tanzania of electricity sold and number of consumers by region.
Consumption of electricity is 11 kV (high voltage supply) and low voltage 400/230 V. Low voltage is four wires (3-phases + 1 neutral) .
Consumers can be divided according to the tariff system in use by TANESCO. A system which is rather complex (see appendix A.4). The tariff system is roughly divided in, (1) residential, (2) commercial, (3) Industrial, (4) agricultural and (5) public demand (water and street lights). Zanzibar is treated as one consumer group. Some data about electricity sales by consumer group in Tanzania are given in table 2.3.

Problems in rural areas
In the rural distribution systems the major problems are long single phase power lines, use of too small conductors, and uncoiling of conductors.
Regarding to frequency control no problems do occur, the variations stay within the margin of 1%. Fluctuations of the low voltage system (240 V) outside the margin of 5% are, however, not unusual, the occurrence of long and undersized conductors and loose connection are the major source.
The power factor[1] of the rural electricity supply should be good while most of the load consists of lighting. Circumstances which can influence the power factor are the use of machines which use predominantly reactive power (for the creation of magnetic fields) such as welding sets an compressors which are used in workshops, garages, blacksmiths, etc.
Concerning the losses no accurate data are available for the rural areas. Record of the difference in units sold and units imported or generated are not available for most of the rural areas. The few quantitative data that are available do suspect a significant amount of losses. A detail study of Babati rural distribution network made it possible to make an accurate determination of losses. The results were that the technical losses varied between the range of 11-19% (see Arnborg et al.). The largest amount of losses did occur in the low voltage distribution system (240 V), about 12%. In the 11 kV system (distribution) the losses appeared to be around 2%.

Table 2.3 Electricity sales by type of use (MWh)

Type of use	1989		1990		1991	
	MWh	perc. %	MWh	perc. (%)	MWh	perc. (%)
Public lighting	5	0.43	5	0,38	8	0,55
Domestic	330	28.65	350	26,84	468	31,95
Commercial & Industrial	753	65.36	897	68,79	932	63,62
Zanzibar	64	5.56	52	3,99	57	3,89

[1] The power factor (PF) is defined as *real power (kW) / ((real power (kW))^2 + (reactive power (kVA))^2)$^{1/2}$*, reactive power is the necessary power to build up electric and magnetic fields in the system, for example in electro-motors.

Table 2.4 Electricity sold by region (MWh)

Region	1989		1990		1991	
	Numb.	%	Numb.	%	Numb.	%
Dodoma	21	1,82	30	2,30	33	2,26
Arusha	75	6,51	87	6,67	97	6,66
Kilimanjaro	66	5,73	76	5,83	83	5,70
Tanga	95	8,25	119	9,13	129	8,85
Morogoro	73	6,34	82	6,29	89	6,11
Coast region*	1	0,09	1	0,08	..	0,00
Dar es Salaam	507	44,01	590	45,25	645	44,27
Lindi	5	0,43	6	0,46	6	0,41
Mtwara	8	0,69	10	0,77	10	0,69
Ruvuma	6	0,52	7	0,54	9	0,62
Iringa	96	8,33	82	6,29	93	6,38
Mbeya	40	3,47	45	3,45	50	3,43
Singida		0,00	5	0,38	6	0,41
Tabora	10	0,87	15	1,15	19	1,30
Rukwa	4	0,35	5	0,38	6	0,41
Kigoma	6	0,52	8	0,61	7	0,48
Shinyanga	9	0,78	17	1,30	46	3,16
Kagera	6	0,52	8	0,61	8	0,55
Mwanza	42	3,65	45	3,45	49	3,36
Mara	12	1,04	14	1,07	15	1,03
Mainland	1088	94,44	1252	96,01	1400	96,09
Zanzibar	64	5,56	52	3,99	57	3,91
Total	1152		1304		1457	

* - For Mafia only, other sales are included under Dar es Salaam

Table 2.5 Number of electricity consumers by region

Region	1989		1990		1991	
	Numb.	%	Numb.	%	Numb	%
Dodoma	5793	3,56	6475	3,70	7012	3,47
Arusha	9661	5,94	10638	6,08	14514	7,18
Kilimanjaro	14674	9,02	16566	9,47	19121	9,46
Tanga	13946	8,57	15242	8,71	18743	9,27
Morogoro	8295	5,10	9106	5,20	10216	5,05
Coast region*	357	0,22	366	0,21	370	0,18
Dar es Salaam	67130	41,26	69613	39,78	78988	39,06
Lindi	1648	1,01	1697	0,97	1702	0,84
Mtwara	3698	2,27	4267	2,44	4474	2,21
Ruvuma	2022	1,24	2296	1,31	1869	0,92
Iringa	4498	2,76	5093	2,91	5666	2,80
Mbeya	7998	4,92	9306	5,32	11799	5,84
Singida	1859	1,14	2027	1,16	2110	1,04
Tabora	3834	2,36	3503	2,00	4603	2,28
Rukwa	..	0,00	..	0,00	..	0,00
Kigoma	2688	1,65	2848	1,63	3219	1,59
Shinyanga	2894	1,78	2791	1,59	3987	1,97
Kagera	2243	1,38	2363	1,35	2420	1,20
Mwanza	7015	4,31	7559	4,32	8406	4,16
Mara	2740	1,68	3358	1,92	2985	1,48
Mainland	162693	100,00	175004	100,00	202204	100,00
Zanzibar	-	0,00	-	0,00	-	0,00
Total	162693		175004		202204	

3 DISTRIBUTION SYSTEMS

In this chapter I will, in the first place, discuss existing distribution systems and their characteristics with regard to their technical properties. The largest part, however, is dedicated to the description of the Single Wire Earth Return (SWER) distribution system. In particular the effects with regard to the return current through the soil.

3.1 EXISTING DISTRIBUTION SYSTEMS

A distribution system comprises power lines, voltage step down equipment and voltage regulators for electric service to industrial, commercial and domestic consumers. The system may comprise distribution lines with operating voltages of 6 to 35 kV (kilo Volt) and three-phase, two-phase and single-phase tapped lines. The construction of the lines can either be underground cables or overhead lines.

Traditional European System (TES)
The High Voltage (HV) lines of traditional European systems have three-phase distribution transformers supplied by three-phase three-conductor Medium Voltage (MV) lines. The neutral point of the HV/MV transformer can be insulated or earthed either directly or through an impedance. The Low Voltage (LV) delivery system is constructed of three-phase lines which have four conductors and, for the lowest loads, single-phase spur lines with two conductors. In both cases one conductor is for neutral and the rest for phases (see Fig. 3.1).

Modified European System (MES)
This system is based on the Traditional European System (TES) but has been developed also for lighter consumption. It is employed in some European countries and in several developing countries.
MES includes both three- and two-phase MV lines. The main MV lines are similar to the ones in TES. The spur lines are also three-phase three-conductor lines if the loads are heavy or medium. For light loads two-phase spur MV lines, single-phase distribution transformers and LV lines are used. Open and closed delta connected transformers are used for medium and heavy loads respectively, although the former are quite rare. The corresponding LV distribution lines are either single-phase (open delta) or three-phase (closed delta) connections (see Fig. 3.2).

North American System (NAS)
The North American System (NAS) was developed and has been used mostly in North and South America. Nowadays many developing countries, especially in South America, but some also in the Far East use this system. In NAS the main MV lines have three-phase conductors and one neutral conductor. For light loads single-phase spur lines with one neutral conductor are used. The distribution transformers and the LV lines are also single-phase. For medium loads the spur lines have another phase conductor and the transformers are open Y (wye) connected. The LV distribution connections can be either single- or three-phase lines. For heavy loads three-phase lines with three conductors are used. The transformers are floating Y (wye) connected and the LV distribution connections are either single- or three-phase lines. Usually only one single-phase transformer type is used and the number of the units varies. The neutral point of HV/MV transformer and the neutral conductor are connected to each other and directly earthed. The latter is also usually earthed in every MV apparatus and at certain intervals, and hence the earth is partly used as a load current path. It can also be formed by the LV neutral conductor (see Fig. 3.3).

Single Wire Earth Return (SWER)
SWER has been developed and successfully utilized in North America and Australia. However, for example in North America most of its lines have been converted to the NAS-type lines as loads have increased and as conductors became cheaper and more readily available since World War II. Nowadays it is still employed in the above-mentioned areas, but also in Ireland and in some other countries.
SWER utilizes the earth as a load current path. Therefore, in this system only one conductor is required. The SWER line is always a spur line from a three-phase main distribution line, and they are usually galvanically isolated from each other by means of isolating transformers.

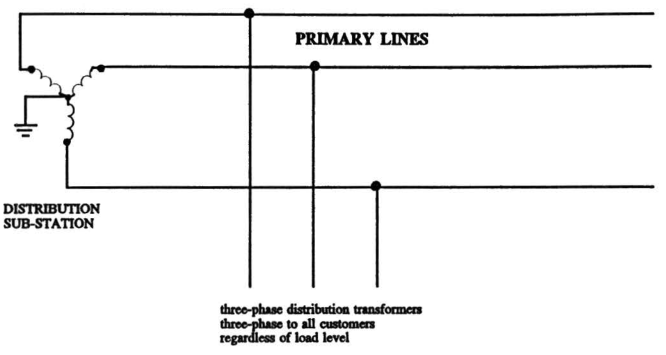


Figure 3.1 Traditional European System (TAS)

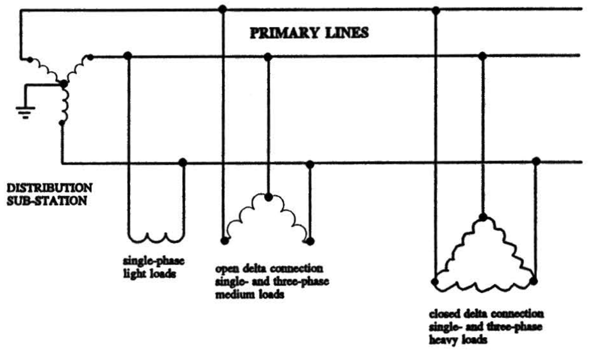


Figure 3.2 Modified European system (MES)

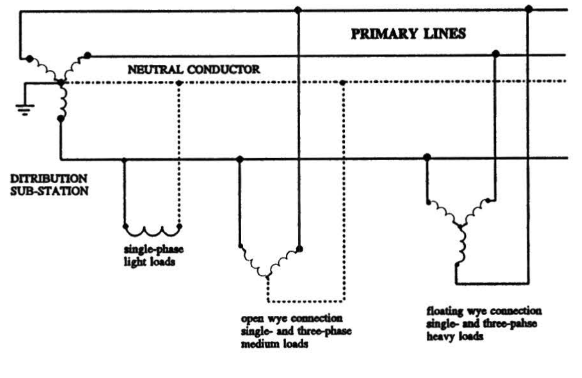


Figure 3.3 North American System (NAS)

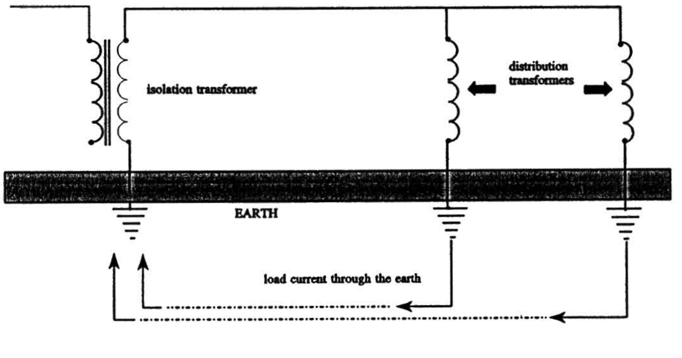


Figure 3.4 : Single Wire Earth Return (SWER) distribution system

The distribution transformer and LV lines are also single-phase (see Fig. 3.4).
The single-phase single-wire distribution MV lines are also successfully utilised in Ghana in combination with insulated shield wires of HV lines [3]. Basically two types of system setup can be identified. The first setup is a distribution system with **scattered individual loads** of around 10 KVA. This system will be of the SWER type all its operational lifetime. Examples of this setup can be found in Australia [6]. These networks can be very extensive.
The second setup is suitable for the distribution of power to some **load centres,** with an initially modest power demand. In a later stage, when demand is growing, the single wire distribution line can be upgraded to a two wire and eventually a three wire three-phase system [4]. In the design of this setup of the system, one has to consider the extension in the selection of materials, so the distribution system is prepared for this, eventual, situation.
In the second setup a limited number of distribution transformers are connected to the line. This is the setup which will be investigated in this report.

Table 3.1 : Major characteristics of the distribution systems

Type of System	PRIMARY SYSTEM			DISTRIBUTION TRANSFORMERS				
	Three-phase	Single-phase	Typical voltage	Three-phase	Single-phase *line to line**	Single-phase *line to earth**	Coverage of second. syst.	Flexibility
TES	Yes	No	11,0 kV	Yes	No	No	Extensive	Very little
MES	Yes	Yes	11.0 kV	Yes	Yes	No	Medium	Good
NAS	Yes	Yes	12.5 kV	Yes	No	Yes	Limited	Very good
SWER	No	Yes	10.0 kV	No	No	Yes	Limited	Very little

* - transformers isolated at primary side

3.2 WHY USE A SINGLE WIRE EARTH RETURN DISTRIBUTION SYSTEM

In the case of rural electrification networks, the common western systems for electricity supply are capital intensive. The fact that the loads are remote, scattered and of low intensity means that the load per km of line length is minimal in comparison with urban networks. Some effects are, more than average energy-losses, voltage drop in distribution networks and low revenue generation per line-length.
If there is an intention to give rural electrification priority one has to look for other technical solutions which are less expensive and still can provide the need with the same quality. The single wire earth return (SWER) distribution system can provide the need of electricity in remote areas with relatively small loads. It uses only one wire and can be upgraded, if the setup of the system supports this option, to a conventional three phase system when loads are growing. In the next paragraphs the specific features of the proposed distribution system will be dealt with.
Table 3.1 summarizes the major characteristics of the distribution systems [1].

3.3 SINGLE WIRE EARTH RETURN (SWER) DISTRIBUTION SYSTEM

There are two possible schemes (1) a direct connection between the main MV distribution line and the local distribution transformer and (2) a configuration with an isolating transformer connected between the main MV distribution line and the spur line to the local grid. In the second option the local grid is galvanically isolated from the main MV line.

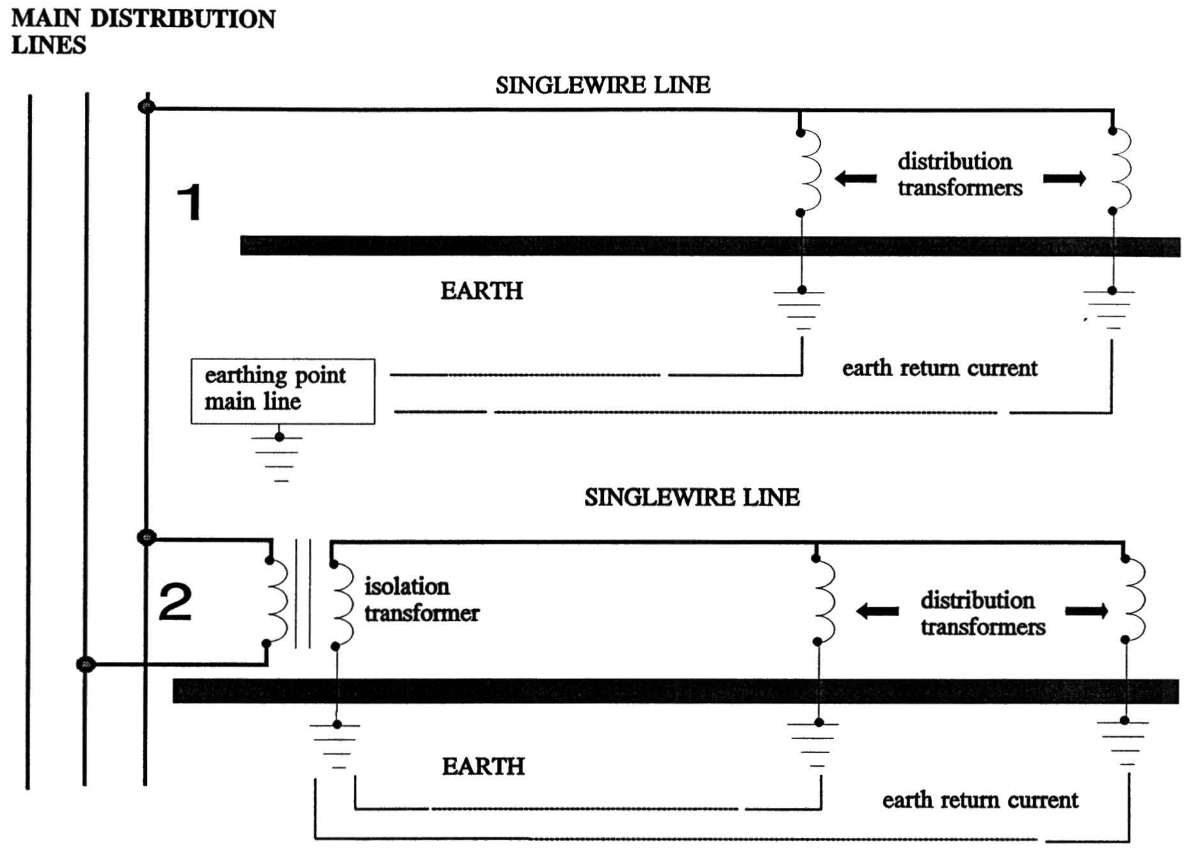


Figure 3.5 Schemes of the Single Wire Earth Return (SWER) system

3.3.1 Soil currents

The specific feature of the SWER system is that the return current flows through the soil. First I will give some attention to the effects and implications of the fact that there will be a continuous earth-current.
The electric conductivity of the soil compared to the conductivity of metals is very low. The two main constituents of the earth's crust, silicon oxide and aluminium oxide, are actually excellent insulators. The conductivity of the soil depends, in large measure, on salts and moisture embedded between the main constituents, silicon oxide and aluminium oxide. On the other hand, even a semi-conductor may carry a considerable amount of current if only the cross section is large enough, and in this respect the soil, by its great depth, presents no limitations. In practice, in the case of 50 Hz currents the path is limited by the skin depth δ.
Due to the high resistivity, all currents flowing through the soil suffer from a considerable voltage drop. A substantial electric-field strength, or potential gradient, can develop and this may affect extended regions of the surface of the soil. There are two different zones which will be considered in detail, (1) the spaces in the proximity of the ground electrodes and (2) the long path between such electrodes.
The soil under the earth's surface is by no means homogeneous, so a rigorous analysis of the distribution of currents is very difficult if not impossible. Random changes caused by weather and seasons, by rain, frost and by other temperature variations, with their influence on the conductivity of the soil, increase the difficulty of analysis. A quantitative analysis of the electric phenomena in the soil, however, is necessary to make numerical calculations and to draw definite conclusions whether the electric system will not experience technical trouble or cause serious problems from time to time. In table 3.2 and corresponding figure 3.6 an overview of the electrical characteristics of the soil will be given.

Table 3.2 : Soil characteristics [2]

CHARACTERISTIC	DESCRIPTION
Soil as grounding medium	Behaviour of a **ground electrode** buried in soil can be described by means of a **circuit of resistors and capacitors** (see figure 3.6). Most soils behave both as conductor and as a dielectric. Except for high-frequency and steep-front waves penetrating a very resistive soil material, the charging current is negligible in comparison to leakage current, and the earth can be represented by a pure resistance.
Effect of current magnitude	Soil resistivity in the vicinity of ground electrodes may be affected by current flowing from the electrode into the surrounding soil. The thermal characteristics and the moisture content of the soil will determine if a current of a given magnitude and duration will cause significant drying and thus increase the effective soil resistivity. A conservative value of current-density, as given by Armstrong [18], is not to exceed 200 A/m² for more than one second.
Effect of moisture, temperature and chemical content	Electrical conduction in soils is essentially **electrolytic**, for this reason the resistivity of most soils rises abruptly whenever the moisture content accounts for less than 15% of the soil weight. The amount of water further depends upon the grain size, compactness and variability of the grain sizes, the resistivity is little affected once the moisture content exceeds 22% [19]. The effect of temperature on soil resistivity is nearly negligible for temperatures above the freezing point. The composition and the amount of soluble salts, acids, or alkali present in the soil may considerably affect its resistivity. Curve 1 in figure 3.7 illustrates a typical effect of salt (sodium chloride) on the resistivity of a soil containing 30% of moisture by weight.
Use of crushed-stone layer	Gravel or crushed rocks coverings , usually about 0.08-0.15 m in depth, are very useful in retarding the evaporation and thus in limiting the drying of topsoil layers during prolonged dry weather periods

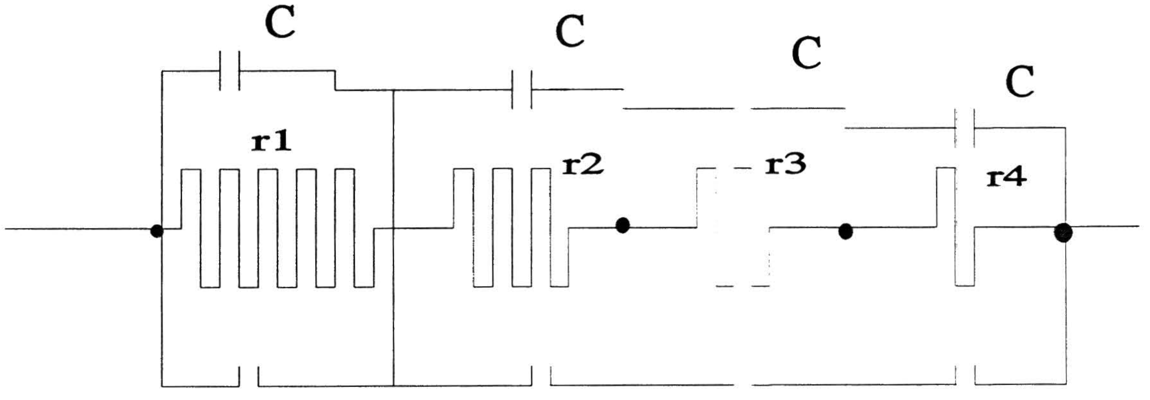


Figure 3.6 : Soil model

Earlier I mentioned that there where two zones, one in the vicinity of the electrode where the current flows into the ground and the other much wider zone between the entrance and exit electrodes of the earth-return current.

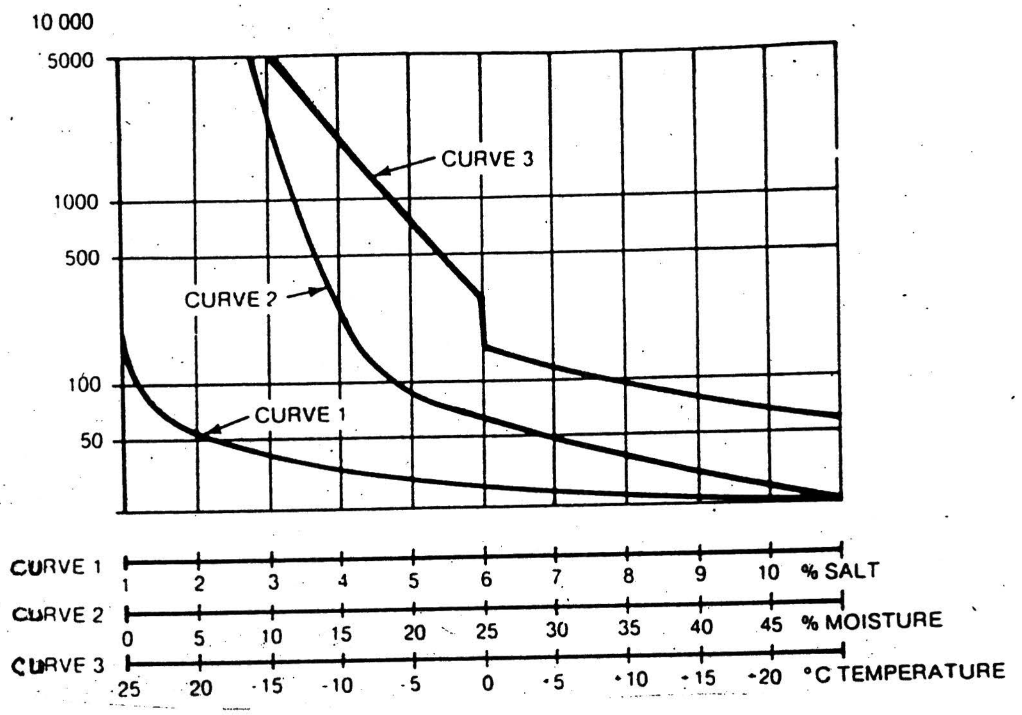


Figure 3.7 : Effects of Moisture, Temperature and Salt upon soil resistivity

The first zone is situated at the substation (isolation transformer) as well as at the distribution transformers, so the grounding system of these transformers is of major importance. In this system the load current of the transformer is flowing through the earthing-electrodes into the soil which causes the following local effects (1) potential(voltage) rise in the surrounding soil, (2) interference with other electric or electronic devices in the ground, (3) effects on conducting structures in the ground or near the distribution line and (4) soil heating. Effects 2 and 3 are due to transferred and induced voltages.

1 - this effect causes step and touch voltages on the soil surface which are relevant to safety criteria for humans and animals being in the vicinity of the grounding system;
2 - these effects are related to, for example, telephone-lines or other electric devices in the ground;
3 - these structures could be oil-pipelines, water supply systems or any other conducting structure near the grounding system;
4 - this effect will cause the earth around the grounding electrodes to dry out and thus could give an uncontrolled rise in the resistance. (see table 3.1).

3.3.2 Local zone of influence

To explain the basic concepts of the ground currents, two simple electrode element will be discussed: a spherical electrode and a driven rod.
The next step of the description involved with the hazard of soil currents to human or animal presence in the vicinity of the earthing electrodes due to the potential rise at the soil surface. The influence on telephone-lines and conducting structures is described by transferred and induced voltages.
The soil resistivity is, among others, dependent on soil moisture level, which is affected by the heat production of the soil current. A paragraph is dedicated to this issue.

Spherical electrode
The simplest form of an electrode is a sphere, either fully or half embedded under the surface plane of the ground. The situation in this case consists of the entrance electrode with the assumption that the influence of the exit electrode is negligible. In a practical situation where the distance between the electrodes can be 20 kilometres or more, it is a valid assumption.

If a current I flows through the electrode, spreading radially in the ground, the current density at distance x from the centre of the hemisphere is [9] :

$$J = \frac{I}{2\pi x^2} \tag{3.1}$$

Such a current produces in the resistivity of the soil, according to Ohm's law, an electric-field strength :

$$E = \rho J = \frac{\rho I}{2\pi x^2} \tag{3.2}$$

The voltage, as line integral of the field strength from the surface of the conducting sphere of radius r to the distance x, is therefore :

$$\Delta V = \int_r^x E dx = \frac{\rho I}{2\pi} \int_r^x \frac{1}{x^2} dx = \frac{\rho I}{2\pi} \left[\frac{1}{r} - \frac{1}{x} \right] \tag{3.3}$$

Current density, field strength. and voltage, in their dependence on distance, are represented graphically in figure 3.8. The total voltage between the spherical electrode and a far distance point with $x = \infty$ is, according to equation 3.3,

$$V_{(x=\infty)} = \frac{\rho I}{2\pi r} \tag{3.4}$$

and, therefore, the resistance experienced by the streamlines of current diverging from the hemisphere is,

$$R = \frac{V}{I} = \frac{\rho}{2\pi r} \tag{3.5}$$

Any additional resistance due to incomplete contact between the electrode and the soil occurs only rarely in practice.

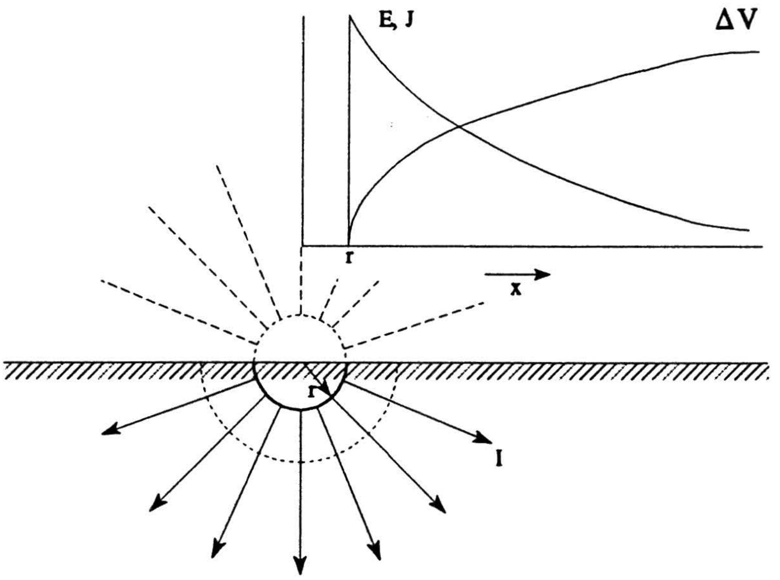


Figure 3.8 : Radial flow of current from spherical electrode to earth

Rod and wire electrodes

Spherical or hemispherical electrodes are not convenient for actual use. In practice rod or wire electrodes, having a relatively small cross section compared with their length, are preferred. We may subdivide with good approximation such a rod electrode driven into the ground, as in figure 3.9, into a large number of nearly spherical elements, which over the length l of the rod in the ground have a mutual distance

$$dl = \frac{l}{n}$$

each feeding a current I/n into the soil, to the exit electrode at the beginning of the distribution line. If y is the distance from any element to a point at the surface of the earth and α is the angle from y to the axis of the rod, the small diagram in figure 3.9 shows that

$$\sin\alpha = \frac{y\,d\alpha}{dl} \qquad 3.6$$

The potential contribution dV of every element is given by the equation $V = \rho I/4\pi y$ with current I/n. By substitution of the distance y from equation 3.6, and use of equation $V = \rho I/4\pi y$, the incremental potential at the surface of the earth becomes

$$dV = \frac{\left(\frac{\rho I}{n}\right)}{4\pi y} = \frac{\rho I}{4\pi n}\,\frac{n}{l}\,\frac{d\alpha}{\sin\alpha}$$

If the limiting value of angle α is denoted by β, as shown in figure 3.9, the potential in the centre plane of a rod of length $2l$, containing $2n$ spheres and thus including the fictitious image[1] above the ground, is given by the integral of dV from + to - ,

$$V = \frac{\rho I}{4\pi l}\int_{+\beta}^{-\beta}\frac{d\alpha}{\sin\alpha} = \frac{\rho I}{2\pi l}\ln\left(\cot\left(\frac{\beta}{2}\right)\right) \qquad 3.7$$

This result would be rigorous if the density of the current emerging from the rod into the earth were uniform over the length, which actually is only a fair approximation.

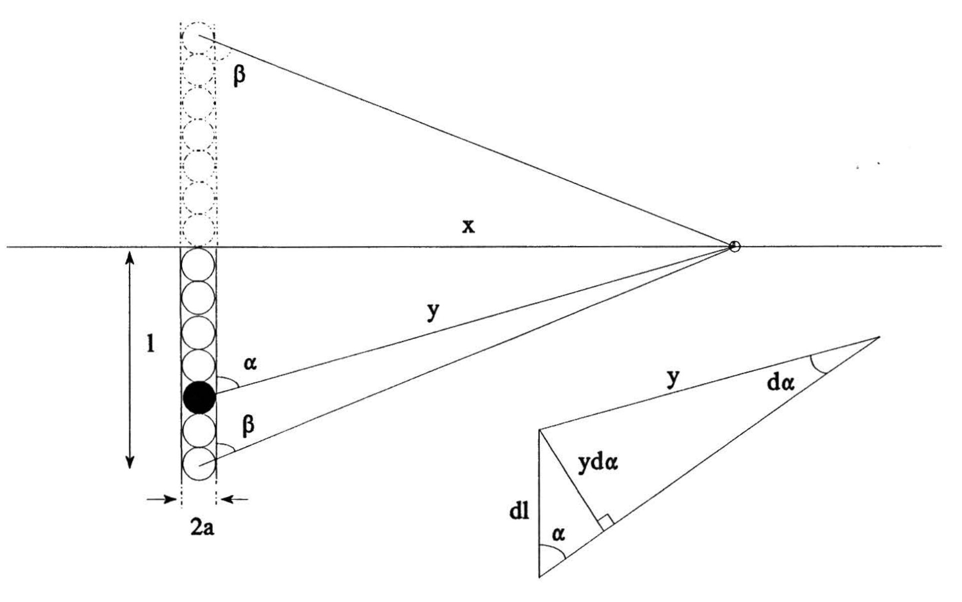


Figure 3.9 Development of the potential around a rod electrode

In this calculation, the soil surface is omitted. In order to meet boundary conditions, no current perpendicular to the surface, image charges are used

The electric potential in the symmetry plane of the driven rod is thus dependent on only four parameters, namely : (1) resistivity ρ of the soil , (2) current I flowing into the rod , (3) its length l within the ground and (4) the angle of vision β between the axis of the rod and the distance from the bottom of the rod to the point under consideration at the surface. Two parameters, 2 and 3, are always given for a specific ground electrode. For any point in this centre plane β is the only variable parameter. For large distance x of the point of consideration from the axis of the rod, the logarithm in equation 3.7 simplifies to

$$\ln\left(\frac{(1+\cos\beta)}{\sin\beta}\right) = \cos\beta = \frac{1}{x} \qquad 3.8$$

and the potential is

$$V_\infty = \frac{\rho I}{2\pi x} \qquad 3.9$$

which is identical with that for a hemisphere.
On the other hand, for the surface of the rod, where the potential V is identical with the voltage U of the electrode, figure 3.9 shows that for small radius a as compared to length l

$$\cot\left(\frac{\beta}{2}\right) \approx \frac{2l}{a} \qquad 3.10$$

Hence the resistance as quotient of voltage and current is

$$R = \frac{V}{I} = \frac{\rho}{2\pi l}\ln\left(\frac{(2l)}{a}\right) \qquad 3.10$$

While the shape of the rod, determining the ratio l/a, is of minor significance since it forms only the argument of a logarithm, the length l of the rod is of major importance, for the ground resistance it is nearly inversely proportional to the length.
A rod of radius a = 2.5 cm. and of length l = 6 m., dimensions often used in practice, a driven into moist soil will present a resistance

$$R = 10^2 \text{ ohm-m}/(2\pi \cdot 6 \text{ m}) \cdot \ln\left((2 \cdot 6)/2.5 \cdot 10^{-2} \right) = 2.65 \cdot \ln 480 = 16 \text{ ohms}$$

This equals that for a hemisphere of two meters in diameter.

Field strength around rod electrode :
The field strength on the surface of the soil, according to figure 3.10 is

$$E = \frac{dV}{dx} = \frac{dV}{d\beta}\frac{d\beta}{dx} \qquad 3.12$$

where the angle β is introduced as a variable. It is correlated to x by

$$\tan\beta = \frac{x}{l}, \quad so$$

$$\frac{dx}{d\beta} = \frac{1}{\cos^2\beta} \qquad 3.13$$

Differentiation of equation 3.7 with respect to β and substitution of equation 3.13 gives the field strength

$$E = \frac{\rho I}{4\pi l}\,\frac{2}{\sin\beta}\,\frac{\cos^2\beta}{l} = \frac{\rho I}{2\pi l}\cos\frac{\beta}{x} \qquad 3.14$$

which is decreasing both with increased x and β.
For large distance x , $\cos\beta = l/x$, approximately, and the field strength

$$E_x = \frac{\rho I}{2\pi x^2} \qquad 3.15$$

becomes identical with that for a hemisphere. For small x, however, $\cos\beta \approx 1$, and the field strength

$$E_x = \frac{\rho I}{2\pi l x} \qquad 3.16$$

becomes much larger than for a hemisphere. This is due to the high concentration of the current around the small circumference of a rod. Along the length of the rod the density of the current from rod to earth is nearly constant, but actually increases at the bottom to about double the value at the centre plane [9], due to the point effect of the end of the rod.

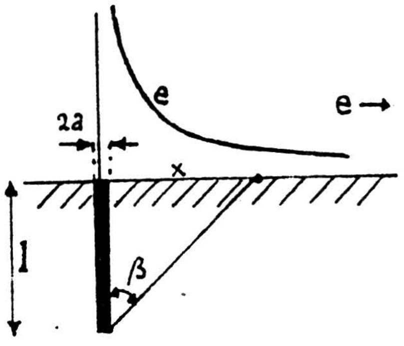
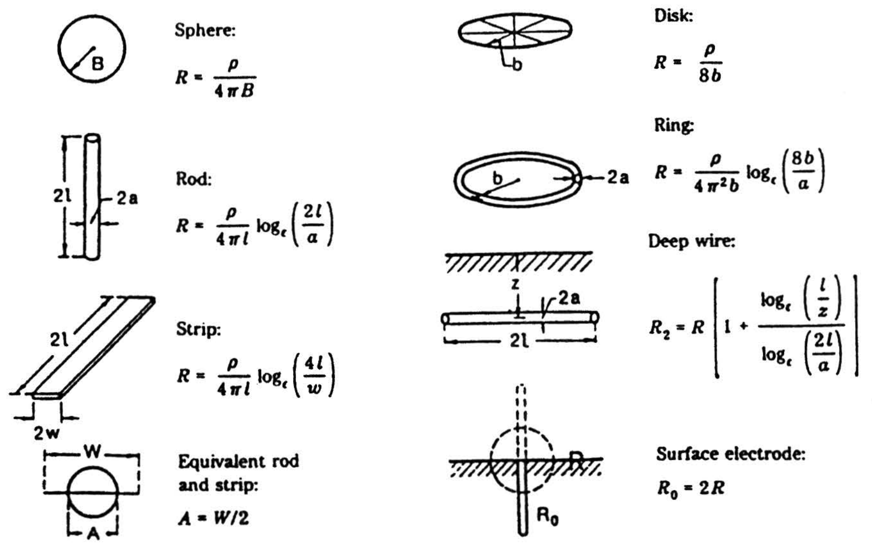


Figure 3.10 Field strength on the surface around a current driven rod

In a similar way the potential and the ground resistance of other forms of electrodes can be derived by superposition of spherical or cylindrical elements. The resistance of a ground electrode near the surface of the earth is always twice that of the resistance of that electrode at greater depth, because the distribution of the current through the upper semi-space is cut off. Table 3.3 gives a survey of some simple forms of deep driven ground electrodes. The flat strip follows a relation quite like that of a circular rod and a strip thus is equivalent to a rod or a wire of diameter equal to half the width of the strip.
The resistance of a ring of wire, having a periphery $2\pi b$, is only slightly greater than that of a straight wire of length $2l = 2\pi b$, the increase being due to the absence of the ends of the rod with their higher current density.
As all the equations show, the resistance is determined mainly by the largest dimension of the electrode and only to a minor extent by the smaller dimensions, like cross section or thickness. Thus the surface of the electrode is unimportant and only the linear extension matters.

Table 3.3 Resistance of simple forms of deep driven ground electrodes [9]



In practice multiple driven rods in circles, triangles, squares and grounding grids are utilised for proper earthing of distribution transformers. In substations and possibly at the isolation transformer of the SWER spur line, grounding mats can be considered. A typical ground mat consists of conductors placed 1.5 to 6 m apart. The ground mat can include many parallel conductors. It is buried in the soil at a depth varying from 0.50 to 1.5 m [24]. The mat resembles in this way a plate with its distance to the surface of the soil much smaller than its dimensions. Studies of the resistance of ground mats show that the most important parameter that determines the resistance is the area covered by the mat. The shape of the ground mat (square, rectangular, etc.) is of secondary importance. thus as a first approximation, it can be claimed that the resistance of a ground mat approximately equals the resistance of a disk near the soil surface which has an area equal to the area of the ground mat [24]. Assuming that the area of the ground mat is A and the radius of the disk is b, $b = (A/\pi)^{1/2}$. From table 3.3 we cab see that the resistance of a disk **near the soil surface (2 times greater)** is $R = \rho/4b$. Upon substitution, the approximate resistance of a ground mat of area A is [24]

$$R = \frac{\rho\sqrt{\pi}}{4\sqrt{A}}$$

This equation is, however, an approximate one an alternative formulae are possible. It can be used by a preliminary design of grounding systems.

Step voltage near the substation [2]

Public safety aspect of soil currents in the vicinity of the earthing electrodes with respect to humans in case of a ground fault and the continuous load current, if the SWER system is utilised. I will describe the calculation and criteria of **step voltages** ***(the difference in surface potential experienced by a person bridging a distance of 1 m between his/her feet without contacting any other grounded object)*** caused by a soil current. The restriction to this aspect of the acceptable potential difference for humans, in the vicinity of the substation, is due to the fact that other aspects relating to the acceptable potential difference are appearing in the direct surrounding and in specific situations at a substation where the general public is not allowed.
The other aspects of the acceptable potential difference for humans are [2] :

(1) **the ground potential rise (GPR)** - the maximum voltage that a station grounding grid may attain relative to a distant grounding point assumed to be at the potential of remote earth, which can only be calculated when the grounding grid resistance is known;
(2) **touch voltage**, the potential difference between the ground potential rise (GPR) and the surface potential at the point where a person is standing, while at the same time having his hands in contact with a grounded structure;
(3) **mesh voltage**, the maximum touch voltage to be found within a mesh of a ground grid;
(4) **transferred voltage**, a special case of the touch voltage where a voltage is transferred into or out of the substation.

Item 4 will be dealt with in the discussion of the effects on conducting structures and telephone-lines existing in the vicinity of the grounding grid.

Effect of frequency :

- humans are very vulnerable to the effects of electric current at frequencies of 50 or 60 Hz. Currents of approximately 0,1 A can be lethal;
- authorities generally agree that the human body can tolerate a slightly higher 25 Hz frequency and approximately a five times higher direct current (DC);
- at frequencies of 3 kHz - 10 kHz, even higher currents can be tolerated[2]. In some cases the human body is able to endure very high currents due to lightning surges

<u>Effects of magnitude and duration [2]</u> :

The most common physiological effects of electric current on the body, in order of increasing magnitude, are perception, muscular contraction, unconsciousness, fibrillation of the heart, respiratory nerve blockage and burning[3]	
Current of 1 mA	these currents are generally recognized as the threshold of perception, that is, the current magnitude at which a person is just able to detect a slight tingling sensation in his hands or fingertips caused by the passage of current[4]
Currents of 1 - 6 mA	these currents are often termed as let-go currents, though unpleasant to sustain, generally do not impair the ability of a person holding an energized object to control his muscles and release it. Dalziel's classic experiment provides data indicating an average let-go current of 10.5 mA for women and 16 mA for men, and 6 mA and 9 mA as the respective threshold values.[5]
Currents of 9 - 25 mA	in this range the currents may be painful and can make it hard to impossible to release energized objects hold by the hand. For still higher currents muscular contraction could make breathing difficult. Unlike the cases of respiratory inhibition from the much greater current mentioned next, these effects are not permanent and disappear when the current interrupted - unless the contraction is very severe and breathing is stopped, not for seconds but for minutes.
Currents of 60 - 100 mA	If this current magnitude is reached ventricular fibrillation, stoppage of the heart or inhibition of respiration might occur and cause injury or death.

[2] Dalziel, C.F., and Mansfield, T.H., Effect of frequency on perception current. AIEE Transactions, vol 69, 1950, pp 1161 - 1168.
Dalziel, C.F., Ogden, E., and Abbot, C.E., Effect of frequency on let-go currents, AIEE Transactions, vol 62, Dec 1943, pp 745 - 750.
[3] Geddes, L.A., and Baker, L.A., *Response to passage of electric current through the body*, Journal of Association for the Advancement of Medical Instruments, vol 2, Feb 1971, pp 13 -18
[4] Dalziel, C.F., *Effect of wave form on let-go currents*, AIEE Transactions, vol 62, 1943, pp 739 - 744.
[5] Dalziel, C.F., and Massogla, F.P., *Let-go currents and volt-voltages*, AIEE Transactions, vol 75, part II, 1956, pp 49-56.

If shock currents can be kept below the value of the fibrillation threshold by a carefully designed grounding system, injury or death may be avoided. The magnitude and the duration of the current that flows through the human body at 50 Hz should be less than those that cause ventricular fibrillation, stoppage of the heart or inhibition of respiration. The duration for which the current can be tolerated by most people is related to its magnitude. It will however not occur until current magnitudes in the range of 60 - 100 mA are reached. As shown by Dalziel, the non-fibrillating current of magnitude I_B at durations ranging from 0.03 - 3.0 seconds is related to tolerable body current as described by the following equation :

$$(I_B)^2 t_s = S_B \qquad 3.17$$

where

I_b	=	root mean square (rms) magnitude of the current through the body;
t_s	=	duration of the current exposure in seconds;
S_b	=	empirical constant related to the electric shock tolerated by a certain percent of a given population.

Based on results of Dalziel's studies, it is assumed that 99.5% of all persons can safely withstand, without ventricular fibrillation, the passage of a current in magnitude and duration determined by the above equation where in addition to the terms previously defined, for equation 3.17

$$k = \sqrt{S_B} \qquad 3.18$$

Dalziel found that the body current that can be survived by 99.5 % of persons weighing approximately 50 kg results in a value of S_b of 0.0135. Dalziel's studies in 1968, on which equation 3.17 is based lead to different value of S_b = 0.0246 as being applicable for persons weighting 70 kg. Thus, k_{50} = 0.116 and k_{70} = 0.157 and the formulae for the allowable body current becomes

$$I_B = \frac{0,116}{\sqrt{t_s}} \quad \textit{for 50 kg body weight} \qquad 3.19$$

$$I_B = \frac{0,157}{\sqrt{t_s}} \quad \textit{for 70 kg body weight} \qquad 3.20$$

The above equations results in values of 116 mA for 1 sec. and 367 mA for 0.1 sec for a person weighing 50 kg and in values of 157 mA for 1 sec. and 496 mA for 0.1 sec. for a person weighing 70 kg. Since equation 3.17 is based on tests limited to a 0.03 - 3.0 sec range, it is not valid for very short or long times, and some current can be tolerated indefinitely [2].

Resistance of the human body

For direct current (DC) and alternating current (AC) at normal power frequency, the human body can be represented as by a non-inductive resistance. The resistance of the human body is taken between extremities, i.e. from one hand to both feet, or from one foot to the other. In either case the value of this resistance is difficult to be found. The resistance of the internal body tissues, not including skin, is approximately 300 Ω, whereas values of body resistance including skin, ranging from 500-3000 Ω, have been suggested in the literature[6] For the purpose of the description of the danger of step voltages for humans in the vicinity of the earthing electrodes the following assumptions are made ;

1 - Hand and shoe contact resistances will be assumed as equal to zero;

2 - A value of 1000 Ω is selected for the calculations that follow as representing the resistance of a human body from hand-to both-feet and also from hand-to-hand, or from one foot to the other.

$$R_b = 1000\ \Omega \qquad 3.21$$

Equations for evaluation of body current due to voltage gradients at the soil surface.
In this paragraph a procedure to determine the electric current that will flow through a human body due to step voltages (see fog. 3.11). In the figure the person is standing in the vicinity of a substation grounding mat. The procedure for the calculation of body currents consists of computing a Thévenin equivalent circuit connected to the points of contact of the person with the ground field. The equivalent circuit consists of the equivalent voltage source (V_{eq}) and the resistance of the ground just beneath the feet, equivalent resistance (R_{eq}) and the human body resistance (R_b). The voltage source (step voltage) equals the open circuit voltage, in this case the voltage between points A and B if the person is not touching. The equivalent internal resistance between the points of contact can be accurately computed with numerical techniques[7]

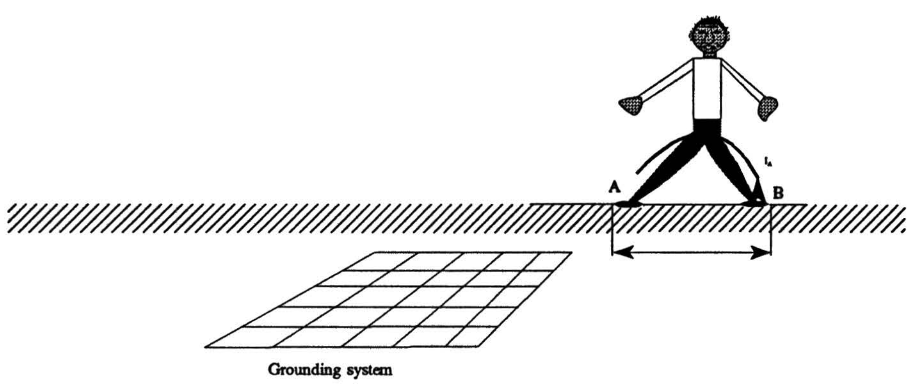


Figure 3.11 Situation of a person in the vicinity of a grounding system

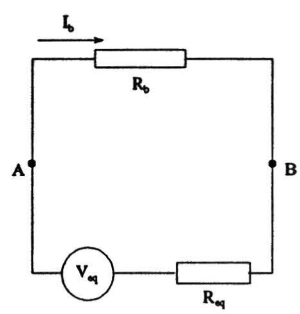


Figure 3.12 Equivalent Thévenin scheme

I_a	=	current through the accidental circuit;
R_{eq}	=	equivalent resistance
R_b	=	body resistance
R_a	=	total effective resistance of the accidental circuit = $R_b + R_{eq}$;
V_{eq}	=	equivalent voltage source (V_{step})

Resistance of the accidental circuit R_a is a function of the body resistance R_b and the footing resistance R_{eq}. The equivalent resistance may affect appreciably the value of R_a, a fact that may be most helpful in some difficult situations. For the purpose of circuit analysis, the human foot is usually represented as a conducting metallic disk and the contact resistance of shoes and socks is neglected. The resistance of a disk to remote earth on the surface is equal to (see Table 3.3)

$$R = \frac{\rho}{4\,b}$$

[6] Dalziel, C.F., *Dangerous electric current*, AIEE Transactions, Vol 65, 1946, pp 579-585, 1123-1124.
Geddes, L.A., and Baker, L.E., *Response to passage of electric current through the body*, Journal of Association for Advancement of Medical Instruments, vol 2, Feb 1971, pp 13-18.
Geiges, K.S., *Electric shock hazard analysis*, AIEE Transactions, vol. 75, part III, 1956, pp 1329-1331.
Kiselev, research into electric shock, Electrical review, vol 31, Dec. 1965.
Osypka, P., *Quantitative investigations of current strength and routing in AC electrocution accident involving human beings and animals*, Technische Hochschule Braunschweig, West Germany, 1966/SLA.
Sunde, E.D., *Earth conduction effects in transmission systems*, New York, McMillan, 1968.

[7] Meliopoulos, A.P., Webb, R.P., and Joy, *Analysis of Grounding Systems*, IEEE Transactions on Power Apparatus and Systems, Vol. PAS102, No. 2, pp. 1039 - 1048, march 1981.

where, ρ is the soil resistivity and b the radius of the disk. The human foot is in reality not a disk. However, it has been observed with scale models and numerical studies that the area in touch with the foot is the determining variable. For this reason, b can be approximated with

$$b = \sqrt{\frac{A}{\pi}}$$

Where A is the area of the foot in touch with the earth. For an adult with large feet, the area A of the person's feet is approximately 200 cm^2. Thus the value of b is computed to be

$$b \cong 0.08\,m$$

In this case the resistance of one foot touching the soil surface is

$$R_{foot} = \frac{\rho}{(4)(0.08)} \cong 3\rho \; ohms \qquad 3.22$$

where ρ is inn Ω.m. Thus approximately the R_{eq} of Figure 3.9 is $3\rho + 3\rho = 6\rho$

If the Thévenin equivalent circuit has been computed (see Fig 3.12), the electric current through the body is computed from

$$I_b = \frac{V_{eq}}{R_{eq} + R_b} \qquad 3.23$$

Criteria related to the step voltage.

The safety of a person depends on preventing the critical amount of shock energy from being dissipated by the body before the fault is cleared and the system de-energized. The maximum driving voltage of any accidental circuit should not exceed the limits defined below. For the step voltage the limit is :

$$V_{step} = (R_b + R_{eq})I_b \qquad 3.24$$

Combining equations 3.17 and 3.19, 3.20 :

$$V_{step50} = (1000 + R_{eq})\frac{0.116}{\sqrt{t_s}} \qquad 3.25$$

or

$$V_{step70} = (1000 + R_{eq})\frac{0.157}{\sqrt{t_s}} \qquad 3.26$$

the actual step voltage V_s, should be less than the maximum allowable step voltage, V_{step}, to ensure safety. The following example gives an illustration of the computations:

Assume a spherical grounding electrode with a current, entering the soil, of ***50 A***. A person is standing at a distance of ***5 m*** from the electrode and the space between A and B is ***1 m*** and a soil resistivity ρ of

300 Ω.m :

The R_{eq}, V_{eq} and I_b has to be computed, V_{eq} is derived by equation 3.3 :

$$R_{eq} = 6\rho = (6)(300) = 1800\ ohm$$

$$V_{eq} = V_B - V_A = \frac{\rho I}{2\pi}\left[\frac{1}{r} - \frac{1}{6}\right] - \frac{\rho I}{2\pi}\left[\frac{1}{r} - \frac{1}{5}\right]$$

$$= \frac{\rho I}{2\pi}\left[\frac{1}{5} - \frac{1}{6}\right] = \frac{(300)(50)}{2\pi}\left[\frac{1}{30}\right] \cong 80V$$

$$I_b = \frac{V_{eq}}{R_{eq} + R_b} = \frac{80}{1800 + 1000} \cong 29mA$$

The maximum duration of the current computed above can be derived according to equation 3.19 and 3.20 :

$$t_{s\ 50kg} = \frac{((1000 + R_{eq})\ 0.116)^2}{V_{eq}^{\ 2}} \qquad 3.27$$

$$= \frac{((1000 + 1800)0.116)^2}{(80)^2} \cong 16s$$

$$t_{s\ 70kg} = \frac{((1000 + R_{eq})\ 0.157)^2}{V_{eq}^{\ 2}} \qquad 3.27$$

$$= \frac{((1000 + 1800)0.157)^2}{(80)^2} \cong 30s$$

Effects of transferred and induced voltages on conducting structures
While with the SWER system a continuous current flows into the soil which is not perfectly conducting, a potential differences may be generated between two grounded points. This affects the conducting structures or other grounding points in the subsoil in the vicinity of the earthing system. This is an effect of transferred voltage.
Due to the changing magnetic field, generated by the alternating current flowing through a power line, a current can be induced in conducting structures nearby the power line. In the case of a telephone line suspended on the same poles as the power line, a current will be induced in the shield wire(s), disturbing the useful signal.
In the case of three-phase systems transferred (and induced) voltages are of concern only during fault and unbalanced conditions. In single-phase systems, with a neutral conductor, transferred (and induced) voltages are of concern, only during fault conditions.
In this paragraph I will describe the effect of induced voltage on telephone lines and the means of protection [24].

Communication circuits can be affected in two ways, (1) induced voltages on these circuits by the load current of the power line(s), causing noise and possible miss-operation, or (2) voltages may be transferred by conduction to communication circuits, which can cause interference problems or damage of communication equipment. In figure 3.13 the two situations are illustrated, where P are the protection blocks and the station can either be a isolation transformer in the case of a SWER system or a substation of a main distribution grid.

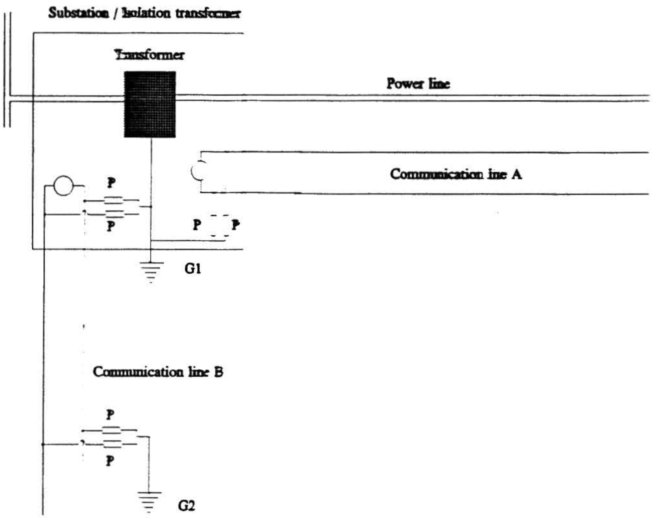


Figure 3.13 Illustration of the two mechanism which communication lines can be interfered

Communication line A, which is parallel to the power line, is subjected to a voltage induced from the currents of the power line. Induced voltages are mitigated by transposing the communication circuit. The second communication line (B), may be subjected to a voltage equal to the difference in the ground potential rise at the two grounding points G_1 and G_2. In general, communication circuits must be protected against transferred or induced voltages.

To describe the means of protection, the following situation is under consideration :
The telephone lines are suspended on the same poles as the power line, the circuit is connected to the substation or isolation transformer grounding system on one side and with the distribution transformers grounding system at the other end through protector blocks.

Three-Phase Three Wire system
In normal operation, almost balanced three-phase currents flow through the power line. The voltage induced on the communication line from each of the phase currents is approximately of the same magnitude. The phase difference between any two is 120°. The total induced voltage is thus approximately zero (in a symmetrical configuration) [24]. The potential rise at the two grounding points, G_1 and G_2 (see Fig. 3.13), is small. Therefore the voltage transferred to the communication circuit is practically zero.
During unbalanced situations the induced voltage may be substantial and at the same time also the potential rise at G_1 and G_2. This results in a substantial induced as well as transferred voltage on the communication circuit.

During fault conditions the currents flowing through the power line and in some situations (short circuits at distribution or substation) the earthing systems (G_1 and G_2) can have high values, although only for a small period of time. Thus the induced and transferred voltages can reach high values which could damage communication equipment

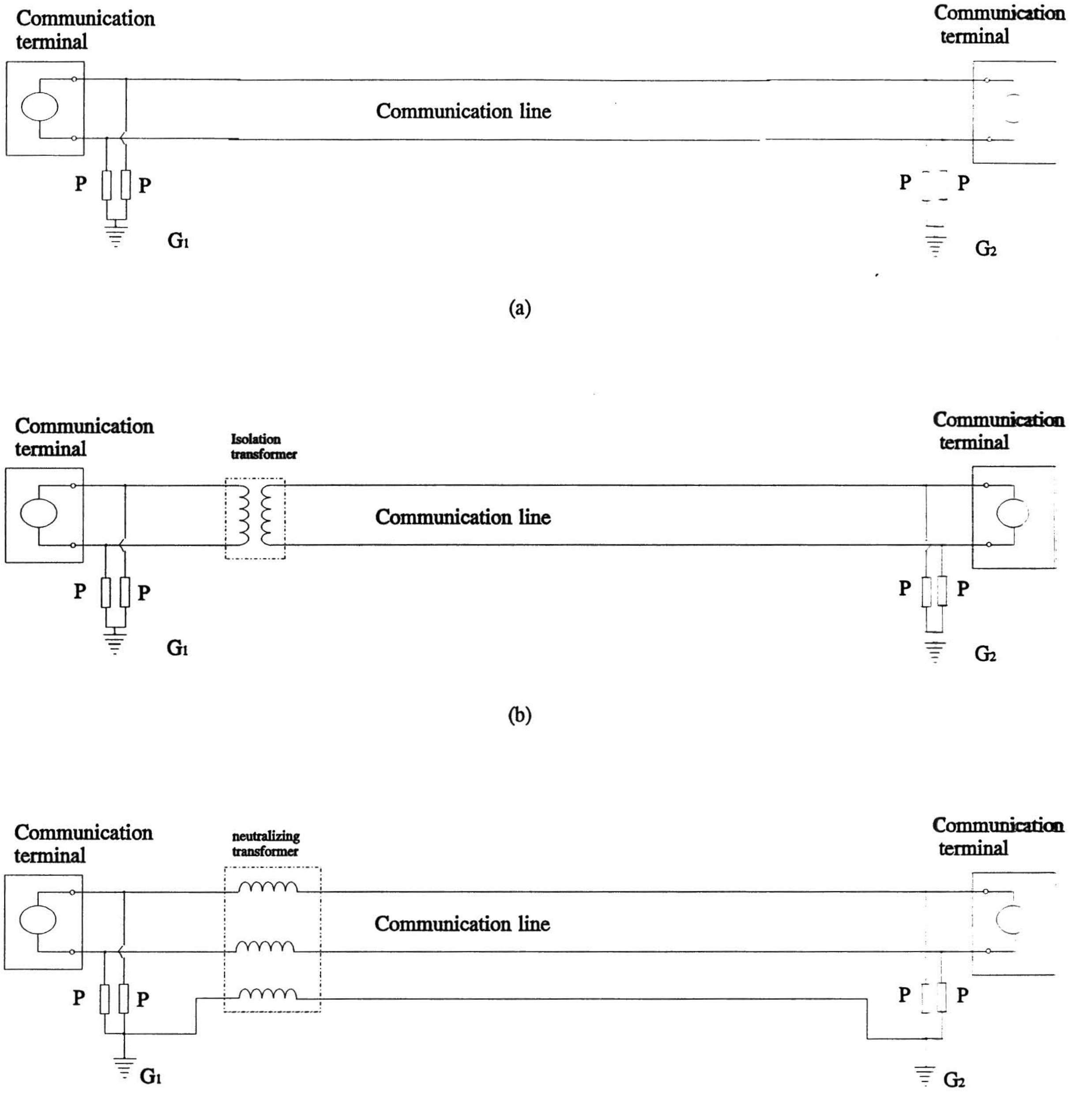
Single-Phase Two Wire system
In normal operation the current through the power line will not induce a voltage on the communication circuit, the current in one conductor is of opposite direction in the second conductor and of the same magnitude. The effect of the currents neutralize each other in a symmetrical configuration. The transferred voltage is approximately zero while no current will flow through the earthing systems at G_1 and G_2, in this situation.
During fault conditions the current through the power line can reach high values inducing high voltages on the communication circuit, even as the current passing through G_1 and G_2, resulting in a substantial transferred voltage. The transferred and induced voltages contribute to the voltage rise on the communication circuit in this situation.

Single Wire Earth Return system
Under normal conditions the current flowing through the power line will induce a voltage on the communication circuit, depending on the load current. The load current is flowing through the grounding system at G_1 to G_2 and this will give rise to a potential difference between these two points, which adds to the induced voltage on the communication circuit.
During fault conditions it is the same as with the single phase Two Wire system.

Selection of the protection depends on the expected level of over voltages during all probable adverse conditions. In particular, the protection scheme should be able to withstand the maximum voltage that may develop between the points G_1 and G_2.
Typical protection schemes are illustrated in Figure 3.14 [24].

- a - this involves protector blocks only, it provides protection for voltages up to approximately 300 V;
- b - this scheme involves protector blocks and an isolation transformer. It is capable of providing protection against much higher voltages, depending of the insulation level of the isolation transformer;
- c - this involves protector blocks and a neutralizing transformer. The neutralizing transformer is a three-winding transformer. The third winding will carry the electric current proportional to the potential difference between G_1 and G_2, which will insert a voltage on the communication circuit approximately equal but of opposite polarity (neutralizing voltage) of the voltage developed across the communication circuit.

Scheme ***b*** is simple, effective and relatively inexpensive and can in my opinion be used with the two and three wire distribution systems. Scheme ***c*** is more appropriate for the SWER distribution system as the consequences of the continuous current through the soil are neutralized and the protector blocks can protect the communication circuit of the induced voltage



(c)
Figure 3.14 Three possible communication line protection schemes

The effects on pipelines can be evaluated by the transferred voltage, which is imposed on the conducting structure, under influence of the soil current.

Heating of the ground

When a ground electrode is to be loaded continuously, or even for a short time only, the **temperature rise** of the soil θ_{rise} must be considered in order to avoid an overloading which might evaporate the moisture in the ground. The current density around a spherical electrode with radius r embedded in the soil varies over the distance x as

$$J = \frac{I}{4\pi x^2} \qquad 3.28$$

indicated in figure 3.10. Thereby an amount of heat ρJ^2 is produced in every volume element, which may be considerable because of the high value of the resistivity ρ. The heat is partly stored in the volume elements of the soil which have an average specific heat $\gamma \approx 1.75 \cdot 10^6$ *Ws/m³ °C* and, partly conducted from higher to lower temperature within the soil, the average heat conductivity being $\lambda \approx 1.2$ *W/m°C* . Although these two thermal constants of the soil are of major significance, their actual values seldom have been measured accurately.

The differential equation of the radial heat conduction about a sphere is

$$\gamma\frac{d\theta}{dt} - \frac{\lambda}{x}\frac{d^2(x\theta)}{dx^2} = \rho J^2 \qquad 3.29$$

It is difficult to obtain a general solution of this equation since J varies with x. However we can discuss two interesting phases of the heating process, giving particular integral's, namely the steady state and the short-time state.

steady state :

For continuous ground currents the time derivative in equation 3.28 vanishes, and the differential equation becomes

$$\lambda\frac{d^2(x\theta_{rise})}{dx^2} + \rho J^2 x = \lambda\frac{d^2(x\theta_{rise})}{dx^2} + \left(\frac{I}{4\pi}\right)^2\frac{1}{x^4}x\rho =$$

$$\lambda\frac{d^2(x\theta_{rise})}{dx^2} + \left(\frac{I}{4\pi}\right)^2\frac{\rho}{x^3} = 0 \qquad 3.30$$

With two integrations the solution for the temperature distribution over distance x becomes

$$\frac{d^2(x\theta_{rise})}{dx^2} = -\frac{\rho}{\lambda}\left(\frac{I}{4\pi}\right)^2\frac{1}{x^3}$$

$$\frac{d(x\theta_{rise})}{dx} = \frac{1}{2}\frac{\rho}{\lambda}\left(\frac{I}{4\pi}\right)^2\frac{1}{x^2} + C_1$$

$$x\theta_{rise} = -\frac{1}{2}\frac{\rho}{\lambda}\left(\frac{I}{4\pi}\right)^2\frac{1}{x} + C_1 x + C_2$$

$$\theta_{rise} = -\frac{1}{2}\frac{\rho}{\lambda}\left(\frac{I}{4\pi}\right)^2\frac{1}{x^2} + C_1 + \frac{C_2}{x}$$

With two boundary conditions the constants C_1 and C_2 can be determined. At $x \rightarrow \infty$ $\Theta_{rise} = 0$ and at the surface of the electrode $x \rightarrow r$ $\Theta_{rise} = maximal$, *thus* $(\Delta\, \Theta_{rise}/\Delta\, x) = 0$

$$\theta_{rise,x} = -\frac{1}{2}\frac{\rho}{\lambda}\left(\frac{I}{4\pi}\right)^2\frac{1}{x^2} + C_1 + \frac{C_2}{x}$$

$$\theta_{rise,x\rightarrow\infty} = 0 + C_1 + 0 = 0$$

thus,

$$C_1 = 0$$

$$\left(\frac{\delta\,\theta_{rise}}{\delta x}\right)_{x=r} = \frac{1}{2}\frac{\rho}{\lambda}\left(\frac{I}{4\pi}\right)^2\frac{1}{r^3} - \frac{C_2}{r^2} = 0$$

thus,

$$C_2 = \frac{1}{2}\frac{\rho}{\lambda}\left(\frac{I}{4\pi}\right)^2\frac{1}{r}$$

The solution for Θ_{rise} becomes then

$$\theta_{rise,x} = \frac{\rho}{\lambda}\left(\frac{I}{4\pi}\right)^2\frac{1}{x}\left[\frac{1}{r} - \frac{1}{2x}\right] \qquad 3.31$$

which is plotted against x in figure 3.10. The maximum soil temperature at the electrode with $x = r$ is

$$\theta_{\max,x=r} = \theta_{rise,r} + \theta_{ambient}$$

$$\theta_{\max,x=r} = \frac{1}{2}\frac{\rho}{\lambda}\left(\frac{I}{4\pi r}\right)^2 + \theta_{ambient} \qquad 3.32$$

and depends only on the three constants ρ, $\theta_{ambient}$ and λ of the ground and on the linear current density I/r.

The admissible current to ground from the spherical electrode is therefore

$$I_{\max} = 4\pi r \sqrt{2\frac{\lambda}{\rho}(\theta_{\max,x=r} - \theta_{ambient})}$$

$$where \quad \theta_{\max,x=r} - \theta_{ambient} = \theta_{rise} \quad so, \qquad 3.33$$

$$I_{\max} = \frac{l}{R}\sqrt{2\rho\lambda\theta_{rise}}$$

here the right hand term is obtained by substituting the resistance $R = \rho/(4\pi r)$. The current-carrying capacity of the electrode is thus determined, in addition to the soil constants, by resistance and permitted temperature rise θ_{rise} only.

Since the heat flow and the current distribution around an electrode of any shape follows the same mathematical law, namely Laplace's differential equation, the right hand expression of equation 3.33 is valid not only for spherical electrodes but for any shape of electrode whether it be a rod, a ring, a disk, or a more complicated form (with the condition that V = 0 when r → ∞). Therefore, if the resistance of the electrode is known, which differs with the shape (see table 3.2), the continuous current-carrying capacity can be determined easily.

If we take, for example, a driven rod of length l = 6 meter, and radius a = 2.5 cm, a maximum temperature of 65 °C, meaning a *θrise* of 40 °C (assuming *θambient* of 25 °C, average in Tanzania [13]) and varying the soil resistivity ρ from *100 Ω.m* to *600 Ω.m*, the following permissable currents, I_{max} are obtained.

I_{max} = 6.7 A	(ρ = *100 Ω.m*)	I_{max} = 3.4 A	(ρ = *400 Ω.m*)
I_{max} = 4.8 A	(ρ = *200 Ω.m*)	I_{max} = 3.0 A	(ρ = *500 Ω.m*)
I_{max} = 3.9 A	(ρ = *300 Ω.m*)	I_{max} = 2.8 A	(ρ = *600 Ω.m*)

The voltage at the ground electrode, measured from the metal to a far distant point is, from the last term of equation 3.38.

$$V_{\max} = IR = \sqrt{2\rho\lambda\theta_{rise}} \qquad 3.39$$

Besides the soil constants, V_{max} at which the maximum temperature rise occurs, is coupled to the temperature rise in the steady state. Conversely, the voltage applied to a ground electrode determines the steady state temperature. These conclusions are true for any shape of electrode.

As an example , for θ_{rise} = 40°C in moist soil,

$$V_{max} = (2\ 10^2\ 1.2\ 40)^{1/2} = 98\ Volts$$

This voltage must not be surpassed if that temperature rise is not to be exceeded.

The admissible current density at the surface of the ground electrode, where the highest temperature exists, determined for a spherical electrode from equation 3.38 is

$$J = \frac{I}{4\pi r^2} = \frac{l}{r}\sqrt{2\frac{\lambda}{\rho}\theta} \qquad 3.35$$

for the former example, where a rod was used to calculate the admissible current, the equivalent radius r is, using table 3.3

$$R_{sphere} = \frac{\rho}{4\pi r}$$

if this is equated to the resistance of a driven rod, then

$$\frac{\rho}{4\pi r} = \frac{\rho}{4\pi r}\ln\left(\frac{2l}{a}\right)$$

$$r = \frac{l}{\ln\left(\frac{2l}{a}\right)}$$

so,

$$J_{max}(\rho = 100\,ohm.m) = \frac{1}{1.8}\sqrt{2\left(\frac{1.2}{100}\right)40} = 0.53A/m^2$$

Thus the **current density** permitted for continuous loading of the electrode in this example is fairly small. The soil surrounding the electrode must not heat up to temperatures which lead to the complete evaporation of the moisture while the current would then be interrupted by the enormous increased resistance.

Short-time heating :
For the short-time loading of the ground electrode the second member of equation 3.29, the heat conduction term, plays only a minor role and thus may be neglected. The remaining differential equation then becomes

$$\frac{d\theta}{dt} = \frac{\rho}{\lambda}J^2 \qquad 3.36$$

If resistivity ρ and specific heat λ are constant, the temperature rise is linear in time, and thus the admissible current density is

$$\theta_{max} = \frac{\rho}{\lambda}J^2_{max}t + \theta_{ambient}$$

$$J_{max} = \sqrt{\frac{\lambda}{\rho}\frac{(\theta_{max} - \theta_{ambient})}{t}} \qquad 3.37$$

the temperature rise thus follows the same law as with ordinary linear conductors. Because the length dimension x does not appear in equation 3.28, this differential equation is true for every volume element of the soil, independent of the pattern of flow of the current. Hence equation 3.42 is valid for any shape of the ground electrode.
For example, an electrode in moist soil and for a θ_{rise} not exceeding 40 °C is permitted to be loaded over a period of 100 seconds by a current density

$$J = ((1.75\ 10^6)/100\ \ 40/100)^{1/2} = 84\ A/m^2$$

which is a fairly high value. For sandy soils with ten times higher resistivity a short-time loading at the same current density is permitted for ten seconds only. Higher current density or longer loading period would evaporate the moisture of the soil in a very short time.

The voltage at the electrode with short-time loading may attain a very high value. In the example for moist soil, the voltage is higher than in the steady state example by the ratio of the current densities and, therefore, it reaches here the value

$$V_{max} = 98 \cdot 84/0.53 = 15.5\ kV$$

which is a purely theoretical value that in practice can not be reached while the necessary current can not be supplied.

The initial rise of temperature over a short time as given by the equation 3.36 is shown in figure 3.15. The final temperature rise, with fixed constants of the soil, would be given by the equation 3.32, and also is indicated in figure 3.15. The intermediate curve follows the complete differential equation 3.29 but is difficult to derive analytically. However, we can easily determine the time constant τ, defined as the time in which the linear initial rise would reach the steady-state temperature, see figure 3.15. For this intersection we have, with use of equations 3.32 and 3.36 and substitution in the former the current density for the current

$$\theta_{rise[3.32]} = \frac{1}{2}\frac{\rho}{\lambda}\left(\frac{J 4\pi r^2}{4\pi r}\right)^2 = \frac{1}{2}\frac{\rho}{\lambda} r^2 J^2 \qquad \theta_{rise[3.36]} = \frac{\rho}{\gamma} J^2 \tau \quad so, \qquad 3.38$$

$$\frac{1}{2}\frac{\rho}{\lambda} r^2 J^2 = \frac{\rho}{\gamma} J^2 \tau$$

Hence the time constant of heating for a spherical ground electrode and its surrounding soil is

$$\tau = \frac{1}{2}\frac{\gamma}{\lambda} r^2 \qquad 3.39$$

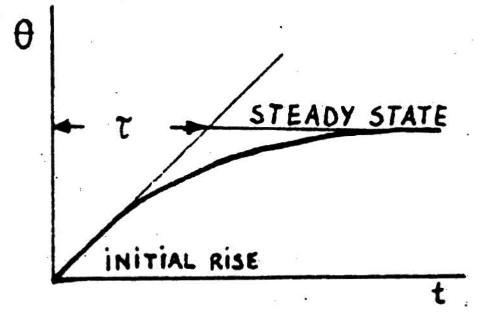


Figure 3.15 Change with time of the ground temperature

In addition to the thermal constants of the soil, τ is dependent only on the square of the radius r. For other forms of electrodes the time-constant follows a similar form except instead that of r another characteristic dimension of the electrode must be used, being somewhere between the maximum and minimum dimensions of the electrode.

For example, for a rod with equivalent radius $r = 1.8$ meter the time constant is

$$\tau = 1/2 \quad 1.75 \cdot 10^6/1.2 \quad 1.8^2 = 2.36 \cdot 10^6\ sec. = 27.3\ days$$

This is a very long period, due to the very low heat conductivity of the soil.

Improvement of soil conductivity around electrodes

It is possible to improve the conductivity of soil around earth electrodes locally by injection of electrolytes such as common salt or sodium carbonate. The resistance of the connection first begins to fall as the salt diffuses into the ground and finally increases again after water has carried the salt away from the electrode.

The time the treatment is effective varies with the permeability of the soil. In many cases it may attain or exceed ten years. On the other hand, it is almost zero when there is an appreciable flow of underlying water or when the ground is very porous.

The diffusion of the salt can be retarded by various means. For example, by using insoluble gels as electrolytes (a system tested by M. Ducrot in 1944 and taken up again in Sweden by M. Sanick).

For the injection of salts to have an appropriate effect on the resistance, the area of ground treated must be large as compared to the main dimensions of the electrodes. Reduction in resistance will be considerable with a rod of small size or plate, but the method will be of no benefit for improving the earthing arrangements of large stations.

Common salt accelerates the corrosion of electrodes, but to an extent which is not serious if copper or soft steel is used. The latter should not be applied with salt, however, in chalky soils.

Another means of improving earth's conductivity consists of surrounding the electrodes with a bed of coke, or better still with wood charcoal, which is distinctly less corrosive.

It should be mentioned that these conducting beds do not, as a rule, increase the largest dimensions of the electrodes to a great extent, so that their effect on resistance is often poor. They also make it necessary to increase the diameter of the excavations, when using rods, and it is then less expensive to increase the number of small cross-section rods. On the other hand, they have the advantage of reducing seasonal variations in resistance at the same time as they increase the current that the electrodes can carry without the ground being heated dangerously.

Another possibility to improve the conductivity of the soil in the vicinity of the electrodes, is the use of bentonite, a natural clay containing the mineral montmorillonite, which was formed by volcanic action years ago. It is non corrosive, stable and has a resistivity of 2.5 Ω.m, at 300% moisture. The low resistivity results mainly from an electrolytic process between water, Na_2O (soda), K_2O (potash), CaO (lime), MgO (magnesia) and other mineral salts that ionize forming a strong electrolyte with ph ranging from 8 - 10. Unlike a salt bed, this electrolyte will not gradually leach out, as it is part of the clay itself. Provided with a sufficient amount of water, it swells up to 13 times its dry volume. and will adhere to nearly any surface it touches. If exposed to direct sunlight, it tends to seal itself off, preventing the drying process from penetrating deeper.

Due to its hygroscopic nature, it acts as a drying agent drawing any available moisture from the surrounding environment. Bentonite needs water to obtain and maintain its beneficial characteristics. Its initial moisture content is obtained at installation when the slurry is prepared. Once installed, bentonite relies on the presence of soil moisture to maintain its characteristics. Most soils have sufficient soil moisture so that drying out is not a concern. The hygroscopic nature of bentonite will take advantage of the available water to maintain its *as installed* condition. However, for the same reason it will not function well in a very dry environment. In dry soils it will not be able to maintain its moisture content and it will shrink away from the electrode, increasing the electrode resistance. When sufficient soil moisture is available, this limitation disappears and bentonite is an excellent backfill material that allows a substantial reduction of the resistance of ground rods in highly resistive soils [8].

3.3.3 Extended zone of influence (area between entrance and exit electrode

Up to now only the effects in the direct surrounding of the substation and distribution stations is discussed, the effects of resistivity without the consideration of any inductive action of the current flowing into the ground. These derivations are true for direct current (DC) and equally valid for alternating current (AC) in the vicinity of the electrodes. In this area the action of the changing magnetic fields is negligible compared with the effect of the high resistivity of the soil. Only for extreme rapid change with time this may be modified.

If ground currents flow over a long distance between entrance and exit electrode, the current lines in the DC case spread out over such a broad traverse area in the earth that the resistance is negligible small

except in the direct surroundingof the electrodes.
For AC, however the self-inductive action of the changing magnetic field becomes more dominant. Under AC conditions the distribution of the current lines in the ground will thus mainly be determined by the inductive effects of the changing magnetic field in the low frequency area. In such a case the currents are so distributed that the energy of the magnetic field and thereby the self-inductance tend to become a minimum. With increasing frequency the resistance will become again an more important factor while the circuit becomes more compact.
Therefore, an alternating return current in the soil under a long distribution line will not spread to a great distance, as direct current does, but will concentrate on paths in proximity of the distribution line, as shown in figure 3.16. Hence the distribution of alternating current in the ground is governed by the laws of skin effect, as well laterally as in depth. As effect of the high resistivity of the soil,

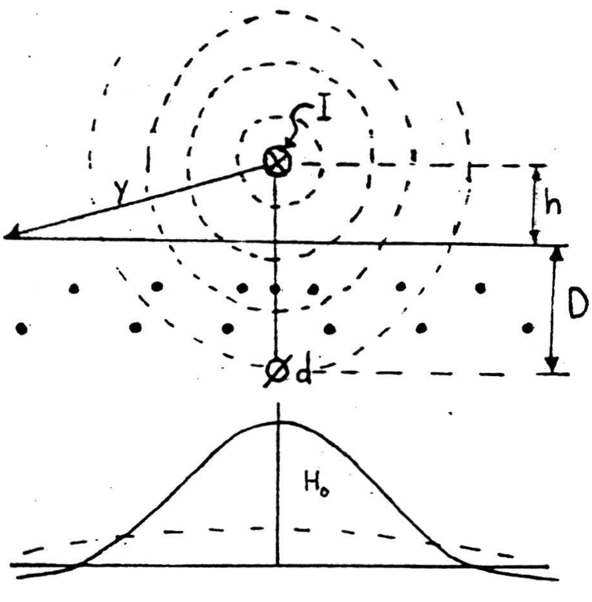


Figure 3.16 current distribution of the soil current beneath a SWER distribution line

much larger dimensions come into consideration than with metallic conductors.
A single distribution line, see figure 3.16, will develop concentric magnetic lines of force of nearly circular form, at least in the neighbourhood of the line, where the magnetic effect of the return current in the ground is of less importance because of its low density. Therefore, the phenomena will be dependent primarily on the distance y from the centre of the wire, carrying the total load current I, to the point considered at the earth.
In the next paragraph a model of the earth path is described.

Equivalent depth of return method

This model of the earth path is based on the concept of the equivalent depth of return. The model is only valid for relatively low frequencies (50 and 60 Hz and skin-depth (δ) >> hight of conductor above the ground) and resistivity's varying from 50 to 500 Ω.m . The steps for the derivation of the approximation are as follows. Consider the problem as illustrated in Fig 3.16, one overhead conductor above the earth. Usually the height of the conductor (*h*) is much larger then its radius. Rudenberg [9] has suggested that

$$J_r = \frac{jk^2}{2\pi} I_t K_o(kr\sqrt{j}) \qquad 3.40$$

the distribution of electric current inside the earth can be approximated with,
where

J_r	=	current density at distance r from the conductor;
I_t	=	total current through the conductor;
j	=	imaginary unit [$=\sqrt{(-1)}$];
k	=	$\sqrt{\omega\mu\sigma}$;
K_0	=	modified Bessel function of the second kind, zero order.

Rudenberg did not provide any reasoning for the suggestion of the foregoing formula. It can be argued that he arrived at this suggestion by considering the general solution for the electric current density in cylindrical geometry.

The electric current density in a circular conductor is determined by the solution of the following equation [24] :

$$\frac{d^2J(r)}{dr^2} + \frac{1}{r}\frac{dJ(r))}{dr} - jk^2J(r) = 0 \qquad 0 < r < a \qquad 3.41$$

where,

$$k^2 \triangleq \omega\,\mu\,\sigma$$

The general solution, describing the skin effect in circular conductors is given in terms of two functions, I_0 and K_0[8]

$$J(r) = A_1 I_0(krj^{0.5}) + A_2 K_0(krj^{0.5}) \qquad 3.42$$

The functions I_0 and K_0 are known as the modified Bessel functions of first and second kind,respectively. The function I_0 and K_0 represent two independent solutions of the differential equation 3.41.

[8] Handbook of Mathematical Functions, U.S Department of Commerce, National Bureau of Standards, 1964

They are defined as follows :

$$I_0(z) = 1 + \frac{\left(\frac{z}{2}\right)^2}{(1!)^2} + \frac{\left(\frac{z}{2}\right)^4}{(2!)^2} + \frac{\left(\frac{z}{2}\right)^6}{(3!)^2} + \dots \qquad 3.43$$

$$K_0(z) = -\left(\ln\frac{z}{2} + \gamma\right)I_0(z) + \left(\frac{z}{2}\right)^2 + \left(1 + \frac{1}{2}\right)\frac{\left(\frac{z}{2}\right)^4}{(2!)^2} + \left(1 + \frac{1}{2} + \frac{1}{3}\right)\frac{\left(\frac{z}{6}\right)}{(3!)^2} + \dots \qquad 3.44$$

where $\gamma = 1.7811\ldots$ and z is any complex number.
The derivation of the two independent solutions above for equation 3.42 is beyond the scope of this report. The functions $I_0(krj^{0.5})$ and $K_0(krj^{0.5})$ assume complex values and can generally be expressed in cartesian
or polar coordinates :
Cartesian coordinates

$$I_0(xj^{0.5}) = ber(x) + jbei(x)$$
$$K_0(xj^{0.5}) = ker(x(+ jkei(x) \qquad 3.45$$

Polar coordinates:

$$I_0(xj^{0.5}) = M_0(x)e^{j\theta_0(x)}$$
$$K_0(xj^{0.5}) = N_0(x)e^{j\phi_0(x)} \qquad 3.46$$

where x is a real number. The cartesian coordinates of the modified Bessel function are known as the Kelvin functions. In figure 3.17 a qualitative description of the functions I_0 and K_0 is provided.
For the figures of the cartesian components (*ber(x), jber(x), ker(x)* and *jker(x)* versus the argument x and the polar components $M_0(x)$, $\Theta_0(x)$, $N_0(x)$ and $\phi_0(x)$ (modulus and phase versus the argument together with a table of the modulus and phase of the function $I0(xj^{0.5})$ for values of the argument x from 0 to 10, I refer to Appendix A.2. These figures and table can be used for practical computations.

While equation 3.42 is not applicable to the problem illustrated in Fig 3.16, (equation formula is derived assuming radial symmetry, meaning solution independent of the angular coordinate ϕ). Rudenberg assumed that it is a reasonable approximation since the height (h) of the line is typically large > 10 m). Upon acceptance of the assumption, it can be observed that as $r \to \infty$, the current density must vanish. Since $I_0(krj^{0.5}) \to \infty$ as $r \to \infty$, it is concluded that the constant A_1 must be identically zero. Thus the solution is

$$J_r = A_2 K_o (krj^{0.5}) \qquad 3.47$$

The total current through the infinite medium is

$$I_t = \int_{r=h}^{\infty} A_2 K_0 (kr\sqrt{j})\, 2\pi r\, dr$$

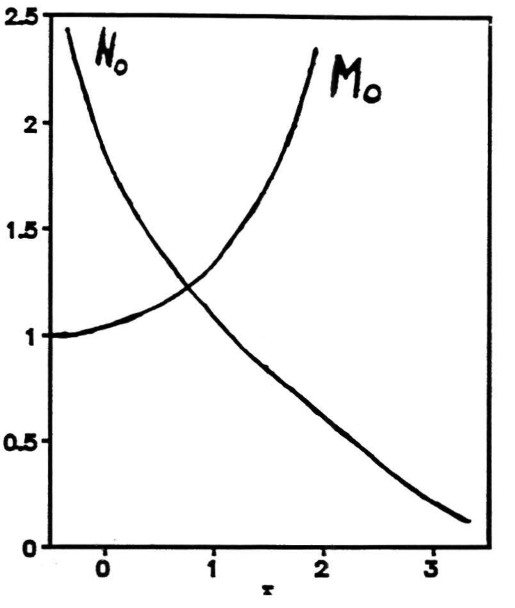


Figure 3.17 Qualitative variation of the absolute value of the functions $I_0(xj^{0.5})$ and $K_0(xj^{0.5})$

the integral of the modified Bessel function K_0 :

$$\int_{z}^{\infty} wK_0(w)\, dw = zK_1(z)$$

Upon application of the identity above, we obtain

$$I_t = \frac{2\pi h\sqrt{j}}{k} A_2 K_1 (kh\sqrt{j}) \qquad 3.48$$

Elimination of the constant A_2 from equation 3.46 with the aid of equation 3.47 yields

$$J_r = j\frac{k^2 I_t}{2\pi} \frac{K_0(kr\sqrt{j})}{kh\sqrt{j}K_1(kh\sqrt{j})} \qquad 3.49$$

It should be observed that for typical soil resistivity and height h of conductors above earth, the quantity of kh is very small. For example assuming a soil resistivity of $200\ \Omega m$, $50\ Hz$ and $h = 10\ m$, $kh = (\omega\mu\sigma)^{1/2} * 10 = 0.028$. A property of the modified Bessel function , K_0 is

$$kh\sqrt{j}\, K_1(kh\sqrt{j}) \approx 1.0$$

Thus

$$J_r = j\frac{k^2 I_t}{2\pi} K_0(kr\sqrt{j})$$

which is exactly the equation suggested by Rudenberg.

The induced voltage V per unit length on the surface of the soil along the conductor is computed from

$$V = \frac{1}{\sigma} J_{r=h} = \frac{jk^2}{2\pi\sigma} I_t K_0(kh\sqrt{j}) \qquad 3.50$$

This voltage will have two components, (1) due to the resistance of the earth path which is in phase with the soil current, and (2) due to the changing magnetic flux density inside the earth. The latter voltage is *90°* out of phase with the earth current. This observation provides the procedure to compute the resistance and reactance of the earth path. Specifically, the resistance per unit length of the earth path is,

$$R_e = Re\{\frac{V}{I_t}\} = Re\{\frac{jk^2}{2\pi\sigma} K_0(kh\sqrt{j})\} \qquad 3.51$$

The inductive reactance per unit length of the earth path is,

$$X_e = Im\{\frac{V}{I_t}\} = Im\{\frac{jk^2}{2\pi\sigma} K_0(kh\sqrt{j})\} \qquad 3.52$$

A simplification of these formulas is achieved by recalling that for soil resistivity's and distribution line designs, the argument *kh* of the modified Kelvin function is very small. In the case the asymptotic expansion of the modified Bessel function for small arguments can be utilized :

$$K_0(kh\sqrt{j}) \cong \ln\frac{1.123}{kh} - \frac{j\pi}{4}$$

Upon substitution of the expression in the equations for *Re* and *Xe*, we get,

$$R_e = \frac{\omega\mu}{8}$$

$$X_e = \frac{\omega\mu}{2\pi}\ln\left(\frac{399.6}{h}\sqrt{\frac{\rho}{f}}\right) \qquad h = meters$$

For the situation that $f = 50$ Hz, $h = 10$ m, $\rho = 200$ Ω.m , $Xe = ...$ and $Re = ...$

Note that *Xe* is the internal inductive reactance of the earth path. Considering the conductor and the earth path as a single-phase line, the voltage per unit length of this line is,

$$V = j\frac{\mu_0\omega I_t}{2\pi}\ln\frac{h}{d} + j\frac{\mu_0\omega I_t}{2\pi}\ln\left(\frac{399.6}{h}\sqrt{\frac{\rho}{f}}\right) + R_c I_t + \frac{\omega\mu_0}{8} I_t$$

or

$$V = (R_c + \frac{\omega\mu_0}{8})I_t + j\frac{\mu_0\omega}{2\pi} I_t \ln\left(\frac{399.6}{d}\sqrt{\frac{\rho}{f}}\right)$$

Define D_e, the equivalent depth of return of earth currents as,

$$D_e = 399.6\sqrt{\frac{\rho}{f}} \qquad meters$$

The formula above leads to,

$$V = (R_c + \frac{\omega \mu_0}{8}) I_t + j \frac{\mu_0 \omega}{2\pi} I_t \ln \frac{D_e}{d} \qquad 3.53$$

where

d = geometric mean radius of the overhead conductor;
R_c = conductor series resistance,
I_t = total electric current through the overhead conductor (also through the soil in opposite direction),
f = frequency of the current,
D_e = equivalent depth of return of the earth currents.

Note that the utilization of the soil as return path has the effect of increasing the resistance by $\omega\mu_0/8$. The effect on the earth return path on the reactance is expressed in terms of the equivalent depth of return, D_e.

The equivalent circuit of a Single Wire Earth Return line (see Fig. 3.18) consists thus of (1) conductor resistance (R_c), (2) conductor reactance (X_c), (3) soil path resistance (R_e), (4) soil path reactance (X_e) and the (5) resistance of the earthing grid at both ends of the line (R_g).

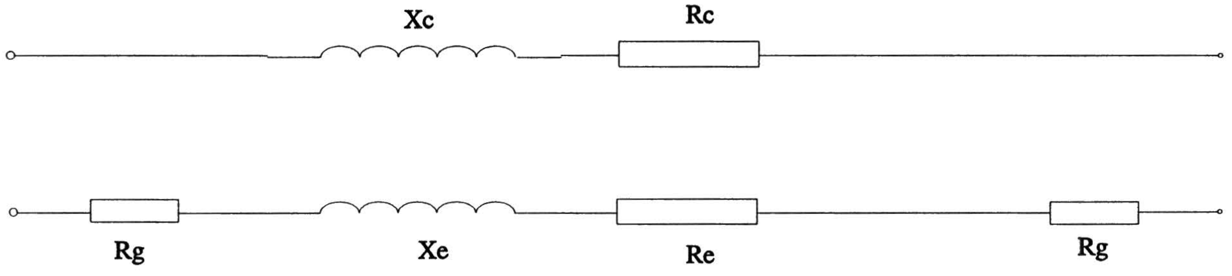


Figure 3.18 Equivalent circuit of a Single Wire Earth Return (SWER) line

3.4 SPECIFIC POWER SYSTEM ISSUES

Power consumption
As result of the permissable earth-return current and thus the load current, the amount of power that can be distributed to individual transformers is limited. It depends on the local conditions with respect to geophysical characteristics of the soil in combination with the climate and the earthing system in operation.

Three-phase loads
Whereas the power line is single-phase another limitation is the use of three-phase loads. It is possible to utilize three-phase loads with a single-phase source, but this will introduce additional equipment and investment for the consumer. The question whether this specific equipment is available is not even mentioned.

Distance from main distribution line
The earth-impedance of the ground-return path is dependent on the length and height of the power line the frequency of the current and soil resistivity. The frequency, soil resistivity and height are assumed to be constant, so the only variable in this context is the length of the power line.
The construction of long distance low power feeders with the SWER system requires special design consideration to minimize costs. The disadvantage of the long distance feeder is twofold, in the first place, SWER feeders exhibit voltage regulation problems which must be designed for (*variation of ± 5.5 % is mentioned as maximum value for distribution systems under normal conditions and a value of 8% in faulty situations [5]*) and in the second place, ground loss adds to the conductor loss [5] .
The voltage regulation in an SWER AC feeder is mainly effected by line reactance which is the main determinate in the voltage drop of a line, a factor which is significantly more important than line resistance.
The line charging currents result in an voltage rise at light load and to compensate for this shunt reactors can be connected in a number of locations. Shunt reactors are however not load sensitive and do not reduce the voltage variation from the no load to full load condition. A voltage regulator could be appropriate in this situation.
If distribution of power, over long distance, for remote loads is under consideration, utilizing a SWER AC feeder, the utility may consider a three-phase AC line in preference to the SWER distribution system [27] .

Voltage regulator
The voltage regulator is a component which is installed in substations and out on the primary system to regulate voltage levels. They may be of two types, the induction regulator and the tap changing under load transformer (TCULP). Both types do raise or lower the voltage level from the substation power transformers.
The voltage regulator in substations can be used in two ways, (1) individual regulators associated with individual outgoing feeders or (2) one, larger in size, that regulates the voltage on a bus from which two or more primary feeders are supplied. A third application is when it is placed out on the primary system on the far end of a primary feeder to maintain satisfactory voltage regulation beyond this point on the feeder.
A voltage regulator is rated according to the percentage it can add or subtract from the applied voltage. The kVA capacity is based on the product of full load amperes and the voltage that the regulator can add or subtract

Losses
The losses for an AC feeder as result of the **earth-return path** is a major issue, since AC return currents remain coupled to the line current and are confined to flow in the ground through a restricted path beneath the conductor [27]. This will take a major part in the design procedure. The best remedy for reduction of these losses is a well designed earthing system and the choice of the suitable conductor size.

System protection
The SWER system is normally isolated by a special isolating transformer to ensure that the three-phase or single-phase lines used to energise the system do not carry zero sequence (earth leakage) currents. As a result of this nature the only form of protection which can be applied for faults and line down conditions on a SWER scheme is over-current protection, either by fusing or by use of reclosers. It must be remarked that there can develop fault conditions where the protection fails to detect the fault resulting from high impedance ground faults where the fault current is not sufficient to operate the protection device [6].

3.5 EQUIPMENT AND MATERIALS FOR DISTRIBUTION SYSTEMS

A variety of situations exist in developing countries with respect to availability of natural resources. The economic use of these natural resources can be reflected in the choice of construction materials of the distribution system. Certainly in the case of rural networks, which usually consist of long lines and relatively small loads, the choice of the materials is of major importance. A selection of local available materials is, therefore, recommended.
The selected material items are poles, conductors and connectors. Table 3.5 gives a summary of the practical and economical aspects of these materials in developing countries [1].

Table 3.5 : Practical and economical aspects of materials used in Developing Countries

MATERIALS	PRACTICAL AND ECONOMICAL ASPECTS
Poles	Prestressed concrete poles are often used for rural electrification, although there is good quality wood abundantly available at a fraction of the cost. It is not unusual for a country to use cast concrete poles for rural electrification, while concurrently exporting cheaper treated wooden poles for use in other countries. Steel poles are also used frequently instead of lower cost concrete. In many instances, considerable savings are also possible through the selection of more appropriate pole designs, safety clearances, and span lengths.
Conductors	In many developing countries Aluminium Clad Steel Reinforced (ACSR) conductors are used for primary lines in rural areas. They are needed for longer spans, when stresses are high, and their performance can be better under actual fault conditions. Some technical disadvantages of ACSR are, (1) greater care must be exercised during construction because aluminium is soft, (2) splicing is more difficult because of steel core, and (3) all connections are critical because aluminium cold-flows under pressure, corrodes when exposed to air, and the corroded coating (aluminium oxide) is an insulator. ACSR is better restricted to most important primary feeders, because of high cost. Few developing countries use all aluminium (AA) wires. Although disadvantages 1 and 3 above also apply to AA, they are lower in cost and easier to handle. However, use of AA lines for secondaries is common. Aluminium alloy conductors (AAC) combine the strength of ACSR and the handling qualities of AA; they should be considered where strength requirements are paramount. However, AAC is more expensive and has higher losses than AA. Lighter loading conditions in most developing countries permit AA to be used for many applications. Very few developing countries use steel conductors available with zinc, copper, or aluminium coatings to prevent rust. The advantages of steel conductors are low cost, simple construction, and high strength. However, their high losses are likely to rule them out in many circumstances where economic optimization is an important determinant of design criteria.
Connectors	Proper splices and connections are essential to the long range successful operation of rural systems using ACSR and AA conductors. Most experienced practitioners agree that only compression splices and connections provide adequate useful life for ACSR and AA conductors. In a survey of nine representative developing countries [1] only some countries have standardized compression fittings, others use bolted parallel grooves connectors and had left splicing to the ingenuity of the lines crew. Although it is considered standard practice in North America (and practically all well run utilities) to use oxide inhibitors and/or grease to prevent corrosion of aluminium connections, this is not being done in the countries sampled. In summary, common reasons for poor connections are, (1) wrong size connectors (if too small, they do not provide sufficient area, or pressure. If too large, they do not grip tightly enough), (2) loose blades and pressure plates on blade disconnects, gauge-operated switches and cutouts, (3) use of bronze connectors on aluminium conductors, which results in corrosion and eventual failure of the connection, (4) use of all aluminium connectors on copper conductors, which results in corrosion and eventual failure of the strands of one conductor around the other. This method works for hard drawn copper conductors, but aluminium strands do not have sufficient tensile strength. Invariably, the connection becomes loose, causes losses, begins arcing, and burns down. Preventing poor connections requires using the right connectors at all times, using compression connectors for aluminium whenever possible, and monitoring of existing connectors. The most effective monitoring devices are infrared detectors, which can be used to pinpoint any hot spots on the system.

For the equipment, the same arguments are valid as for the materials. First search for local available inputs before taking decisions. Table 3.6 shows the practical and economical aspects of the equipment in developing countries [1].

Table 3.6 : Practical and economical aspects of equipment.

EQUIPMENT	PRACTICAL AND ECONOMICAL ASPECTS
Distribution transformers	Distribution transformers take power from the primary system at the general level between 6 and 35 kilovolts and transform it to a voltage level in the range of 100-400 volts. The standard sizes and costs vary widely from country to country. The single-phase costs are derived from a blend of the following types of transformers : - 1. primary insulated for line to line voltage, two primary bushings; - 2. primary insulated for line to neutral voltage, two primary bushings; - 3. primary insulated for line to neutral voltage, one primary bushings. Distribution transformers can constitute a significant share of rural electrification investment. It is important that a sufficient variety of types and sizes are available to match the needs of consumers. Some poor practices to be avoided are : - 1. purchasing only large transformers (e.g., 50 KVA (kilo-Volt-Ampere) and above); - 2. installation of large transformers for small loads; - 3. purchasing only three-phase transformers, especially when loads are light.
Voltage regulators	These components are installed in substations and out on the primary system to regulate voltage levels. Generally speaking, rural lines are voltage restricted; voltage drop is the major limitation on the length of line and number of consumers that can be served from a specific feeder. For example, without regulation, the typical primary in Figure 3.14 is restricted to about 7 km in length, if a minimum voltage level of 95 percent is maintained. With a station regulator and a line regulator, the coverage of the feeder could be extended an additional 8 km. However, selecting conductor sizes based on the optimal level of losses will often result in circuits having acceptable voltage characteristics without need for regulators under normal load conditions. The actual application of regulators requires in-depth studies of the economic/engineering balance among losses, service reliability and power factor control. Station regulators and the line regulators are used in many rural electrification systems, but not in systems using primary capacitors for controlling both power factor and voltage.
Capacitors	Capacitors have been used on distribution primary systems to control power factor for over 25 years. The major benefits are, (1) reduced losses, (2) reduced demand (which releases capacity), (3) better voltage levels. In rural systems, correction of power factors* up to 98 percent is economically justified in many cases. Unfortunately, few countries are seriously involved in power factor control. However, the introduction of primary capacitors is only beginning.
Protective devices	When properly applied, protective devices assure continuity of service and the isolation of faults from the remainder of the system. It is essential that each developing country's rural electrification program include a major initiative in the protection of lines and equipment. This effort should include periodic fault current studies, coordination studies, concern and enforcement of protective guidelines. It should also include the development and enforcement of equipment specification and usage of modern equipment -- such as fuses having known characteristics, reclosers, sectionalizes, fault limiting fuses, load break cutouts, air blast breakers and vacuum switches -- where it is necessary and justified for rural systems. If such an effort is not made, it is likely that service will deteriorate and valuable equipment will be damaged unnecessary. Careful selection of lightning arresters specifications is a critical part of developing rural electrification design standards, since lightning arresters characteristics can determine the insulation class to be used for all equipment in the system. Accordingly, price should not be the sole criterion. Judicious use of arrestors, at points such as those near substations and on long secondary circuits, will often prevent expensive damage to other equipment in the system.

$$Power\ factor\ (pf) = \frac{power(kW)}{\sqrt{(power(kW))^2 + (reactive power(kVAR))^2}}$$

- power (kW) is consumed electric energy by the consumers;
- reactive power (kVAR) is the energy needed to maintain the voltage level on the power line.

The situation in Tanzania, with respect to a selection of the former discussed issues, is summarized in following box.

Availability and use :

The materials utilised, which are locally produced or manufactured in Tanzania, for the rural distribution systems are the following [1] :

- impregnated wooden poles;
- ACSR conductors;
- Compression type and parallel groove connectors (locally manufactured)

The equipment, utilised and produced or manufactured in Tanzania, are the following [7]:

- transformers and switch gear;
- components for installation such as conductors and fuse boxes;
- appliances like hot plates, light bulbs and refrigerators

3.6 PRELIMINARY CONCLUSIONS

Utilisation of earth as load current path in the SWER distribution system, causes difficulties, not only for the **population** but also for **telecommunication and other electrical devices** so an **environmental study** is in its place. The system requires proper earthing and soil with adequately low resistivity year round.
Single Wire Earth Return (SWER), when used without isolating transformer, has the cheapest investment costs but higher losses. The use of isolating transformers could raise the investment costs on a higher level than costs for an alternative system (e.g. single-phase two wire).
To prevent the adverse effects, the grounding system needs to have sufficiently large dimension and only limited current flows are tolerated in each sub-station. At least the next variables are of interest in the design of the earthing system:

- **soil resistivity;**
- **existence of conducting structures in the ground.**

A general selection of a suitable region with respect to soil resistivity and heat conductivity can be performed by a selection procedure which includes the physical conditions determining areas with preferable properties.
The indicators for these physical conditions are found in the variables (1) rainfall and temperature, in combination with, (2) the existing soil moisture and temperature regime in the area and (3) type of soil(s). As result of an analysis, areas with potential suitability can be identified.
When a location is selected, field measurements are necessary to investigate the local environmental conditions of a potential site for the substation. The field measurements can consist of direct measurements of the soil resistivity, soil type classification, identification of the conducting structures present in the subsoil (e.g. pipelines, telephone lines) to evaluate the suitability of the specific site for the soil current conduction. Some methods which are suitable will be described in chapter 4.
The entire system including **whole infrastructure** should be taken in consideration. Present and future domestic appliances and other consumers, determination of type and magnitude of growth.

A practical case for the SWER distribution system shows the following figures [3] :

Distribution transformer at load centre :
$I_{load,max} = I_{soil}$ = generally less than 12.5 A.
In situations with larger values of the load current, extended earthing measures are required. In the particular article [3] two towns will be supplied with electricity using the SWER system, with load currents of **42 A** and **20.5 A** respectively. In these two towns several MV/LV transformers are required scattered over a relatively large area. Multiple grounding systems will be build, one for each MV/LV distribution transformer, interconnected via a ground overhead conductor running along the phase conductor feeding the transformers.

Practical situation at supply station at main distribution line :

- **$I_{load} = I_{soil}$ = 30 - 50 A**
- **Calculated station grounding resistance = 0.3 - 1 Ω**
- **Measured soil resistivity = 90 - 400 Ω.m**
- **Total ground mesh voltage to remote earth = 50 V**

They believe that under these conditions there is no need to improve the grounding systems for the continuous return current in the soil.

Table 3.7 : Technical aspects of Single Wire Earth Return distribution system

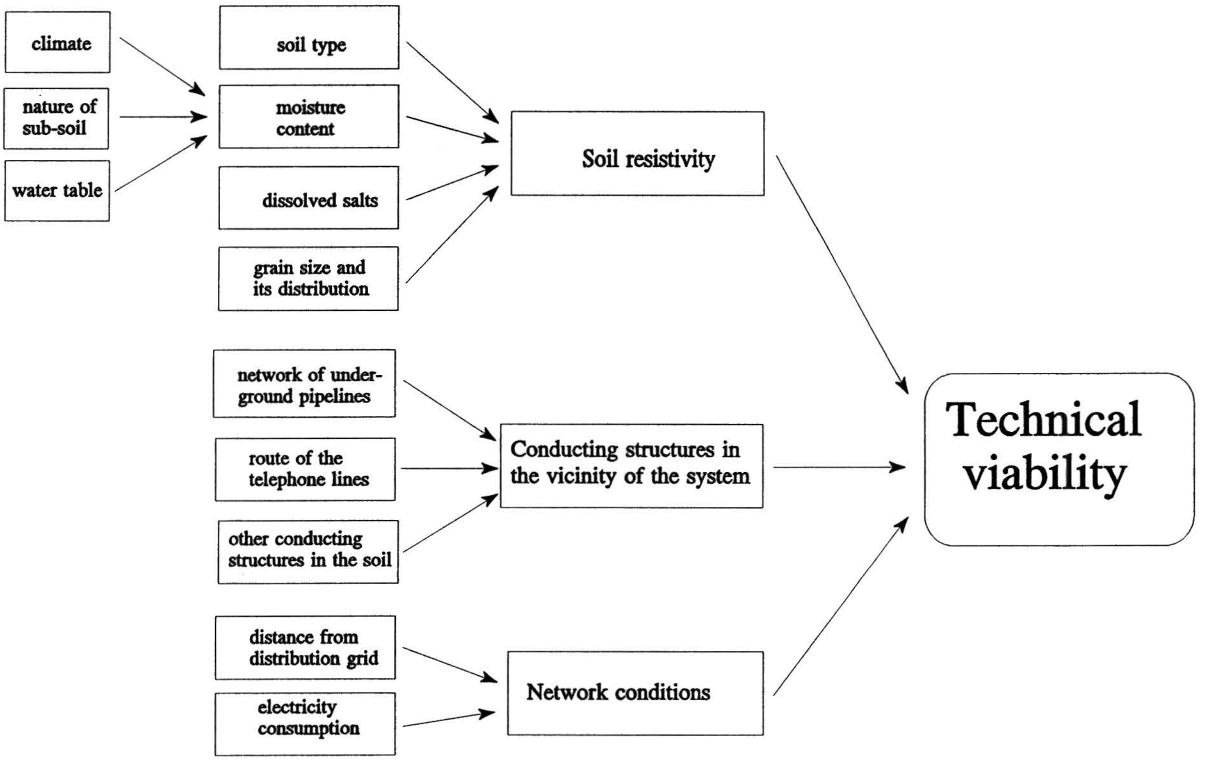
<table>
<tr><th colspan="4">SINGLE WIRE EARTH RETURN (SWER)</th></tr>
<tr><td>Characteristics</td><td colspan="3">- single-wire single-phase spur line between main distribution system and load centre.
- single-wire distribution line galvanically isolated by an isolating transformer at main distribution system.
- load current flows through the soil, from the earth electrodes in the ground, to the surrounding soil.
- soil between the isolating transformer (main distribution system) and distribution transformer (load centre), serves as return path of the load current.</td></tr>
<tr><td>Properties</td><td colspan="3">Current inflow into the soil at substation (local zone of influence)
- heating of surrounding soil;
- Ground Potential Rise (GPR).

Ground return path between entrance and exit electrodes
- the passage of the currents tends to take place by following the feeder lines at an average depth of several hundred of meters.
- the resistance and the reactance along the line of this return path are dependent on the nature of the soil and the frequency of the current and are generally in the vicinity of a rather small fraction of an ohm per kilometre.
- the tendency of the return current in the soil to follow the lines can be more or less falsified if they find other paths which are good conductors, such as metal conduits, cable sheathing, telephone lines, etc.
- certain inconveniences may result from this, especially when the electrical continuity of these paths or their links with neighbouring ground electrodes is badly arranged [10].</td></tr>
<tr><td>Restrictions</td><td colspan="3">Physical environment - soil resistivity ≤ 500 Ω.m;
Line length - around 50 km, depending on physical conditions of the soil;
Power consumption - a maximum of 250 kW per distribution transformer;
Three-phase loads - possible but requires additional equipment;
Voltage level - voltage level of 10 kV is usual.</td></tr>
<tr><td rowspan="2">Simplified comparison of benefits of SWER</td><td colspan="3">Situation : length of line 50 km to a load centre
Single Wire Earth Return (SWER) | Single-phase two wire | Three-phase three wire</td></tr>
<tr><td>- 50 km of conductor
- single wire poles
- one time the amount of insulators
- simpler and shorter construction time</td><td>- 100 km of conductor
- two wire poles
- two times the amount of insulators
- longer construction time</td><td>- 150 km conductor
- three wire poles
- three times amount of insulators
- longer construction time</td></tr>
</table>

4 TECHNICAL SELECTION VARIABLES AND INVESTIGATIONS

In the former chapter the distribution system, with its particular fields of concern was described. In this chapter, the following question is asked : in which areas of Tanzania is the Single Wire Earth Return (SWER) distribution system technically viable ?
The technical viability of an area can be divided in three sets of variables indicating the suitability :
- 1 soil resistivity, the environmental variables of **geophysical nature** which indicate preferable conditions for a permissable soil resistivity ;
- 2 conducting structures in the vicinity of the system, either embedded in the soil or near the power line, implying that the adverse effects of the soil current is limited;
- 3 network conditions of the system.

The identification of suitable areas, from a technical point of view, based on these conditions, will be performed. These areas can thus be marked as possible service areas for the Single Wire Earth Return (SWER) distribution system in Tanzania. This leads to the technical selection criteria at the National level.
If a rural electrification project is planned in an area with preferable conditions for utilising the Single Wire Earth Return (SWER) system, local investigations need to be performed to define the actual technical viability of the system. This incorporates selecting the site of the distribution station and isolation transformer, based on environmental conditions which meet the required criteria. At the local level, specific values of soil parameters and other environmental conditions will indicate the actual technical viability of the system.
A selection method at the National level and investigation methods at the local level together with criteria, will be discussed in this chapter.



4.1 TECHNOLOGICAL SELECTION CRITERIA

Soil resistivity

Most soils and rocks, when completely dry are non-conductors of electricity. Exceptions are certain mineral bodies which are conductors because of their metallic content. Sands, loams and rocks are, however, in themselves of such high resistivity that they can be considered as non-conductors. When they contain water, their resistivity drops considerably and then they must be considered as conductors, although very inferior ones when compared with metal. For example, the resistivity of pure copper is $0,016*10^{-6}$ Ω.m, when a quite usual value for soil would be 100 Ω.m . The resistivity of soil is basically determined by its moisture content and the resistivity of this moisture. In other words, conduction through the soil becomes conduction through the water held in the soil and so the conduction must be electrolytic. Thus the main factors , some of which are discussed in detail in this report, which determine the resistivity of soil are the following [11]:

a - moisture content;
b - concentration of the salts dissolved in the water;
c - chemical composition of salts dissolved in the contained water;
d - type of soil;
e - grain size of the material and distribution of grain size;
f - soil temperature;
g - closeness of packing and pressure.

a - Effect of moisture content and dissolved salts in the water
Since the conduction of current is largely electrolytic, it follows that the moisture content and the nature and amount of the dissolved salts will play an important role in determining the resistivity. The actual moisture content is dependent on a number of factors and will likely be a variable amount. It will vary with the weather, time of year (seasons), the nature of the sub-soil and the depth of the permanent water table if any. Moisture content is likely to increase with depth in most locations, but it must not be assumed that the presence of a lot of water (high moisture content) automatically means that the resistivity is low. A simple experiment with dry sand and distilled water will soon show that this is not the case.

b/c - Effect of dissolved salts in the water
Since the moisture content in the soil is a major factor in the determination of the resistivity, it follows that this resistivity is dependent on the resistivity of the moisture. It is known that the resistivity of water is governed by the amount of salts dissolved in it. The curves in Fig. 4.1 show quite clearly that a small quantity of dissolved salts can reduce the resistivity very considerably from the infinite value for pure water. It will also be noted that different salts have different effects and this is part of the explanation why the resistivity's of similar soils from different locations vary considerably. In the first place, the moisture content may differ and secondly, the quantity and nature of the dissolved salts may not be the same.

d - Effect of type of soil
The type of soil is very important in determining the resistivity of the soil. Unfortunately, types of soil are not too clearly defined, for example, the word clay can cover a wide variety of soils. This is why it is quite impossible to state that clay, or any other kind of soil, has a resistivity of a specific value of so many Ω.m . The same general type of soil occurs in various locations and is often found different in one location from the other.

e - Effect on grain size and its distribution Grain size and the presence of grains of various sizes undoubtedly plays an important role in the determination of the resistivity. The grain size and its distribution has an effect on the manner in which the moisture is held. With large grains, moisture is probably held by surface tension at the points of contact with the grains. If, however, grains of various sizes are present, the spaces between the large grains may be filled with smaller ones and the resistivity will be reduced as result.

f/g - Effect of temperature and pressure
Since the resistivity is largely determined by the moisture content and the fact that the resistivity of water has a large temperature coefficient, it is reasonable to assume that the resistivity will increase when temperature is decreasing. If the temperature falls low enough for the water to freeze then the resistivity will rise sharply due to the high value of ice. With respect to pressure it is only to be expected that higher pressure resulting in a more compact or denser body of soil will result in lower resistivity's. The small amount of experimental evidence available, however, does not support this theory. From a practical point of view it is reasonable that the effect of pressure can safely be neglected [11]

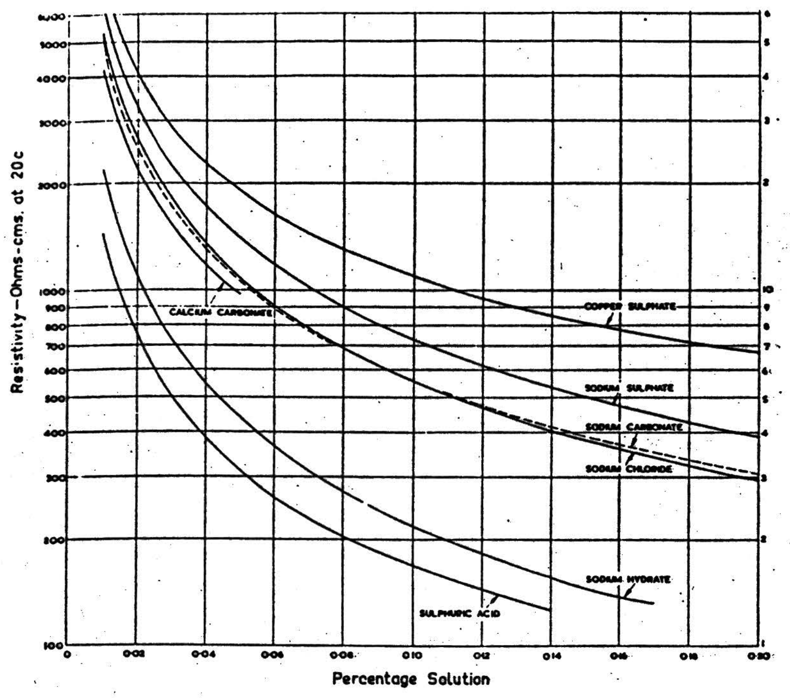


Figure 4.1 : Typical resistivity curves of solutions

Conducting structures in the vicinity of the system
These conditions are associated with **infrastructural facilities in the area** :

a - **network of underground pipelines**, if situated in the vicinity of the entrance or exit electrodes the soil current can cause corrosion of the pipeline, if the pipeline crosses the return path of the current at larger distances from the earthling electrodes it causes voltage rise at the pipeline.
b - **route of telephone lines**, the return current through the soil and induced voltages of the power line can cause voltage rise on the telephone line which can severely disturb communication;
c - **other conducting structures in the soil**, where the soil current can causing the same effects as mentioned in the first example.

Network conditions

a - **course of the main electricity distribution network**, a maximum distance of around **50 km** is preferable between main distribution grid and individual load centres due to maximum tolerable voltage drop between begin and end of the line
b - **electricity consumption at load centre(s)**, a maximum load of **250 kW** per distribution transformer is permitted due to the limited load current of 10 Ampere [3] and related energy losses.

4.2 SELECTION PROCEDURE AND METHODS OF INVESTIGATION

The selection of suitable areas can be performed by evaluation of the above mentioned **environmental conditions** affecting the soil resistivity, adverse effects of soil current and technical losses. Diagram 4.1 shows the variables and their relations in a schematic way. In table 4.10, at the end of this paragraph, the criteria are summarized.

At the **National level** I will describe the following variables :

A - climatological conditions; **rainfall, evaporation and temperature.**
B - **type of soil.**
C - **soil moisture content** in terms of soil moisture and soil temperature regimes;
D - **course of electricity grid,** infrastructure.

At the **local level** I will describe the following investigation methods :

A - direct measurement of **soil resistivity;**
B - analysis of **grain size and distribution of grain size** of the soil material.

4.2.1 Selection procedure at national level

A) CLIMATOLOGICAL CONDITIONS

Rainfall, evaporation and temperature
Rainfall condition of areas is one of the indicators in the selection procedure. Data are often accessible and available for quite a lot of stations in the country. Although, much is not understood about rainfall pattern over East-Africa because certain data, particularly those of the upper air, are missing. A complete physical interpretation is not possible. The air temperature is not a very influential factor and will be dealt with as a constant [20].
Relevant aspects of the data on rainfall are, **(1) monthly averages** over several years to balance the extreme maxima and minima, **(2) the occurrence of seasons** and the **(3) variability** of rainfall which can be illustrate by a rainfall probability map (see Fig. 4.2). From a practical point of view, the analysis of rainfall is of limited use without reference to evaporation rates. A rainfall amount of 750 mm per year is more than adequate for agriculture in many parts of the world. However, because of the high evaporation rates in Tanzania, this figure is taken by some people to be the limit below which cultivation is marginal, although much depends on the seasonal distribution and variability in amounts of rainfall over the years. In Holland for example, the amount of rainfall is not much larger than 750 mm a year, but the two factors, evaporation and variability, are of a much lower value compared with Tanzania, where variations of 25 % or more are not uncommon [21]. **This value (750 mm\year) will be used as a limit in the procedure of selecting suitable areas, to meet the need for moisture content in the soil.**
Potential evaporation tends to decrease with altitude, this being predominantly a reflection of the variation of cloud cover with height [20].
If probable rainfall, also taking evaporation into consideration, is used as an indicator for the suitability of areas, the following criterium can be applied :

- an annual average probability of ≥ 750 mm, with which amount there will grow enough vegetation to produce good humus content in the soil [12]. Conditions then indicate acceptable resistivity values within the limit of 500 Ω.m .

With this approach the selection is based on the assumption that, with the probable amount of rainfall, the soil is containing some moist the whole year through to keep the soil resistivity at a tolerable value. No account is given to other aspects like, soil type, water table or nature of the subsoil which also affect the soil moisture content. These aspects are more specific and depend on local conditions and could be investigated at that level.

Rainfall in Tanzania

Examination of the mean monthly averages shows in general terms a north-south seasonal movement which can be linked to the average pressure and wind conditions. Ignoring the effects of highland areas the pattern is as follows [20] :

Table 4.1 Rainfall pattern in Tanzania

Month	Pattern
January and February	the area south of an irregular line Dar es Salaam to Lake Victoria can be considered 'rainy'. At Tanga in the north-east these two months produce only 5 percent of the annual total compared to 42 percent at Kala Mission in the south-east.
March	As the rainbelt moves north, the percentage contribution to the annual total is fairly similar over the whole country.
April	This month is wet over the whole country, with the exception of perhaps the extreme south-west, but the percentage of the annual total varies considerably (e.g. from 28 % at Narok to 7 % at Kala Mission)
May and June	With the continued northwards movement of the rainbelt, in these months, west and central Tanzania are dry. The two months together produce only 1% of the annual total at Kala Mission.
July to October	Apart from the lake area and to a lesser extent the extreme north-west, July to October is dry, this period produces only 1 % of the annual total at Mpwapwa
November	At this time the rain has returned to the north-eastern areas, producing 9 % of the annual total at Narok.
December	With the continuing movement to the south of the rainbelt, this month produces as much as 21 % of the annual total at Kala Mission in the south-east but only 6 % at Tanga in the north-east

The semi-permanent low-pressure over the Lake Victoria area is associated with a much more even distribution of rainfall over the year than in other areas, although much of it falls in the period March-May.

Annual rainfall

The distribution of the annual rainfall shows a simple pattern in general terms. The wedge shaped coastal zone, most of which has more than 800 mm, is narrow in the north, highland areas having the largest totals. Very striking rainfall gradients occur over the highlands. Inland from this zone a drier zone is situated where some parts have less that 400 mm/year, further west, rainfall begins to increase over the plateau area.

Seasonal rainfall

If the, arbitrary, criteria of 100 mm per month is used as definition of 'wet' season, the following seasonal distribution can be defined for Tanzania.

Over much of the country, except the north and north-east, the 'wet' season is from November or December to March or April. In the north and north-east, some or all of the months March to May are wet. In certain areas of this region a second 'wet' period is experienced in November/December, although the rainfall is irregular and failure is not uncommon.

The complex patterns and longer seasons of the highlands such as the Usambaras and Kilimanjaro in the north-east, the Uluguru Mountains west of Dar es Salaam and the Southern Highlands stand out significantly as well as the longer seasons of the Lake Victoria areas.

Variability

The variability of rainfall is the criterium for the indication of preferable areas. An important point is that many areas experience a series of consecutive dry years. In perspective of the variability, as a selection criteria for the suitability of this system, it is necessary to assess the reliability of rainfall. A type of map to illustrate this, is presented in Fig. 4.2. From this map can be concluded that only about 20 % of the country has a high probability to receive at least 750 mm in a year. **It further emphasizes the dry conditions in central Tanzania.**

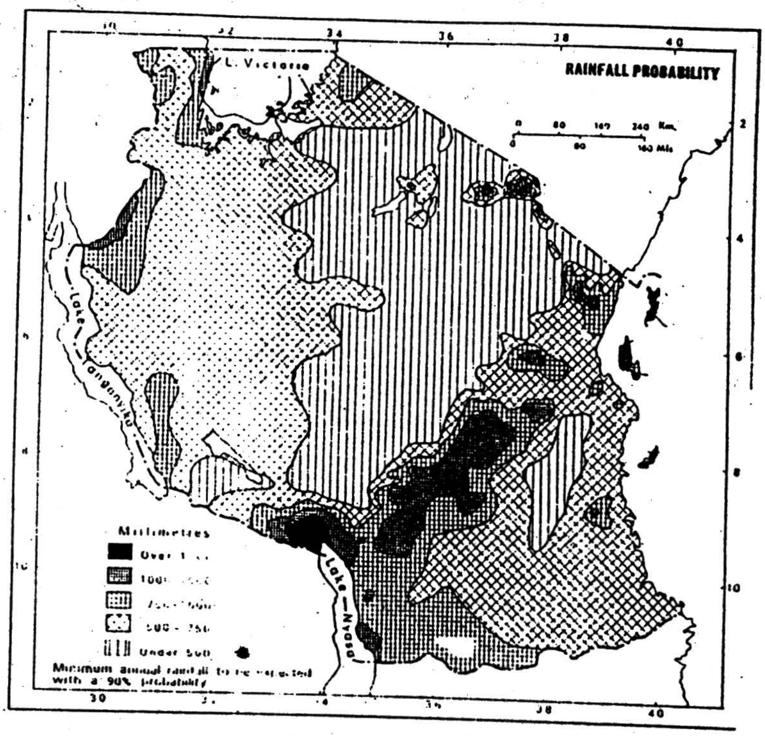


Figure 4.2 : Rainfall probability in Tanzania [20]

B) TYPE OF SOIL

The determination of the type of soil is useful to investigate the properties which are related to the resistivity or more correct the ability to conduct electrical current, which were summarized in the beginning of this chapter. In the next paragraph a classification system for soils will be briefly described.

Soil classification (US Department of Agriculture) [12]
The richest and best developed soils consist of three zones which form the soil profile, some soils have all three zones and some have even none.

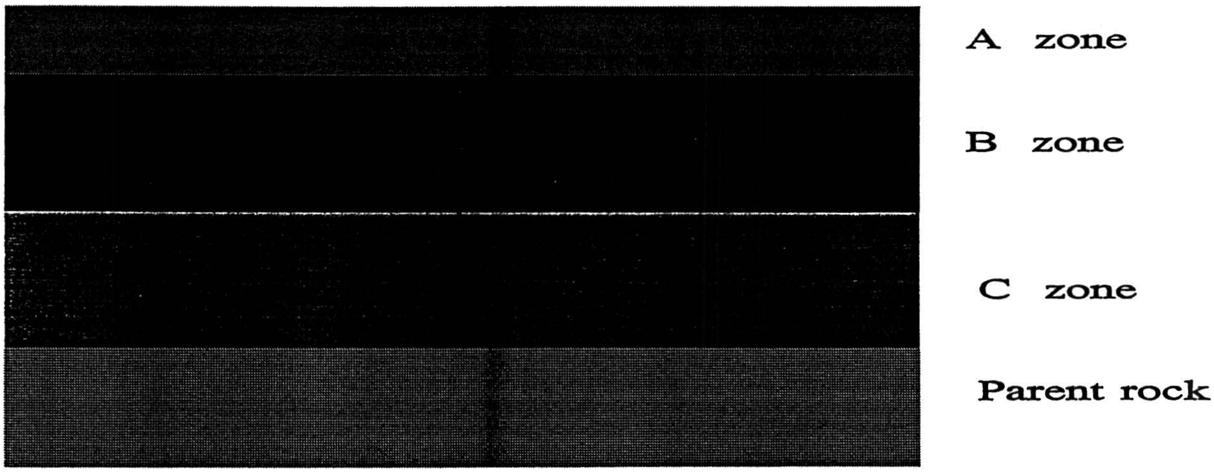


Figure 4.3 : Schematic view of a soil profile

- Soils without differentiated horizons (termed, auto-ingesting soils) are homogenized by the effect of alternate wetting and swelling. These soils have only one horizon above the C horizon.
- Transported soils (floodplain, alluvium and sand dunes) may have only one horizon.
- Soils formed over long periods are subjected to complicated processes including climate, weathering of parent rock, biological commodities, topography, chemical activity, mechanical activity, and time.

Climate : The two most important aspects of this variable are the rainfall and temperature. **The optimal amount of rainfall is 750 mm/year.** With this amount of rainfall a year, there will grow enough vegetation to produce good humus content in the soil profile, without washing and leaching away humus and nutrient minerals. With less rainfall there will grow an insufficient amount of vegetation to produce enough humus. A further decrease may even result in saline soils.
If the rainfall exceeds the optimum, more and more leaching of both humic and mineral nutrients occurs. Consequently soils are not as rich and less suitable for agriculture.

Temperature : This variable is less important, biological and chemical processes are accelerated at higher temperatures.

Table 4.2 : Classification of the different zones.

Chemical horizon	Transfer status	Description
A	zone of elevation of removal (leaching) of minerals	Top of A zone, if organic material only, called A_0, zone of maximal leaching, upper part may be dark coloured because of organic content, remainder usually light because of leaching
B	zone of illuviation or addition (accretion) of minerals	zone of maximum accretion or (accumulation of mineral materials, either leached from A zone or brought by rising water of C zone.
C	little transfer except desert soil	weathered parent material
R	none	unweathered bedrock

The U.S. department of Agriculture adopted, over the years modified, a classification system of soils, developed by Russian soil scientists. Although not used any more, it is referred to because of the fact that it has been used by a lot of nations. The classification system is based on the development of profiles and horizons and it classifies soils in a hierarchy of three major categories : orders, suborders and great soil groups.

- Many soils, if reasonable mature, differ according to the climate in which they matured, this is the **zonal order,**
- Others, such as bog soils and saline soils, are related to local drainage conditions, this is the **intra zonal order,**
- The third group, consisting of young soils without profile development, fall within the **azonal order** (recent sand dunes, alluvium soil and floodplain)

Most classifications take important phenomena into account like climate (temperature, rainfall), nature of parent rock, topography, capillary rise, ground water in relation to leaching, etc.

Table 4.3 : Description of zonal soils at suborder and great soil group level

Suborder	Great soil group	Description
Soils of cold zone	Tundra	thin, rocky, but may be high in humus and nutrients
Desert soils	reddish desert soils	thin, reddish or light brown soils with little or no A horizon and with calcareous horizons frequently saline : hot arid climates
	sierezoms (light grey desert soils)	thin grey soils with little or no A horizon and with calcareous horizons frequently saline : cool or temperate climates
Grassland soils	prairie soils	dark brown soils with some leaching in A horizon and calcareous B zone
	chernozems	dark brown to nearly black
	chestnut soils	dark brown soils with moderately deep humus layer and accreting A and B zones
	reddish chestnut and brown soils	brown soils with thinner humus profile and highly accreting A and B horizons
Temperate forest soils	podzols	light coloured soils with leached A zone and thin dark humus zone (A_0), B zone may be thin
	grey podzol soils	grey soils with leached A zone and thin dark humus zone (A_0), B zone may be thin
	brown podzol soils	brown soils with leached A zone and thin dark humus zone (A_0), B zone may be thin
	red-yellow podzolic soils	red and yellow soils with leached A zone and thin dark humus zone (A_0), or leached humus, B zone may be thin
Latozols (soils of the tropical woodlands)	lateric latozols	red and reddish soils leached of soluble minerals and of alumina, and silica, retaining iron oxides and hydro oxides
	bauxite latozols	red and reddish soils leached of soluble minerals and of iron and silica, retaining aluminum oxides
	siliceous soils	grey and reddish soils leached of soluble minerals and of alumina and iron, retaining or accreting silica
Mountain soils		rocky, usually thin, extremely variable spotty

Table 4.4 : Description of intrazonal soils at suborder and great soil group level

Suborder	Great soil group	Description
Saline and alkaline soils of arid and near shore regions	all of these saline soil produced by peculiar and local environments	soils of various colours accreting soluble salts in all horizons, particularly the A zone
Hydromorphic soils	various kinds of bog and march soils formed in peculiar and local ground water conditions	mostly dark and peaty or muddy soils, poorly drained
Calcimorphic soils	soils in which limestone parent rock overrides the leaching effect of climate	dark or light soils with calcareous A and B horizons, some have been termed false chernozems
Terra rosa soils	usually developed on limestone parent rock	reddish, thin, lightly leached
Auto-ingesting soil	usually developed on montmorilontic claystone parent rock	shrinkage during dry periods allows cracking, humus and surface materials fall into the cracks, through time, the soil profile is homogenized and distinct horizons do not develop

Table 4.5 : Description of azonal soils at suborder and great soil group level

Suborder	Great soil group	Description
Transported soil	usually alluvial : sand dunes and also sand fields	horizons are not developed, original depositional feature still preserved
Negosols and Lithosols		rocky soils are soils, made up of fragments of unaltered parent rock

Favourable types of soil profiles are those which have layers with sufficient depth to penetrate electrodes to an average of six metres, which is common practice and those soils which possess properties that indicate a low resistivity. The existence of all the three zones is preferable. Volcanic soil which receive enough rain, is an example of a suitable type of soil.

C) SOIL MOISTURE AND TEMPERATURE REGIMES

The information on the soil moisture and temperature regimes is derived from a publication with calculated soil moisture and temperature regimes in Africa [13]. The regimes have been calculated using atmospheric data as inputs (rainfall and temperature) for a computation model developed by F. Newall ('72)
Three kind of maps are presented in the publication : (1) soil temperature regimes , (2) soil moisture regimes and (3) tentative subdivisions of soil moisture regimes. For this issue I will only give a brief description of the scientific classifications of the above mentioned variables and indicate preferable regimes and the areas which have these characteristics in Tanzania (table 4.9 and figure 4.12). For the data for the total area of Tanzania I refer to Appendix A.1.

Limitations of the model
The used temperature and rainfall data were obtained from various sources. The monthly data are usually averages over many years. Individual extreme years are, therefore, reduced in influence. Conclusions from these calculations should be made with care, after checking probabilities of occurrence for stations where monthly rainfall over several years are available.
In the present model, Thornthwait's potential evaporation was used to estimate the removal of water from the soil. In all instances the soil temperature was calculated by adding 2,5 °C to the mean annual air temperature. The amplitude of temperature variation at 50 cm depth between winter and summer was reduced by 33% of the difference between air temperatures for the same seasons. The seasons months where December, January, and February or June, July, and August for winter or summer depending on the hemisphere.
Moisture regimes are defined on basis of conditions existing in the moisture control section[1] which is located well below the surface horizons in the profile. The topsoil is not considered.
All rainfall is considered effective; percolation of water through the profiles is unrestricted. Storage of water as snow on top of soil is not considered in the model.

Table 4.7 : Soil temperature regimes (soil taxonomy 1975)

Temp. regime	Description
Pergeli	Mean annual soil temperature is < **0°C**. These are soils that have **permafrost** if they are moist, or **dry frost** if excess water is not present.
Cryic	Mean annual soil temperature is > **0°C** but < **8°C**.
Frigid	Soil is warmer in summer than one in the **Cryic** regime, but its mean annual soil temperature is < **8°C**, difference between mean winter and mean summer soil temperature is > **5°C** at a depth of 50 cm.
Mesic	Mean annual soil temperature is ≥ **8°C** but < **15°C**, the difference between mean summer and mean winter soil temperature is > **5°C** at a depth of 50 cm.
Thermic	Mean annual soil temperature is ≥ **15°C** but < **22°C**, the difference between mean summer and mean winter soil temperature is > **5°C** at a depth of 50 cm.
Hyperthermic	Mean annual soil temperature is ≥ **22°C** , the difference between mean summer and mean winter soil temperature is > **5°C** at a depth of 50 cm.
If the name of a soil temperature regime has the prefix **iso** the mean summer and mean winter soil temperature differ by **less than 5°C** at a depth of 50 cm.	
Isofrigid	The mean annual soil temperature is < **8°C**.
Isomesic	The mean annual soil temperature is ≥ **8°C** but < **15°C**.
Isothermic	The mean annual soil temperature is ≥ **15°C** but < **22°C**.
Isohyperth.	The mean annual soil temperature is ≥ **22°C**.

[1]The soil moisture control section lies approximately between 10 and 30 cm if the particle-size class is fine loamy, coarse-silty, fine-silty or clayey. The control section extends approximately from a depth of 20 cm to a depth of 60 cm if the particle size class is coarse loamy, and from 30 to 90 cm if the particle size is sandy. Coarse fragments deepen this limits to the extent that the fragments do not absorb and release water. In addition to the particle-size class, difference in structure, differences in pore-size distribution and in other factors that influence the movement and retention of water in the soil also affects the soil moisture control section.

Classes of soil moisture regimes (soil Taxonomy 1975)

The moisture regimes are defined in terms of the ground water level and in terms of the presence or absence of water held at a tension <15 bars in the moisture control section (MCS) by periods of the year. It is assumed in the definitions that the soil supports whatever vegetation it is capable of supporting.

Table 4.6 Classes of soil moisture regimes

Classes	Description
Aridic and Toric	Aridic (toric) moisture regime, moisture control section (MCS) in most years is **(1) dry in all parts more than half the time (cumulative)** that the soil temperature at a depth of 50 cm is > 5°C, and **(2) never moist in some or all parts for as long as 90 consecutive days** when the soil temperature is > 8°C at a depth of 50 cm.
Udic	This implies that in most years the soil moisture control section (MCS) is **not dry in any part for as long as 90 days (cumulative)**. This regime is **common to soils of humid climates** that have **well-distributed rainfall or that have enough rain in summer** that the amount of stored moisture plus rainfall is approximately equal to or exceeds the amount of evapotranspiration.
Ustic	Intermediate between the **aridic** and the **udic** regime. The concept is one of **limited moisture**, but the moisture is present at a time when conditions are suitable for plant growth.
Xeric	It is typified in **Mediterranean climates**, winters are moist and cool and summers are warm and dry. The moisture coming in winter when potential evapotranspiration is at a minimum is particularly effective for leaching.

Table 4.8 : Key to tentative subdivision of moisture regimes

Key to subdivision of ARIDIC	
Extreme Aridic	A moisture regime in which the **MCS is always completely dry.**
Typic Aridic	**A moisture regime** in which the MCS is **moist in some or in all parts at some time in one year for 45 consecutive days or less when the soil temperature at 50 cm depth is > 8°C.**
Weak Aridic	These are **moist in some or all parts of the MCS for more than 45 consecutive days** during the time that the soil **temperature at 50 cm depth is > 8°C. Maximum** length of the time that **some water is available in the MCS is < 3 months.**
Key to subdivision XERIC	
Dry Xeric	Soils with **wet winters and dry summers**, a **Xeric moisture regime** in which the MCS is **dry in all parts for more than 3 months during summer.**
Typic Xeric	Those soils in which the MCS is **completely moist during more than 45 consecutive days during the four months following the winter solstice.** The **MCS dries out completely between 45 and 90 days in the summer.**
Key to subdivision of USTIC	
Aradic Tropustic	A moisture regime in which there is **acute moisture stress lasting several months.**
Typic Tropustic	These are **dry in some or all parts for more than 3 months during one year.** Time that the **MCS is completely or partly moist without interruption,** and **the soil temperature is > 8°C, varies between 6 and 9 months.**
Udic Tropustic	The **MCS is dry in some or all parts for more than 90 cumulative days.** number of **consecutive days that there is some available water in the MCS is 270 or more.**
Xeric Tempustic	It has all the characteristics of a **Xeric** moisture regime **except the temperature requirement** implied in the definition of xeric.
Wet Tempustic	These soils **suffer from moisture stress** in the MCS **for more than 3 months , but they never dry out completely during the four months after the summer solstice for more than 45 days.** They are **completely moist in winter for more than 45 days in the period of four months following the winter solstice.**
Typic Tempustic	It has **marked seasonal variation both in temperature and moisture.** There are **more than 90 days in one year** that the **MCS is dry in some or all parts.**
Key to subdivision of UDIC	
Typic Udic	The **MCS is moist in all parts for at least eleven months in one year.** The **MCS seldom dries out completely.** There is **at least one month** where the **evapotranspiration is > actual precipitation.**
Dry Tropudic	The soils have **at least nine months in one year that the MCS is completely moist.** However **at least one month has some dryness;** some soils **dry** out completely in the control section but seldom for more than one month. In **iso-hyperthermic regimes** there is **almost always some moisture in the control section for approximately 10 consecutive months.**
Dry Tempudic	This is a regime with **a minimum of nine months in one year** during which **the MCS is completely moist.** However, the length of the time that **the MCS is dry in some parts is at least one month.**
Perudic	Moisture regime **defined by properties of the atmospheric climate.** For each month the rainfall exceeds the potential evapotranspiration. **When considered on a monthly basis the MCS is always completely moist.**

Suitable regimes are those where **the MCS (Moisture Control Section) of the soil almost never dries out in the whole year**. Following the determination of soil moisture according to Franklin Newhall system of computation, the following tentative moisture regimes, with their manifestation in Tanzania, will be suitable :

Table 4.9 : Preferable tentative moisture regimes and appearance in Tanzania

Tentative moisture regime	Place of appearance	Cumulative days in one year that MCS is			Max. consecutive days MCS is moist
		Dry	Partly moist	Moist	
Dry Tempudic	-	-	-	-	-
Dry Tropudic	Kisauni	0	63	297	360
Perudic	-	-	-	-	-
Typic Udic	Amani	0	0	360	360
	Bukoba	0	0	360	360
	Lushoto	0	0	360	360
	Lyamungo	0	0	360	360
Udic Tropustic	Arusha	12	89	259	348
	Biharamulo	0	100	260	360
	Mbulu	5	100	255	355
	Mwanza	21	115	224	311
Wet Tempustic	-	-	-	-	-

D) COURSE OF THE ELECTRICITY GRID IN TANZANIA

On the map with the main electricity distribution network, the potential service area of the Single Wire Earth Return system in the present situation can roughly be illustrated (see Fig. 4.3.

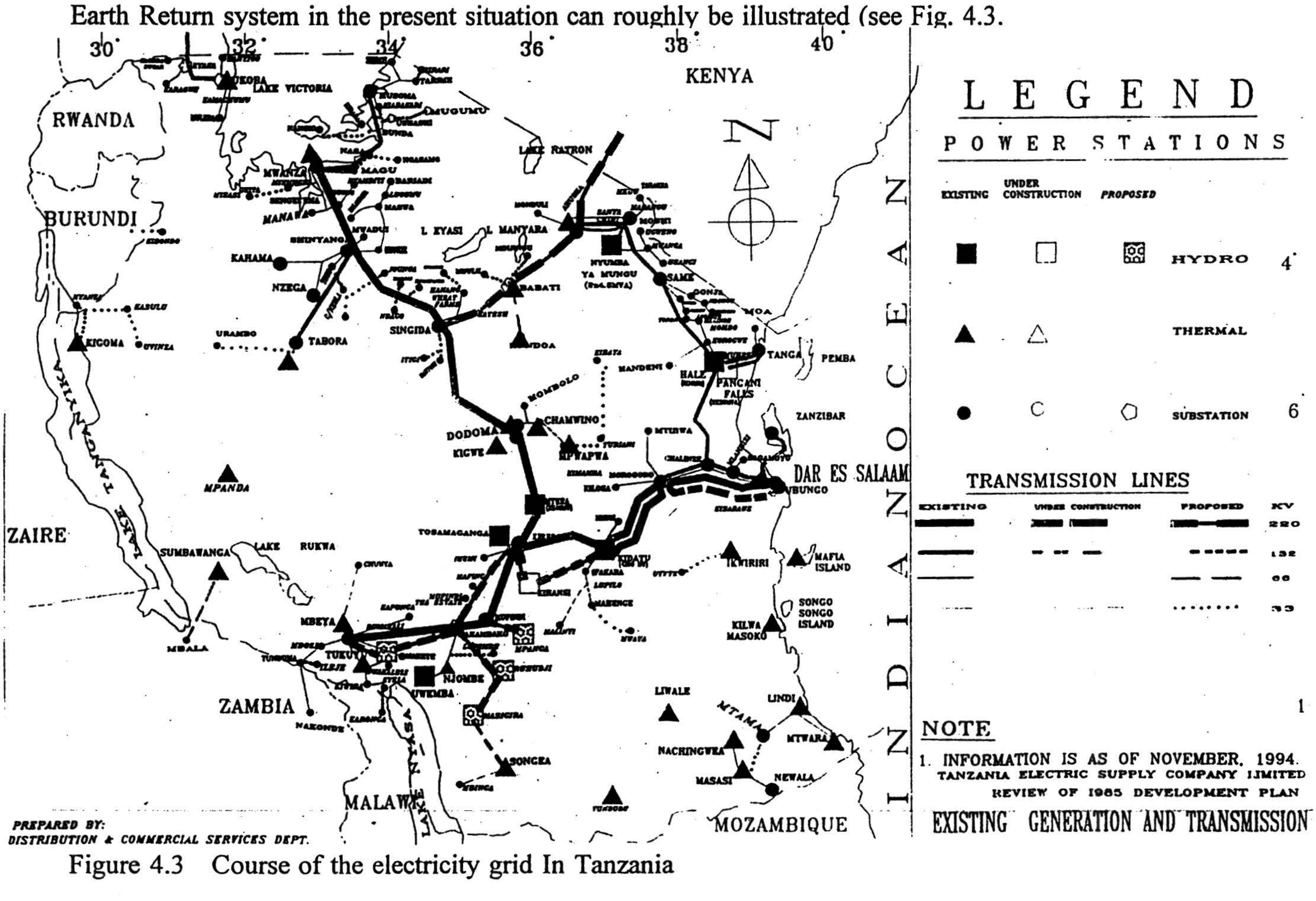


Figure 4.3 Course of the electricity grid In Tanzania

Table 4.10 : Summary of the main criteria in relation to the technical viability

Variable	Relation to Viability	Criteria
Soil moisture regime	soil resistivity	MCS moist or partly moist whole year through
Rainfall probability	soil resistivity	≥ 750 mm/year
Soil type	soil resistivity	types with high chance that ρ ≤ 500 ohm.m
Depth of soil profile	sufficient for a safe earthling system	minimum depth of 6 m
Distance from main distribution network	maximum voltage drop along the distribution line	maximum ≈ 50 km
Electricity consumption	maximum allowable load current of the distribution line	P ≤ 250 kW per distribution transformer

4.3 INVESTIGATIONS AT LOCAL LEVEL

At the local level the technical question is to determine a site for the substation. Taking into account the specific aspects of the soil current, a safe and reliable place in the specific area is of major importance. Field investigations, of a station site, are therefore essential to determine both general soil composition and some basic ideas as to its homogeneity. Drilling test samples and other geological soil investigations can provide useful information on the presence of various layers and the nature of soil material which will lead to some ideas about their resistivity and the range of values at the site (less than 500 Ω.m).
This information is used to design the grounding system. According to the soil resistivity and the division in layers the type of grounding system and its depth of burial can be selected. In situations where in greater depth the soil resistivity is lower than in the upper layers, deep driven rods are an option. On the contrary, if the soil resistivity in the upper layers is lower, the use of a grounding mat buried in the upper layer is an option.
There are two methods, which can be combined, on which a conclusion can be based.

1 - measurement of resistivity, if possible including temperature data, information on the moisture condition of the soil at the time of measurement and all data available on buried conductors already known or suspected to be in the area studied [2] and
2 - classification of the soil on basis of grain size and distribution of grain size and closeness of packing and pressure.

4.3.1 Direct measurement of soil resistivity

The measurement of soil resistivity is usually executed by the injection of a current into the earth by a pair of current probes and measurement of the resulting fall of potential by a second pair of probes. The equations, of the four electrodes configuration, for the resistivity as function of electrode spacing, voltage drop and depth of the electrodes, are derived in the following paragraph. As result two expressions, one for the equal electrode spacing and one for the unequal electrode spacing are obtained.

Derivation of equations

The derivation of equations for the expression of the resistivity by a four terminal measuring method are as follows. In Fig 4.4, which represents part of an infinite conductor of uniform resistivity, suppose a unit current enters at the point marked 1. This current will flow away radially from the point of entry and at a distance r from the point 1 the current density will be $1/4\pi r^2$. This follows from the fact that at a radius r, the current will be uniformly distributed over a sphere of radius r and hence of area $4\pi r^2$ Now the potential gradient is equal to the current density multiplied by the resistivity. So

$$-\frac{\partial V}{\partial r} = \frac{\rho}{4\pi r^2} \qquad (1)$$

where V is the potential at a distance r from the point 1.
The difference in potential (V_1 - V_2) between two points with distance r_1 and r_2 from 1 is obtained by integrating the potential gradient from $r = r_1$ to $r = r_2$ i.e.

$$V_1 - V_2 = \frac{\rho}{4\pi}\int_{r_1}^{r_2}\frac{dr}{r^2} = \frac{\rho}{4\pi}\left(\frac{1}{r_1} - \frac{1}{r_2}\right) \qquad 4.2$$

If V_x is the potential difference between the points 2 and 3 distant a and $2a$ from 1, caused by the unit current flowing radially outward from 1, then equation 4.2 gives

$$V_x = \frac{\rho}{8\pi a} \qquad 4.3$$

Again if V_y is the difference in potential between 2 and 3 caused by unit current flowing radially towards 4,

$$V_y = \frac{\rho}{8\pi a} \qquad 4.4$$

If unit current enters the conductor at 1 and leaves at 4, the current density at any point is the vector sum of that due to unit current flowing from 1 and that due to unit current flowing towards 4. Also, the potential difference between any two points is the sum of that which results from the flow of unit current from 1 and that which results from the flow of unit current towards 4.
So the potential difference between points 2 and 3 due to unit current entering at 1 and leaving at 4 is

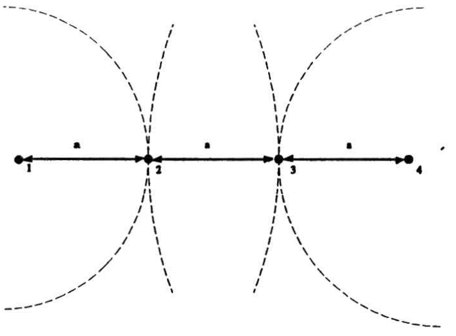


Figure 4.4 Terminals in an infinite conductor

$$V_x + V_y = \frac{\rho}{4\pi a} \qquad 4.5$$

Since the difference in potential for unit current using 1 and 4 as current terminals and 2 and 3 as potential terminals, is the resistance *R*,

$$R = \frac{\rho}{4\pi a} \qquad 4.6$$

R is actually the resistance between the equipotential surfaces on which the potential electrodes are placed.
In the practical case however, it is not possible to assume an infinite conductor, unless the distance between the electrodes is small compared with their distance below the surface, and so equation 4.6 is not applicable.
To deal with the practical case consider an arrangement of Fig. 4.5 which represents an infinite conductor again. We simulate the presence of a non-uniformity at plane MN by the use of additional current source 5 and 6. If now V_1 is the potential difference between the points 2 and 3 caused by the unity current entering the conductor at 1, then from equation 4.2

$$V_1 = \frac{\rho}{4\pi}\left(\frac{1}{r_{12}} - \frac{1}{r_{13}}\right) \qquad 4.7$$

Also the potential difference between 2 and 3 caused by unit current leaving at 4 is V_4, that caused by unit current entering at 5 is V_5, and that caused by unit current leaving at 6 is V_6, then

$$V_4 = \frac{\rho}{4\pi}\left(\frac{1}{r_{43}} - \frac{1}{r_{42}}\right) \qquad V_5 = \frac{\rho}{4\pi}\left(\frac{1}{r_{52}} - \frac{1}{r_{53}}\right) \qquad V_6 = \frac{\rho}{4\pi}\left(\frac{1}{r_{63}} - \frac{1}{r_{62}}\right)$$

now if a current I enters at 1 and leaves at 4 and at the same time an equal current enters at 5 and leaves at 6, the potential difference ▲V, between 2 and 3 is $(V_1 + V_4 + V_5 + V_6)$ or,

$$\Delta V = \frac{I\rho}{4\pi}\left(\frac{1}{r_{12}} - \frac{1}{r_{13}} + \frac{1}{r_{43}} - \frac{1}{r_{42}} + \frac{1}{r_{52}} - \frac{1}{r_{53}} + \frac{1}{r_{63}} - \frac{1}{r_{62}}\right) \qquad 4.9$$

In deriving this equation it has been assumed that 1, 2, 3, 4, 5 and 6 represent points. The equation can however be used without appreciable error where these six points represent metallic electrodes or terminals on a conductor of relatively high resistivity, provided that the dimensions are small in comparison with the distance between them. If the points 5 and 6 are so placed that it is possible to choose a plane (represented by the line *MN* in Fig 4.5 through the conductor, such that the lines joining 1 and 5, and 4 and 6 are normal to and bisected by it, it will be evident on the account of the symmetrical arrangement, that no current passes through this plane. So the part of the conductor on one side of the plane can be removed without changing the conditions on the other side.

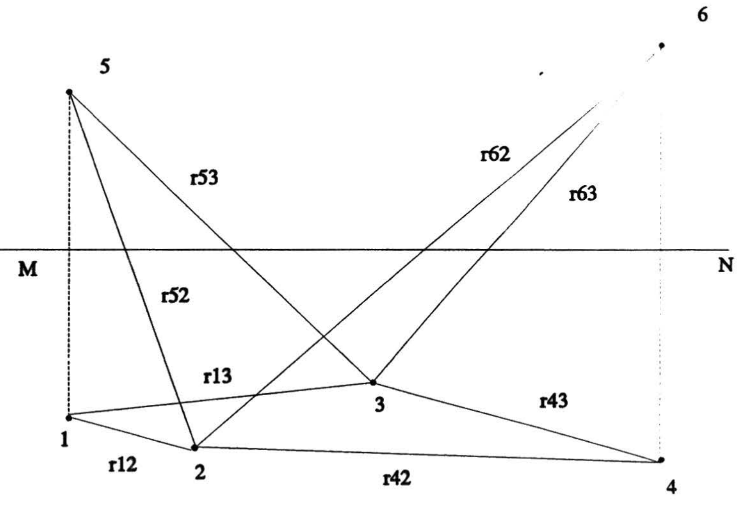


Figure 4.5 Showing relations between the variables

Thus the equation applies to a semi-infinite conductor having four terminals. This does not, however, require that the potential terminals be in the same plane as the current terminals and their images, as they are in Fig 4.5.

Since the drop in potential V between 2 and 3 divided by the current I, entering at 1 and leaving at 2 is the resistance R, it follows from equation 4.9 that

$$R = \frac{\rho}{4\pi}\left(\frac{1}{r_{12}} - \frac{1}{r_{13}} + \frac{1}{r_{43}} - \frac{1}{r_{42}} + \frac{1}{r_{52}} - \frac{1}{r_{53}} - \frac{1}{r_{63}} - \frac{1}{r_{62}}\right) \qquad 4.10$$

It will, therefore be evident that the equation gives the relation between the resistivity, resistance, depth and distance between small electrodes in the earth as shown in Fig. 4.4, or in the more general case when the electrodes are not in a straight line. If the electrodes are all at a uniform depth d and at a uniform distance apart a in a straight line, then

$r_{12} = a$, $r_{13} = 2a$, $r_{43} = a$, $r_{42} = 2a$, $r_{52} = \sqrt{(a^2 + 4d^2)}$, $r_{53} = \sqrt{(4a^2 + 4d^2)}$, $r_{63} = \sqrt{(4d^2 + a^2)}$ and $r_{62} = \sqrt{(4d^2 + 4a^2)}$

$$R = \frac{\rho}{4\pi}\left[\frac{2}{a} - \frac{1}{a} + \frac{2}{\sqrt{a^2+4d^2}} - \frac{2}{\sqrt{4a^2+4d^2}}\right] \qquad 4.11$$

In the practical case the depth d of the electrodes is negligible small in comparison to distance between the electrodes, practical values are depth (d) $\leq$ 0,15 m and electrode spacing (a), for the Wenner configuration, $\geq$ 3 m.

For the configuration where the electrodes are at equal distance a, the Wenner configuration (see Fig. 4.6 a), this will lead to the following expression for the resistivity ρ with,
$r_{12} = a,\ r_{13} = 2a,\ r_{43} = a,\ r_{42} = 2a,\ r_{52} = a,$
$r_{53} = 2a,\ r_{63} = a$ and $r_{62} = a$

$$R = \frac{\rho 2}{4\pi a} = \frac{\rho}{2\pi a}$$

$$\rho = 2\pi a R = 2\pi a \frac{V}{I} \qquad 4.12$$

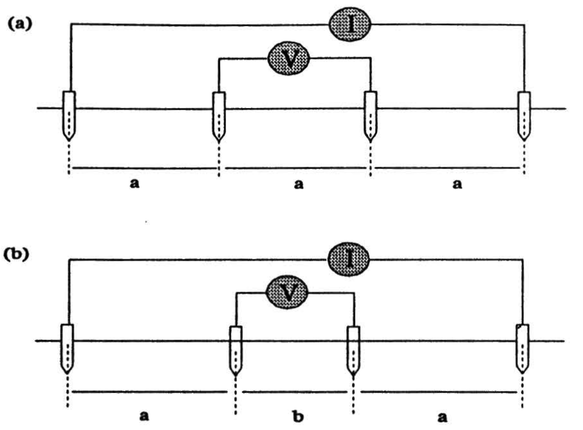


Figure 4.6 Wenner (a) and Schlumberger (b) configuration

For the configuration with unequal electrode spacing, called the Schlumberger configuration (see Fig. 4.6b), the expression of the resistivity ρ, with a = distance between current and potential electrode and b = distance between current electrodes,
$r_{12} = a,\ r_{13} = a + b,\ r_{43} = a,\ r_{42} = a + b,\ r_{52} = a,\ r_{53} = 2b,\ r_{63} = a$ and $r_{62} = a + b$
is the following,

$$R = \frac{\rho}{4\pi}\left[\frac{4}{a} - \frac{4}{a+b}\right] = \frac{\rho}{\pi}\left[\frac{b}{(a^2+ab)}\right]$$

$$\text{if } a \gg b \text{ then} \qquad 4.13$$

$$\rho = \pi\left[\frac{a^2}{b}\right]R = \pi\left[\frac{a^2}{b}\right]\frac{V}{I}$$

In the practical situation resistivity's are referred to as apparent[2] resistivity's as result of inhomogeneity of the subsoil. The expressions derived in this paragraph can be used in the analysis of actual measurements. In the next paragraph an analysis method of apparent resistivity in a multi-layer soil structure will be described, with the application of the Wenner configuration.

[2] apparent resistivity, because the subsurface may perhaps consist of several layers with different resistivity's. As the current is input into the subsurface it penetrates to various depths depending on this subsurface and characteristics of the current. When potential difference and intensity of current between two electrodes is measured the result does not give the resistivity of the subsurface but its apparent resistivity.

4.3.2 Analysis of apparent resistivity

In the design procedure of the grounding system, which is a key factor in the design of the total distribution system, estimation of soil resistivity is not the only parameter of concern. The presence of different layers of soil and their corresponding depth and resistivity are the most relevant parameters (see the introduction of this paragraph). For this purpose a multi-layer analysis can be performed at the potential site of a isolation transformer or distribution transformer.
The soil is nearly always non-homogeneous and these non-homogeneities can take many forms. In most cases there are several layers of soil, which can consist of loam, sand, gravels, clay or a mixture of these and rocks. These layers may be approximately horizontal and parallel to the surface or may be inclined at an angle to the surface. It should be noted that the water table acts as an additional layer, since the increase in moisture content below the water table will result in a significant change in resistivity in a number of instances. Theoretically, the parallel layer problem is a comparatively simple one, although the result may not be considered as being very simple.
Lateral changes in resistivity can be produced by a vertical fault and the soil on each side of this fault may be of different constituents or the depths to the various layers may change. In either case, there is likely to be a significant change in resistivity and such a change can be detected and used to locate the position of the fault. Buried objects can also be located under certain favourable conditions, since the presence of such a body can produce a difference in the apparent resistivity's obtained when the electrode system is well removed from the vicinity of the object [11].
A description of a method to analyze multi-layered soil is put forward in the next paragraph. The method is referred to as the *ρ-a* curve method, where the Wenner four electrode measurement is used [22].

Derivation of equations for soil resistivity calculations.

The problem is illustrated in Fig. 4.7. We consider the electrode as a point current source. The location is at the soil surface. The problem to be answered is the voltage at the soil surface as a function of the soil resistivity. The voltage, V(x, ϕ, z), at a point (x, ϕ, z) inside the earth must satisfy the Laplace equation.

$$\nabla^2 V(r,\phi,z) = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial V(r,\phi,z)}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2 V(r,\phi,z)}{\partial \phi^2} + \frac{\partial^2 V(r,\phi,z)}{\partial z^2} = 0 \qquad 4.14$$

where x, ϕ, z are the coordinates of a point relative to a system of cylindrical coordinates. Because of the symmetry of the problem, the solution is independent of the coordinate ϕ. Thus V(x, ϕ, z) = V(x, z). Then the Laplace equation becomes

$$\nabla^2 V(x,z) = \frac{1}{x}\frac{\partial}{\partial x}\left(x\frac{\partial V(x,z)}{\partial x}\right) + \frac{1}{x^2}\frac{\partial^2 V(x,z)}{\partial z^2} = 0 \qquad 4.15$$

The general solution to this equation is known[3]. It is given in terms of the Bessel function of zero order, J_0 :

$$V(x,z) = \frac{I\rho}{4\pi}\int_{k=0}^{\infty} \theta(k) J_0(kx) e^{\pm kz}\, dk \qquad 4.16$$

while the current source is at the soil surface

$$V(x,z) = \frac{I\rho}{2\pi}\int_{k=0}^{\infty} \theta(k) J_0(kx) e^{\pm kz}\, dk$$

where, k is a dummy variable and Θ(k) is an unknown function of k.

[3] *Handbook of Mathematical Functions*, U.S. Department of Commerce, National Bureau of standards, 1964.

The fundamental solution is given by the following equation [11]

$$V_0 = \frac{I\rho_0}{2\pi}\int_0^\infty e^{-k|z|} J_0(kx)\, dk \qquad 4.17$$

The arbitrary function Θ(k) depends on the boundary conditions for a specific problem.
A solution of the potential at any point in the soil consists of the combination of the fundamental solution plus the additional function(s) corresponding to the influence of the other layers. For a current I flowing through a point electrode situated on the surface, assuming a homogeneous and isotropic soil resistivity, is given by the fundamental solution (Eq. 4.17). In this description a low frequency domain is assumed in which all current can be treated as direct current.

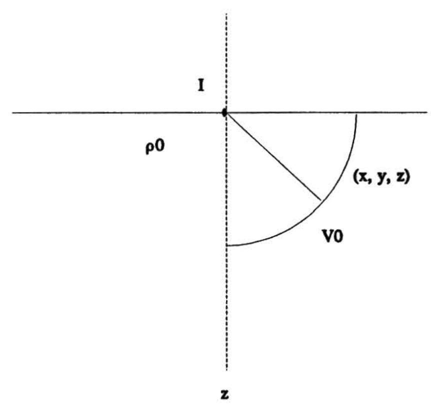


Figure 4.7 Potential at any point in the soil

Horizontal stratified two-layer soil model.
In Fig. 4.8 a model of the two-layer soil is shown. In this figure h_1 is the thickness of the first layer and ρ_1 and ρ_2 are the resistivity's of the two layers. The potential for any point in each layer is given by the equation 4.17

$$V_1 = V_0 + V_1^{\prime} \qquad 4.18$$
$$V_2 = V_0 + V_2^{\prime}$$

V_0 is the potential for a homogeneous soil of resistivity ρ_0 and can be expressed by the fundamental solution (Eq. 4.16). In this equation we can let $|z| = z$, since the direction along the z-axis from the origin downward is taken as positive. The terms $V_1^{\prime}$ and $V_2^{\prime}$ in equation are correction terms corresponding to the influence of the second layer and are expressed in the following equations. Where the unknown function f(k) and g(k) are used.

$$V_1^{\prime} = \frac{\rho_1 I}{2\pi}\int_0^\infty \{ f_1(k)\, e^{-kz} + g_1(k) e^{kz} \}\, J_0(kx) dk \qquad 4.19$$

$$V_2^{\prime} = \frac{\rho_1 I}{2\pi}\int_0^\infty \{ f_2(k)\, e^{-kz} + g_2(k) e^{kz} \}\, J_0(kx) dk \qquad 4.20$$

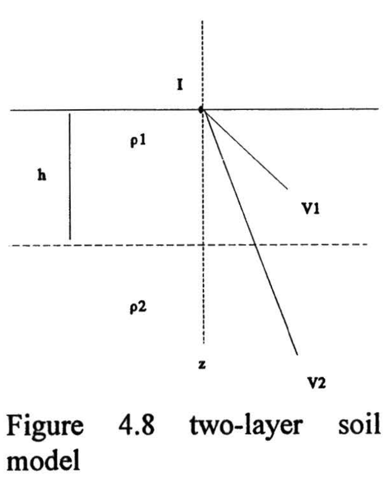


Figure 4.8 two-layer soil model

Substitution equations 4.17, 4.19 an 4.20 into equation 4.18, we get

$$V_1 = \frac{\rho_1 I}{2\pi}\int_0^\infty \{ [1+f_1(k)]\, e^{-kz} + g_1(k) e^{kz}\}\, J_0(kx)\, dk \qquad 4.21$$

$$V_2 = \frac{\rho_1 I}{2\pi}\int_0^\infty \{ [1+f_2(k)]\, e^{-kz} + g_2(k) e^{kz}\}\, J_0(kx)\, dk \qquad 4.22$$

The unknown functions *f(k)* and *g(k)* are determined according to the following boundary conditions, (1) at z -> ∞ the voltage is zero, (2) at the soil surface (off-axis) the electric field in z-direction is zero, (3) the voltage must be a continuous function, (4) the electric current must be a continuous function :

1 - $As\ \ z \to \infty,\ V_2 \to 0$

2 - $At\ \ z = 0,\ \frac{\partial V}{\partial z} = 0$

3 - $At\ \ z = h,\ V_1 = V_2$

4 - $At\ \ z = h,\ (\frac{1}{\rho_1})(\frac{\partial V_1}{\partial z}) = (\frac{1}{\rho_2})(\frac{\partial V_2}{\partial z})$

Thus, solving for these two functions with the above boundary conditions we get

$$f_1(k) = \frac{k_{r1} e^{-2kh}}{1 - k_{r1} e^{-2kh}}$$

$$g_1(k) = f_1(k)$$

$$where \qquad k_{r1} = \frac{(\rho_2 - \rho_1)}{(\rho_2 + \rho_1)}$$

Substituting these expressions for $f_1(k)$ and $g_1(k)$ into equation 4.21, and rearranging, the potential at the soil surface *(z = 0)* can be expressed by

$$V_x = \frac{\rho_1 I}{2\pi x}[1 + F_2(x)] \qquad 4.23$$

$$where \qquad F_2(x) = 2x\int_0^\infty \frac{k_1 e^{-2\lambda h}}{1 - k_1 e^{-2\lambda h}} J_0(\lambda x)\, d\lambda$$

The reflection coefficient k_r is an important quantity. It varies between -1 and +1 and if the second layer is a pure insulator $\rho_2 = \infty$, then $k_r = +1$ and if the second layer is a perfect conductor, $\rho_2 = 0$, then $k_r = -1$, and so depends on the ratio ρ_2/ρ_1 alone. The values of ρ_2/ρ_1 corresponding to various values of k are given in Table 4.11 [11] .

$$k = \frac{(\rho_2 - \rho_1)}{(\rho_2 + \rho_1)} = \frac{\rho_2/\rho_1 - 1}{\rho_2/\rho_1 + 1}$$

Table 4.11 Values of k_r

Value of k_r	ρ_2/ρ_1	Value of k	ρ_2/ρ_1
+1,00		-1,00	0,00
+0,90	19,00	-0,90	0,05
+0,80	9,00	-0,80	0,11
+0,70	5,67	-0,70	0,18
+0,60	4,00	-0,60	0,25
+0,50	3,00	-0,50	0,33
+0,40	2,33	-0,40	0,43
+0,30	1,86	-0,30	0,54
+0,20	1,50	-0,20	0,67
+0,10	1,22	-0,10	0,82
0,00	1,00		

Three to five-layer soil model

Extending the two-layer soil model described in the previous paragraph now we develop a model for a horizontal stratified three to five layer soil structure.

In order to determine a general solution for the potential, we consider corrective terms reflecting the influence of other layers in the same way as equation 4.18, and establish the following boundary conditions, (1) the potential in the lowest layer as z goes to infinity is zero, (2) the current flow at the soil surface is zero, (3) the potential at a boundary is the same for the layers on either side of the boundary and (4) the current is continuous at the boundary between two layers. On the basis of the above, we must now determine the values of the unknown functions.

The overall objective is to determine the potential at the soil surface. Consequently, although all of the unknown functions are necessary in the calculation process, in the end, determining only those in the expression for the V_1 potential in the first layer is sufficient.

Thus, using the equations for the potential in the various layers and employing the above boundary conditions, the unknown functions in the potential equation for the first layer are solved as shown in Table 4.12. Note here that g(k) and f(k) will be equivalent to each other in any multi-layer soil structure.

If we now substitute the unknown functions in Table 4.12 into the potential equation for the first layer, the potential at the soil surface can be determined. For example, in the case of a three-layer structure, we obtain the following equation

$$V_3 = \frac{\rho_1 I}{2\pi x}[1 + F_3(x)] \qquad 4.24$$

where

$$F_3(x) = 2x\int_0^\infty \frac{K_{31}e^{-2kh_1}}{1 - K_{31}e^{-2kh_1}} J_0(kx)\,dk$$

Table 4.12 : Values of functions f(k) and g(k)

earth structure	$f1(\lambda)$	$g1(\lambda)$	Notes
2	$\dfrac{k_1 e^{-2\lambda h_1}}{1 - k_1 e^{-2\lambda h_1}}$	$f1(\lambda)$	$k_1 = \dfrac{\rho_2 - \rho_1}{\rho_2 + \rho_1}$
3	$\dfrac{K_{31} e^{-2\lambda h_1}}{1 - K_{31} e^{-2\lambda h_1}}$	$f1(\lambda)$	$K_{31} = \dfrac{k_1 + k_2 e^{-2\lambda h_2}}{1 + k_1 \cdot k_2 e^{-2-\lambda h_2}}, \quad k_2 = \dfrac{\rho_3 - \rho_2}{\rho_3 + \rho_2}$
4	$\dfrac{K_{41} e^{-2\lambda h_1}}{1 - K_{41} e^{-2\lambda h_1}}$	$f1(\lambda)$	$K_{41} = \dfrac{k_1 + K_{42} e^{-2\lambda h_2}}{1 + k_1 \cdot K_{42} e^{-2-\lambda h_2}}$ $K_{42} = \dfrac{k_2 + k_3 e^{-2\lambda h_3}}{1 + k_2 \cdot k_3 e^{-2\lambda h_3}}, \quad k_3 = \dfrac{\rho_4 - \rho_3}{\rho_4 + \rho_3}$
5	$\dfrac{K_{51} e^{-2\lambda h_1}}{1 - K_{51} e^{-2\lambda h_1}}$	$f1(\lambda)$	$K_{51} = \dfrac{k_1 + K_{52} e^{-2\lambda h_2}}{1 + k_1 \cdot K_{52} e^{-2-\lambda h_2}}$ $K_{52} = \dfrac{k_2 + k_{53} e^{-2\lambda h_3}}{1 + k_2 \cdot K_{53} e^{-2\lambda h_3}}$ $K_{53} = \dfrac{k_3 + k_4 e^{-2\lambda h_4}}{1 + k_3 \cdot k_4 e^{-2\lambda h_4}}, \quad k_4 = \dfrac{\rho_5 - \rho_4}{\rho_5 + \rho_4}$

Horizontally stratified N-layer soil model

The theoretical model for a horizontally stratified N-layer soil structure is shown in Fig. 4.9. Solving for unknown functions by the same method as in the three to five-layer soil model described above, the potential at any point x on the soil surface for a current I entering a surface point electrode can be expressed by the following equation :

$$V_N = \frac{\rho_1 I}{2\pi x}[1 + F_N(x)] \qquad 4.25$$

where $$F_N(x) = 2x\int_0^{\infty} \frac{K_{N1} e^{-2\lambda h_1}}{1 - K_{N1} e^{-2\lambda h_1}} J_0$$

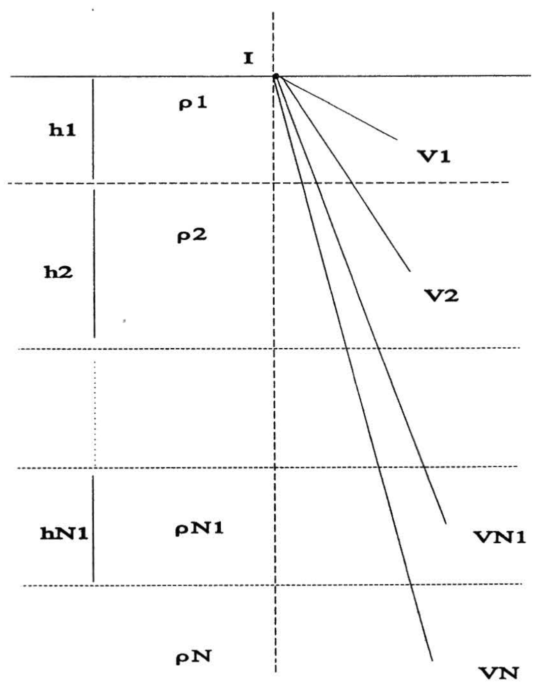


Figure 4.9 N-layer soil model

4.3.3 Application to Wenner's four electrode configuration

The placement of electrodes in Wenner's configuration for a N-layer soil structure is shown in figure 4.10. The distance between any two electrodes is a, and current I is made to flow through the soil by applying a power source between electrodes c_1 and c_2. Given that a potential difference V appears between electrodes p_1 and p_2, the apparent resistivity ρ_a can be expressed by the earlier derived equation 4.12 :

$$\rho_a = 2\pi a \frac{V}{I} \qquad 4.26$$

Labelling the electrodes as electrodes 1 to 4, it can be considered that thew potential due to current I from electrode 1 and that due to current -I from electrode 4 exist independently. Furthermore, since the potentials here assume a N-layer soil, they can be calculated using previously derived equation 4.23. Thus, for electrode 2, if we indicate the potential due to electrode 1 (I) as V_{21}, and that due to electrode 4 (-I) as V_{24}, we obtain the following equations

$$V_{21} = V_N(a) = \frac{\rho_1 I}{2\pi a}[1 + F_N(a)] \qquad 4.27$$

$$V_{24} = V_N(2a) = \frac{\rho_1 (-I)}{4\pi a}[1 + F_N(2a)] \qquad 4.28$$

Likewise for electrode 3 :

$$V_{31} = V_N(2a) = \frac{\rho_1 I}{4\pi a}[1 + F_N(2a)] \qquad 4.29$$

$$V_{34} = V_N(a) = \frac{\rho_1 (-I)}{2\pi a}[1 + F_N(a)] \qquad 4.30$$

We thus obtain the following expression for the potential difference appearing between electrode 2 and 3

$$\begin{aligned} V_N &= V_2 - V_3 = (V_{21} + V_{24}) - (V_{31} + V_{34}) \\ &= \frac{\rho_1 I}{2\pi a}[1 + 2F_N(a) - F_N(2a)] \end{aligned} \qquad 4.31$$

if we now substitute equation 4.31 into the basic equation 4.26, we can obtain the theoretical expression for the apparent resistivity ρ_a in a horizontally stratified N-layer soil model :

$$\rho_a = \rho_1[1 + 2F_N(a) - F_N(2a)] \qquad 4.32$$

where $F_N(x) \big|_{x = a, 2a}$ is of the same form as in equation 4.25

Equation 4.32 is the general equation for calculating the apparent resistivity in the case of a horizontally stratified multi-layer soil structure.

Example of a four layer soil structure

One example will be described, a four layer soil model. Setting the thickness of each layer constant and using soil parameters listed in Table 4.13, the ρ-a curves of figure 4.10 are obtained for a four layer soil structure. Although all curves reflect their corresponding soil parameter values, curves A, B and E in particular have two extreme values. This is due to the irregular way in which the ρ values change . On the other hand, the gradual increase of ρ for curve C and the gradual decrease of ρ for curve D produces no extremity, and a clear distinction between the different layers does not appear.

Table 4.13 Soil parameters for four layer soil

Curve Fig. 4.8	[Thickness (m) = h_1=5, h_2=10, h_3=20] resistivity ρ (Ω.m)			
	ρ_1	ρ_2	ρ_3	ρ_4
A	10	500	10	100
B	100	10	100	10
C	10	50	100	500
D	500	100	50	10
E	500	50	100	10

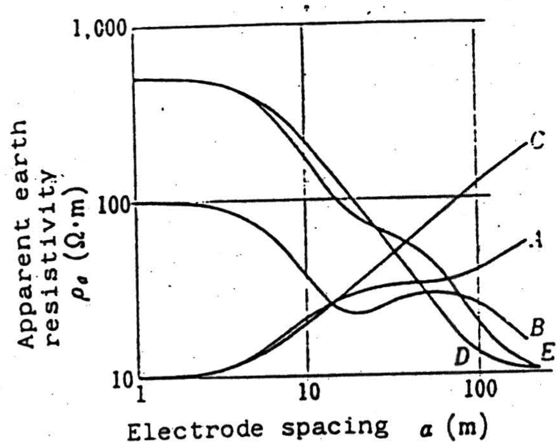


Figure 4.10 Typical apparent resistivity curves resistivity for four-layer soil

With this method it is possible to prepare ρ-a curves according to a variety of soil parameters on the basis of the derived equations. These curves can be looked upon as standard curves, and the features of different layers can be understood according to curve-patterns. It can thus be considered that a correspondence of these curves with ρ-a curves obtained from actual readings should be applicable to the estimation of soil parameters, in this case depth and resistivity of different layers of soil.

The comparison method is as follows. Measurement data obtained by four-electrode Wenner method are plotted on a log-log grid and ρ-a curves are drawn. In addition, arbitrary soil parameters are input and calculated values are compared with the above drawn curves. In the event that agreement is found, the input parameters become then the estimated soil parameters.

4.3.4 Soil investigations

In this paragraph I will describe a method for soil classification called the Unified Soil Classification system [14].
For preliminary or general descriptions customary in connection with such classifications to assign the names "silt" or "sand", to different grain size fractions. Grain size only is likely to be misleading because the physical properties of the finest soil fractions depend on many factors other than grain size.

Unified Soil Classification System (USC)

There are three major groups
- **coarse-grained**
- **fine-grained**
- **highly organic (peat)**

Boundary between coarse-grained and fine-grained is identified by the 200-mesh sieve (0.074 mm).
In the field the distinction is based on the fact if particles can be seen with the bare eye (unaided). If more than 50 % of the soil weight is judged to consist of grains that can be distinguished separately it is considered to be coarse-grained.

C - coarse-grained; G - gravely soils; S - sandy soils

Depending on whether more or less than 50% of the visible grain are larger than No. 4 sieve (3/16 inch), each is further divided into four groups.

W - well graded (U>4); fairly clean (<5% finer than 0.074 mm)
P - poorly graded (gap graded or U<4 for grave, 6 for sands), fairly clean (<5% finer than 0.074 mm)
C - well graded ; dirty (>12% finer than 0.074 mm) plastic (clayey) fines (I_w>7, also plots above A-line in plasticity chart)
F - poorly-graded ; dirty (>12% finer than 0.074 mm) ; non plastic or silty fines (I_w<4, or plots below A-line in plasticity chart) for example GW or SP, border line GW-GP

Fine-grained : divided in three groups
M - inorganic silts,
C - inorganic clays,
O - organic silts and clays.

There is a further division into those having liquid limits lower than 50% (L) or higher (H).
The distinction is made on basis of plasticity chart CH, CL above A-line OH, OL, MH below the A-line.
Organic (O) is distinguished from the inorganic soils M and C by their characteristic odour and dark colour or, in doubtful instances the influence of oven-drying on the liquid limit is a suitable test.
In the field, the fine-graded soils can be differentiated by their dry strength, their reaction on the shaking test, or their toughness near plastic limit.

Table 4.14 : Differentiation of fine-graded soils

Group	Dry strength	Reaction to shaking test	Toughness at plastic limit
ML	none to very low	rapid to slow	none
CL	medium to high	nine to very slow	medium
OL	very low to medium	slow	slight
MH	very low to medium	slow to none	slight to medium
CH	high to very high	none	high
OH	medium to high	none to very slow	slight to medium

Shaking test
shaken in the palm of the hand, a pat of saturated inorganic silt expels enough water to make its surface appear glossy -> if peat bent between fingers surface becomes again dull, after peat is dried, it is brittle.

Comments on method
USC classification system permits reliable classification on the basis of relatively few and inexpensive laboratory tests. With experience it also provides a practical basis for visual or field classification. Like all procedures based on grain size or the properties of remoulded materials, it cannot take into consideration the characteristics of the intact materials as found in nature. Hence, it can serve only as a starting point for the description of the properties of soil masses or soil deposits. Soil classification and suitability for ground electrodes using

Unified Soil Classification (USC) :

Soil component	Symbol USC	Description	Permeability*
Gravel	GW	Well graded gravel, gravel/sand mixtures, little or no fines	P
	GP	Poorly-graded gravels, gravel/sand mixtures, little or no fines	VP
	GM	Silty gravels, poorly-graded gravel/sand/clay mixtures	SP - IP
	GC	Clayey gravels, poorly-graded gravel/sand/clay mixtures	IP
Sand	SW	Well graded sands, gravelly sands, little or no fines	P
	SP	Poorly-graded sands, gravelly sands, little or no fines	P
	SM	Silty sands, poorly-graded sand/silt mixtures	SP - IP
	SC	Clayey sands, poorly graded sand/clay mixtures	IP
Silt and clay (liquid limit < 50)	ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands with slight plasticity	SP - IP
	CL	Inorganic clays of low to medium plasticity, gravely clays, sandy clays, silty clays, lean clays	IP
	OL	Organic silts and organic silt/clays of low plasticity	SP - IP
Silt and clay (liquid limit > 50)	MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts	SP - IP
	CH	Inorganic clays of high plasticity, fat clays	IP
	OH	Organic clays of medium to high plasticity	IP
Organic matter	O	Organic matter in various sizes and stages of decomposition	P
	PT	Peat and other highly organic soils	P

* P = permeable, VP = very permeable, SP - semi-permeable, IP - impermeable

Suitability for ground electrodes :

- GM and GC are not suitable for any form of ground electrode.
  Sandy soils may be suitable for land electrodes if permanently saturated, but are not optimal and require great care in design.
- ML and CL are less likely to be suitable than OL soils, but all are possible for ground electrode siting. Moisture conditions of these soils are critical and must be thoroughly investigated.
- MH, CH, and OH are generally favourable, with MH and OH preferable to CH, but all types must be thoroughly investigated on water content.
- Organic soils may be favourable, but must be individually investigated.
- Peat is not suitable.

4.4 RECOMMENDATIONS

4.4.1 Selection procedure at National level

The selection of the area with suitable conditions at National level could be indicated by the areas which perceive an annual probability of rainfall above 750 mm and possess a suitable(calculated) soil moisture regime. This area is illustrated on the next two maps(Fig 4.11 and 4.12). It covers the Kilombero valley and further to the south-west the region of Mbeya, and some small parts in the far west and around Lake Victoria.

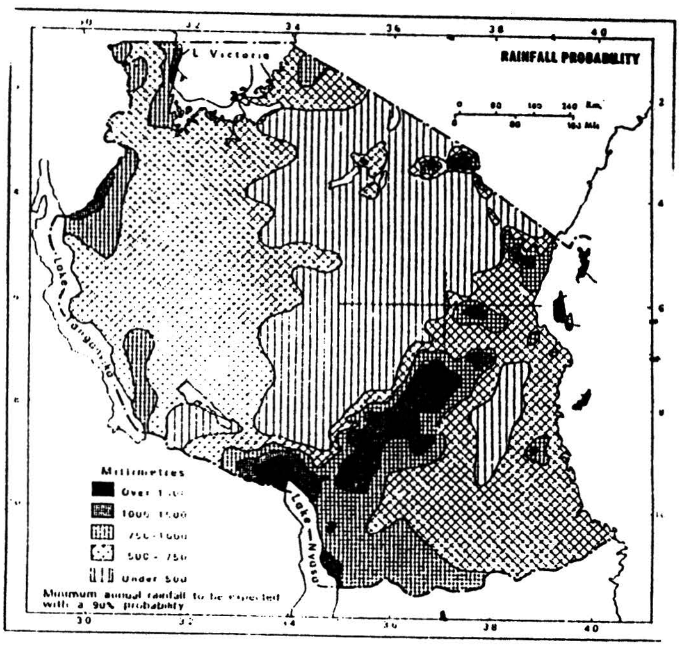


Figure 4.11 Probability of rainfall in Tanzania

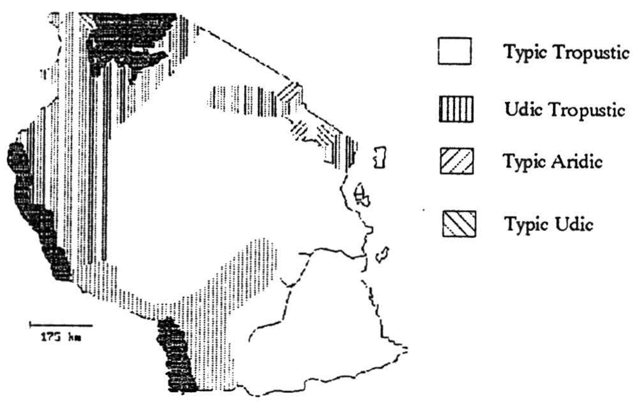


Figure 4.12 Calculated soil moisture regimes

4.4.2 Investigations at local level

At local level the first method, direct measurement of the soil resistivity, is recommended. With a limited amount of time and money a analysis can be made of the existing situation at the site with respect to the most important property and different layers of soil. In this context the application of the Wenner configuration has been described.
With the second method, soil investigations on basis of grain size, liquid limits and permeability, only an approximation of the soil resistivity can be derived. It requires also more experienced personnel to carry out the actual investigations. Although, it can be used as additional information in combination with the direct measurements of the soil resistivity.

5. SWER IN RELATION TO RURAL ELECTRIFICATION AND METHODS OF INVESTIGATION

5.1 MAIN OBJECTIVES OF RURAL ELECTRIFICATION

Rural electrification (RE) is defined as the supply of electricity to district townships, other small townships, villages, development centres, settlements, agro-based industries and other small industries outside the towns.
Electricity will be an additional form of energy in the mix of available sources for these areas.
The main objectives of rural electrification in Tanzania according to the rural, electrification policy document [32] can be divided in three groups : **(1) Protection of natural resources** by substitution of biomass fuels with electricity, **(2) Promotion of economic development** by the improvement of the productive sector of the rural economy and **(3) Improvement of the standard of living** for the rural population.
To assess the role of the SWER distribution system within the rural community these aspects need to be identified in a pilot area. The impact on development and improvement of living conditions is related to the possibilities to utilise the SWER system for the above mentioned objectives.
As electrification of an area can have an impact on all sectors and levels of the rural community some attention is given to Integrated Regional Development Planning.
To assess the need for electricity, a power market survey is necessary, with attention to the specific conditions related to the SWER (Single Wire Earth Return) distribution system. The results of the power market survey are the basis for the grid design and analysis of the project.
For the purpose of this study the following sectors are proposed, according to the electricity tariff system in Tanzania :

1. **Residential** - premises used exclusively for domestic and private residential purposes. The residential consumer group can further be divided by income level : low-income, medium-income and high- income groups.;
2. **Light Commercial** - shops, restaurants, theatres, hotels, clubs, harbours, schools, hospitals, airports, lodging houses, group of residential premises with one meter, premises where similar business or trade is conducted. The sector can further be divided in the different kind of establishments incorporated by the sector, which also counts for the light industrial and agricultural sector.
3. **Light industrial** - premises engaged in production of any article/commodity or in industrial process where the main use is for motive power or electrochemical or electrothermal processes [consumption < 7,500 kWh/month];
4. **Agricultural** - agricultural consumers engaged in direct raw farm produce production and/or processing;
5. **Public sector** - public lighting and water supply. The public sector is divided in street lighting and water pumping facilities.

5.2 SWER AND RURAL ELECTRIFICATION OBJECTIVES

The objectives of the rural electrification as mentioned before are defined as follows :

1. **Protection of natural resources** by substitution of biomass fuels with electricity;
   - a - avoidance of deforestation, desertification and denudation of soils; thus minimizing avoiding the potential firewood crises - the energy problem for the country's millions of poor and marginal people in the rural areas

2. **Promotion of economic development** by the improvement of the productive sector of the rural economy :
   - a - provision of electric power to isolated areas;
   - b - promotion of industrial development for a higher degree of processing of agricultural products;
   - c - establishment of a base for development of small scale industry;
   - d - support to agricultural development, construction industry, and other starting/initiating industrialization in Tanzania;

3. Improvement of the standard of living for the rural population by :

a - use of electricity for basic health care;
b - use of electricity for education and information systems;
c - use of electricity for water supply and irrigation ;
d - use of electricity for food production, storing and processing;
e - use of electricity for security by lighting of homes and private and public installations;

The relation of the development perspectives to the SWER system in the above mentioned aspects are summarized in Table 5.1.

Table 5.1 Development perspectives of the SWER system in the rural areas

Development goals of rural electrification	Relation to the SWER (Single Wire Earth Return) system
1. Protection of natural resources	
Protection of natural resources by substitution of biomass fuels with electricity	Fire wood, charcoal and agricultural wastes are the main sources for cooking and heating purposes in households of the rural areas. Electric power (not necessarily SWER) can substitute these sources, thus reducing the pressure on the natural reserves in the area. Convertors for this purpose are the following : electric oven; water heater; hot-plate; This development perspective is, however, only viable if the rural population can afford the appliances and is willing to change its habits.
2. Promotion of economic development	
Provision of electric power to isolated areas	For this goal this system has promising perspective in the following situations : - isolated loads with an expected demand of < 250 kW; - regions where a geographical division of service areas, on the basis of prospected peak demand of 250 kW, is achievable; - maximum distance of 50 km from main distribution network.
Promotion of industrial development for a higher degree of processing of agricultural products	In this context the utilization of the SWER system is related to the electric appliances that are available for the particular industrial processes. The determining aspect is identification of energy needs which can be provided by *single-phase* power supply[1].
Establishment of a base for development of small scale industry	In this context the SWER system can support development by additional supply of energy for productive purposes : motive power, lighting and food processing. Establishing education centres to assist the entrepreneurs in the proper operation of electrical tools in the small scale industry.
Support to agricultural development, construction industry, and others starting/initiating the industrial revolution in Tanzania	Agricultural development has perspectives in relation to higher productivity by irrigation and processing of agricultural products (assuming isolated loads). For industrial development, where in the long run, energy needs will be substantial this system could only support the initial stage.
3. Improvement of the standard of living for the rural population	
In the context of these development perspectives, the SWER system can be utilised for all the mentioned purposes when the power demand is relatively small, predominantly lighting and single-phase loads or isolated (irrigation)	
The use of electricity for basic health care	lighting
Education and information systems	lighting, telecommunication appliances
Water supply and irrigation	pumping (single-phase)
Food production, storing and processing	milling, cooling, heating, drying
Security by lighting of homes and private and public installations	lighting

Integrated Regional Development Planning

As electrification can affect the total situation in an area, it involves all sectors of economy in the rural community, it should, in my opinion, be part of an Integrated Regional Development Plan. Integrated is referred to as planning for all functional sectors and activities within a geographical area. With this effort a functional and spatial 'harmony' between activities of different sectors and the most effective distribution of resources between agencies could be achieved [31].

[1]Although three-phase power supply is possible, but only with an additional conversion device.

5.3 METHODS OF INVESTIGATION

A) SOCIO-ECONOMIC ASPECTS

5.3.1 Power market survey

The need for electricity at a load centre (village or small town) and surrounding area, in the pilot area must be identified. A power market survey, desegregated into geographical areas and in type of consumers (see paragraph 5.1), can be conducted.
A survey should include relevant aspects to estimate the electrical load which has to be supplied by the distribution system. Main factors are summarized in the beginning of the paragraph. The goal of the survey is to establish the demand of electricity and the time of the day when the power is needed. With the data of the survey in a pilot area, the maximum demand need to be derived to design a grid and analyze the project.
I will describe aspects which are relevant for a survey to establish the need for electricity and the suitability of a SWER system to supply demand.
A project area is considered to be a town together with a surrounding area consisting of scattered populations, smaller townships and isolated agricultural processing enterprises.

1. Economical characteristics :

- prices of energy sources and appliances;
- location and classification of agricultural processing industries;
- location and classification of the light industrial establishments;
- location and classification of the light commercial establishments;
- classifying public lighting and water supply facilities;

An important aspect is the **price of energy sources and appliances**, which differ from place to place and even during the year. Energy sources contain the commercial sources charcoal, kerosine, diesel and batteries. The prices of appliances can be obtained from the nearest population centre (village, town) where these are available.
The classification is related to the proposed sectorial division in this study and this information provides a preliminary estimation of the type and division of loads which can be expected. In this respect the distinction between single- and three-phase load types is essential for the suitability of the SWER distribution system. Three-phase loads cannot be supplied without additional equipment.
Agricultural loads, outside the population centres, assuming single-phase demand less than 250 kW, can be supplied by this system.
If the **industrial sector** has a major share in the economical structure of the area, special attention should be given to the location of industrial loads. Locations outside population centres and power demand not exceeding 250 kW during a longer period of time are suitable to be fed through a separate transformer. Nevertheless, in this situation one should consider the option of a three-phase distribution system, while in this sector three-phase appliances are common, certainly if one has to take account of future development of the load in this sector. The small scale industrial establishments within the villages are assumed to have less influence on the system.
The **light commercial** establishment are assumed to have only light loads, predominantly lighting and small appliances using single-phase power. In relation to the light industrial sector, this sector will consume less electricity per consumer.
The **street lights** and **water supply** facilities for public service are assumed to take a small share in the total demand for electricity.

The economic consumer groups which indicate the suitability of the SWER (Single Wire Earth Return) distribution system can be summarized as :

- **isolated agricultural/industrial establishments;**
- **light commercial/small scale industrial establishments;**
- **street lighting and public water supply**

In relation to the development perspective of the SWER system, the economic structure is very important. The existence of a substantial industrial sector is not appropriate for this system, except when the locations of enterprises in this sector are more or less separated from other consumers and demand will stay within the limit during a longer period of time.

2. Accessibility

- distance from main distribution grid (or generating station in isolated system);
- distance from major cities;
- distance between the major load centre and loads outside the village;
- state of the roads.

These data are essential for the design of the network.
They could also be an indicator of the likelihood of electrification. Assume that in the nearest, electrified, population centre there is only a limited variety of appliances available in combination with poor public transport. If the distance to an isolated load outside the main load centre, e.g. agricultural processing enterprise or village, is far, electrification is not likely. Assuming that the roads are in a poor state, it follows that the construction of the distribution line will take more efforts.
The perspective for this system is thus determined by distances between load centres and in general the mobility of the population.

3. Infrastructure
Location and classification of the infrastructural facilities, water supply, schools, health care, banks, etc...
The classification is incorporated in the light commercial sector together with the public sector as defined for this study. It is dealt with as a separate aspect while it serves the goal to improve the standard of living of the rural population as a whole. It could improve the quality of the services by better lighting, water pumping and assuming power consumption is small a considerable part of these facilities could benefit.

4. Demographic aspects

- number people;
- division of population;
- growth rate.

The total number of the inhabitants is necessary to construct a sample and to make a preliminary estimate of the demand. The division of the population over the pilot area has two different functions : (1) grid design, (2) in combination with the location of the industrial, commercial and agricultural establishments to evaluate the suitability of the system (see item economic characteristics)). A growth rate of the population is important in relation to the establishment of a growth factor of electricity demand.

5. Integrated Regional Development Plans
As mentioned before, the existence of regional integrated development plans could be a tool to promote rural electrification. In practice it could mean that complementary measures are included in such plans. For example, credit access to farmers and light industrial entrepreneurs for the initial investment costs in electrical equipment. Local participation in the construction of the distribution system. Improving the accessibility during construction of the line (roads, telephone).

5.3.2 Questionnaire to assess the need for electricity of individual consumer groups

For the survey related to individual consumer groups a questionnaire was compiled which could not be put into practice as a result of lack of time. I will evaluate, however, the aspects that are included in the residential questionnaire with respect to their relevancy for the purpose of this study. Two questionnaires have been compiled, one for the residential group and one for the other consumer groups in the economy.

A) Residential questionnaire

1 - General information of the household
Under this heading a general picture of the household can be obtained with respect to the composition and activities of the family and education level of the head of the household. A division of labour can be compiled.

2 - Economic activities
The economic activities include profession and sources of income of the family by commercial activities like selling agricultural products from their own plot. It contributes to the estimate to which income group a household belongs.
The income group has a major influence on the chance of electrification of the household since the initial connection charges are a constraining factor. The electrical installation in the house is also an expensive matter.

3 - Energy use pattern
This question includes :

a. type of energy sources used per month and related costs;
b. energy source related to purpose (cooking, lighting and heating);
c. how the energy sources are obtained and the time spent;

This information is useful to estimate for which purposes electricity could be used, the time of the day when it is used, the analysis of the benefit in terms of costs when a source is substituted by electricity, the analysis of benefits in terms of improvement of standard of living (less time spent to obtain energy sources, less labour intensive activities).

4 - Housing conditions

a. Characteristics of the house (building materials for walls and roof),
This aspect is included to determine if the house is suitable to get a connection. It has to satisfy the requirements of the standard used by TANESCO : **roof material** - iron sheets or roof tiles; **walls** - burnt bricks or cement blocks; **floor** - cement.
b. Sanitary conditions :
Information for an indication of the welfare position of the household.
c. Type of water supply (potable) :
This aspect can be used to evaluate the improvement of the public water supply system with the use of electrical pumps. The direct responsibility to improve the water supply lies, however, with the local authorities and will not occur automatically. Only if the goal of an rural electrification project also includes the improvement of the water supply system this public service can undoubtedly benefit from the project.
d. Accessibility of the house, state of the nearby road system :
In relation to the wiring to the house, construction and maintenance.
e. Means of transport :
Possession of means of transport, to contribute to identify the income level of the household.

5 - Opinion of electricity
This question includes the present knowledge of electrical equipment/appliances and experiences with electricity. The possible benefits of electricity of which one is aware of and a concluding open question to give one's opinion on the electrification of the area.

B) Commercial, Industrial, Agricultural and Public sector questionnaire

This survey will incorporate the economic activities of the selected area. The sampling procedure is dependent on the number of potential consumers in each category. The establishments, already supplied with electricity by, for example, their own generator, are given priority for participating in the survey sample. By investigation of these consumers a picture can be formed of similar establishments in this specific area to make a better load-forecast. A similar sampling procedure as with the household survey is followed. The next aspects will be taken into account.

1/2 - General overview of the establishment
First of all a general picture of the enterprise will be obtained by gathering information about, the type of enterprise (divided over the four economic sectors), the structure, ownership, division of labour to level of work, some information on the owner in relation to possible additional economic activities if possible to obtain.

3 - Energy use pattern
With this question the identification of the present energy use will be obtained. A presentation by diversification to source and purpose of the different energy is collected. An assessment of the replacement of certain energy sources by electricity can be obtained with this data, so input for load-forecast. When efficiency factors of the equivalent electrical tool and current tool, or output efficiency are available a determination of energy savings can be accomplished. Monetary savings, gained when certain activities are replaced by electrical convertors, may be computed as result of this information.

When the enterprise in question already owns a electricity supply, an additional set of data will be collected. The reason for this situation, since how long, the reliability and quality of this supply, the appliances utilised, opinion about electrification of the township/area, connection to public supply when available? Cost of electricity supply per month, per kWh, fuel cost per kWh, fuel situation ; availability, quality, technical data of generator set. Utilisation of generated electricity by the enterprise. In this situation a good comparison can be made of the costs related to grid connected/public supply of electricity.

4 - Housing conditions
This incorporates the state of the building, building materials and infrastructural facilities of water-supply and sanitation, ownership and size of the building.
With the information on housing conditions the necessary modification (TANESCO regulations, cement floor and iron sheets or roof-tiles) to obtain electricity can be estimated. The chance of electrification is directly related to this matter. The access to water, which is a public facility, has in my opinion, a higher priority so it has to come together or after a reliable water supply system. In relation to question five, if the production depends on a reliable water supply, electricity could mean an improvement.

5 - Production of the commercial, industrial or agricultural or public enterprises
In this part, data on the production of the different sectorial groups are obtained. The means of production are also included to obtain information about possible use of electrical convertors which can replace current production function.
The performance of the enterprise in relation to energy can be assessed if enough information can be obtained. Socio-economic benefits can be computed with different replacements (actual energy source to electrical convertor) scenarios. Some possible benefits are listed below :
- less energy-use, decreasing cost of energy, better quality of output, improving working conditions (less human power, lighter work), demand for skilled personnel (pull factor for other areas), longer opening time (service sector), irrigation of arable land.

6 - Accessibility
The degree of accessibility can be of importance for example in relation to future growth of production, meaning also more space for new buildings and additional transport of people as well as material goods (output,input). When a good transport system is present in the area, the socio-economic benefits have a more prominent chance to commence.

7 - Transport status
This issue is related to the former question in the sequence. Its purpose is to investigate the grade of dependency on means of transport. So the grade of importance of transport of people and materials in the overall production process of the establishment.

8 - Knowledge or experience with electricity
This issue is the last one in the sequence. It should give an indication of the willingness of the economic sectors in the area to get connected to a public electricity grid. In the survey, already proven benefits of electricity can be put forward giving examples and ideas. Reactions on this subject could give an indication of the awareness of the value of electrification in socio-economic development.

A) TECHNICAL ASPECTS

5.4.1 Measuring method

For the measurements of the soil resistivity at a site where the distribution transformer can be situated I refer to the methods described in Chapter 4. In paragraph 4.3.1 a description is given of two measuring methods for direct measurement of soil resistivity.
The actual soil resistivity measurements where performed by the Megger method since an instrument to employ the Wenner or Schlumberger method could not be obtained. In this paragraph I will give a description of the Megger method with its application in the evaluation of soil resistivity of a site. Maps of the soil resistivity measurements as well as the situation of the direct surroundings of the sites in the two townships are reported in Chapter 6.

When a current flows into the ground the total resistance of the current path can be divided into three parts. 1) resistance of conductor connecting the earth electrode to the system, 2) contact resistance between surface and main body of earth, 3) the resistance of the body of earth immediately surrounding the electrode [11].

1) normal conductor resistance (in our case negligible small),
2) contact found negligible small,
3) main part is that of the body of earth surrounding the electrode.

The actual measurements at the two sites are realised with the fall of potential method, also known as the Megger method.
A known current is passed between the electrodes *C* and *E* and the potential difference between *P* and *E* is measured. If the current is *I* and the potential difference is *V* then, the quotient *V/I* will give a resistance which under suitable conditions will give the resistance of E. It is evident that in this method, resistance of auxiliary electrodes are not included. Electrode *C* is in the main path and its resistance is one of the main factors determining the value of current *I*, but this in turn determines the value of *V*, so that the quotient *V/I* is independent of the resistance of *C*. Again the resistance of auxiliary electrode *P* is part of the circuit used to measure the potential difference *V* and, if this is a null balance system so that at balance no current is passing through *P*, then the resistance of this electrode can have no effect on the measured value. In this case the resistance of this electrode can have no effect on the measured value. If on the other hand, a high resistance voltmeter or its equivalent is used to measure *P*, then it may be possible to make this resistance so high that the values of *P* normally encountered in practice have no effect,or to arrange to measure *P* and apply a suitable correction.
It is essential that the effective radius of the electrodes do not overlap, this can be checked by plotting earth resistance curves.
The conditions necessary to obtain the required result can be demonstrated in the following manner [11].

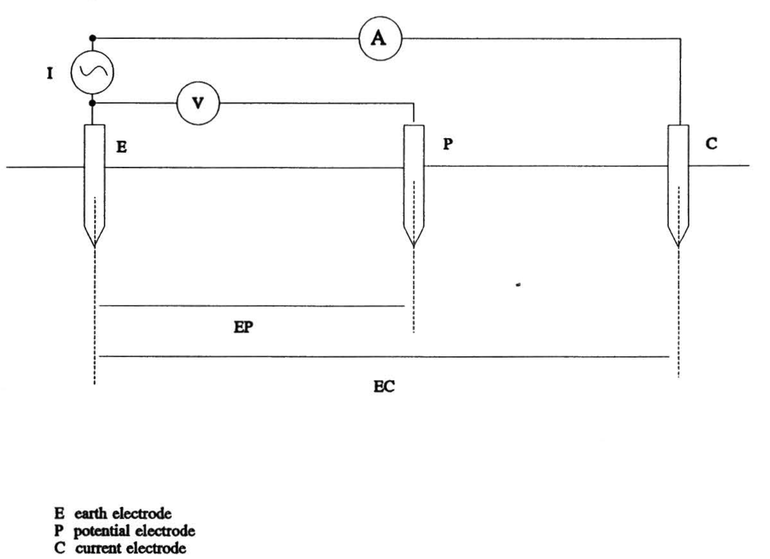


Figure 5.1 The Megger configuration

Suppose that the test area can be considered to be a hemisphere (using the same technique as in paragraph 4.3.1) Current electrode *C* is set at distance *EC* from centre of hemisphere and potential electrode *P* at a distance of *EP* (see Fig.5.1). Let a current *I* enter at *E* and leave at *C*. Then the potential difference at *E* due to the current *I* entering at *E* is

$$V_{E(I_E)} = \frac{I\rho}{2\pi r}$$

and the potential difference due to the current leaving at *C* is V_{EC}

$$V_{E(I_C)} = \frac{-I\rho}{2\pi(EC-r)}$$

Again the potential difference at *P* due to the current *I* entering at *E* is V_{EP}

$$V_{P(I_E)} = \frac{I\rho}{2\pi EP}$$

and the potential difference at *P* due to the current *I* leaving at *C* is (V_{EC} - V_{EP}) :

$$V_{P(I_C)} = \frac{-I\rho}{2\pi(EC-EP)}$$

The total potential difference at *P* is (V_{EP} - (V_{EC} - V_{EP})):

$$V_P = \frac{I\rho}{2\pi\left[\frac{1}{EP} - \frac{1}{(EC-EP)}\right]} \qquad 5.1$$

The potential difference between *E* and *P* is :

$$V_{EP} = \frac{I\rho}{2\pi\left[\frac{1}{r} - \frac{1}{(EC-r)} - \frac{1}{EP} + \frac{1}{(EC-EP)}\right]} \qquad 5.2$$

The measured "resistance" is :

$$R = \frac{V}{I} = \frac{\rho}{2\pi\left[\frac{1}{r} - \frac{1}{(EC-r)} - \frac{1}{EP} + \frac{1}{(EC-EP)}\right]} \qquad 5.3$$

The true resistance of a hemisphere is, ***ρ/(2*π*r)***, where *r* is the radius of the hemisphere. To replace a driven rod for a hemisphere the following equation is applicable, where the radius of the equivalent hemisphere can be calculated :

$$\frac{\rho}{2\pi r} = \frac{\rho}{2\pi l}\left(\ln\frac{8l}{d} - 1\right)$$

$$r = \frac{l}{\ln\left(\frac{8l}{d}\right) - 1}$$

Where l,d and r are in cm

so the measured resistance expressed as fraction of true value is :

$$\frac{\left(\frac{1}{r}-\frac{1}{(EC-r)}-\frac{1}{EP}+\frac{1}{(EC-EP)}\right)}{\frac{1}{r}}$$

$$= 1 - \left(\frac{r}{(EC-)}+\frac{r}{EP}+\frac{r}{EP}-\frac{r}{(EC-EP)}\right) \qquad 5.4$$

$$= 1 - \frac{1}{\left(\frac{EC}{r}-1\right)}+\frac{1}{\left(\frac{EP}{r}\right)}-\frac{1}{\left(\frac{EC}{r}-\frac{EP}{r}\right)}$$

now let $EC/r=c$ and $EP/r = p$ then the ratio :

$$\frac{measured\ resistance}{true\ resistance} = 1 - \left[\frac{1}{(c-1)}+\frac{1}{p}-\frac{1}{(c-p)}\right] \qquad 5.5$$

and the expression in the brackets represents the factor error due to the values of EC and EP chosen for the measurement. Approximations of c an p, with $EC = 10\ m$ and $EP = 20\ m$, are for $c = 142$ and $p = 285$. taking these values in mind the following the following assumptions are made:

$$\frac{1}{(c-1)} \approx 0 \ ; \quad \frac{1}{p} \approx 0 \ ; \quad \frac{1}{(c-p)} \approx 0 \qquad 5.6$$

so

$$\frac{measuredresistance}{true\ resistance} \approx 1$$

The resistivity ρ is then :

$$\rho_{true} \approx 2\pi Rr \qquad (\Omega.m) \qquad 5.7$$

The measured resistivity is determined by the area in the direct surrounding of the earth electrode. Only the top soil is thus incorporated, meaning a limited stretch of soil. The conclusions based on this measuring method can only give a general indication of the resistivity of the piece of land under study With the effective radius (r_1) symbolized by the geometric factor ($\pi(½EC)^2/EC$), the fraction of the area that is included in the measurement (x) can be derived:

$$x = 1 - \frac{r}{r_1} \ ; \quad r_1 = \frac{r}{(1-x)} \qquad 5.8$$

r = *equivalent hemisphere*
r_1 = *effective radius*

The dimensions and distances used in this study are as follows :

- Depth of electrodes in ground : **30 cm / 40 cm** ;
- Equivalent hemisphere : **9 cm / 11 cm** ;
- Diameter of electrodes : **2.25 cm** ;
- Distances between electrodes, EC = 2*EP : **EP = 5, 10, 15 m ; EC = 10, 20 , 30 m** ;
- Fraction included in the three cases : $x_{1(EC=10\ m)}$ **= 0.98** ; $x_{2(EC=20\ m)}$ **= 0.99** ; $x_{3(EC=30\ m)}$ **= 0.99**.

5.4.2 LOAD-FORECASTING

To determine the demand of electricity and to design the distribution system for a given area, a load forecast of the electricity demand has to be performed. Main factors which determine the demand are summarized as follows [1] :

- price of electricity versus alternative energy sources;
- availability of energy sources;
- reliability of supply;
- technical and economic characteristics of electrical equipment and appliances;
- population growth;
- income;
- rate of urbanisation;
- social habits;
- acceptability;
- knowledge by potential users.

To establish the need for electricity of a specific area, the structure of demand has to be identified. The structure of demand includes the desegregation by **geographic area, type of consumer** and **over time** as well as characteristics such as **load factor (LF), diversity factor (DF)** and **system losses.**
The need for desegregation is due to the fact that demand characteristics vary by consumer group, geographic area as well as over time. The nature of the aggregate demand can thus be quite different from that of the desegregate demand figures.
In the case of distribution system planning, the demand pattern at each load centre in the area is required to design the distribution system.
First I will give a definition of **Energy** and **Power.**
Energy - the unit of energy in heavy current electrical applications is the kilowatt-hour **(kWh)**;
Power - the rate of energy per unit of time, kilowatt **(kW)**.
Energy in **kWh** is the product of **power** in **kW** and the **time in hours.**
This is an important distinction while the same amount of energy may be delivered in a small interval of time at a relatively high rate of power flow, or over a longer period at a lower power level.

Load factor
The load factor is the ratio of average demand to maximum (or peak) demand in kW, over a given interval of time (usually 15, 30 or 60 minutes), which may be calculated at various levels of aggregation, commonly used is the aggregation to type of consumer on a daily basis. The importance of this factor is due to the fact that the size or capacity and, therefore, cost of power system components are determined to a great extent by their capability to handle peak power flows. As the majority of the customers require their maximum kW demand only a short period of the day, the **LF** is also a measure for the intensity of capacity use. The **load factor (LF)** can thus be used to convert peak power demand into energy consumed during a period of time and visa versa.
Assume a load factor of 0.25 (6 hours per day) and a residential load of 180 Watt (3 light bulbs of 60 W) :

$$\textit{energy consumed per month} = 0.25 * 180\ W * 730 = 33\ kWh$$

or energy per month of 500 kWh and a load factor of 0.4 (8 hours a day) of a light industrial establishment :

$$\textit{peak power} = 500/(0.4 * 730) = 1.7\ kW$$

In general, the kW peaks of the different customers in a consumer group will not occur at the same time. The **diversity factor (DF)** for a group of customers is a measure of the divergence of spreading over time of the individual peak loads. This permits the computation of the combined peak load for a group in terms of desegregate peak values.
For the actual peak power of the system, the load pattern of the different consumer groups during the day has to be established. A load curve can thus be constructed of each consumer group and the maximum

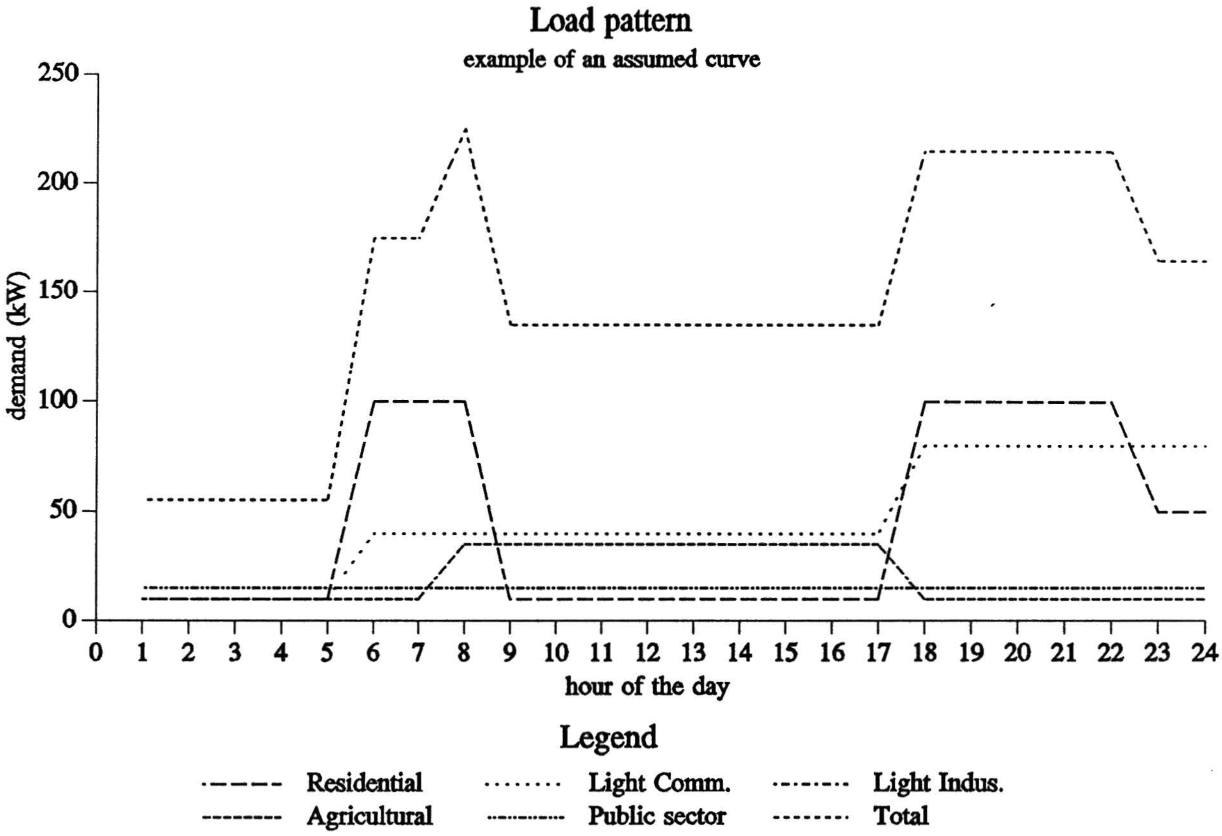


Figure 5.2 Load curves of individual consumer groups and the aggregated load curve

demand (peak power) determined by addition of the individual curves. An example of such a pattern is shown in Figure 5.2. The following assumptions are made with respect to a pattern suitable for this system :

- most of the consumers are assumed to be residential
- the commercial consumer group is assumed to be the second group
- light industrial and agricultural consumers are assumed to be equal and consuming a small part of the power demand
- the public sector (lighting and water supply) has a small constant demand

Load pattern per group :

1. a peak in the morning of the residential load for heating/lighting, in the evening heating/lighting diminishing after 22.00 hours;
2. commercial load from 6 till 24.00 hours refrigerating/heating in the day time and additional lighting in the evening;

3./4. load from 8.00 till 17.00 hours

5. street lights from 18.00 till 6.00 and water supply during the daytime

System losses

The total amount of both energy (kWh) and power (kW) generated at the source will be greater than consumed values of power and energy due to the losses in the system. Generation losses consists of station use, driving auxiliary equipment at the power plant itself. Transmission and distribution losses are of resistive nature including transformer losses. The energy loss in conductors loss, which is manifested in dissipated heat, can be calculated by the product of power and time. Power is the product of voltage and current.

From Ohm's law ($V = I * R$), this can be derived from the product of the square of the current (I) flowing through the conductor and its resistance (R) :

$$Energy_{loss} = Power * time = I^2 R * time\ (hour)$$

Growth factor
A growth factor for the consumption of electricity can be established from earlier data of similar villages. Consumption can be assumed to be steady after 10 years. The population growth is another factor of consideration.

6. EMPIRICAL PART OF THE RESEARCH

The actual fieldwork took place in two townships, Mboga and Gairo. Mboga is a little village along the road from Chalinze to the North, direction Tanga/Arusha/Moshi. A rural electrification project was under construction at the time of my visit. This project will supply the Mandera ginnery, including the villages along the route of the distribution line (including Mboga). Gairo is situated on the road from Morogoro to Dodoma some 130 kilometres distance from Morogoro. The information of a feasibility study of some years before is used to describe the project area.
Each area will be described according to the issues mentioned in the former chapter. First the socio-economic aspects, consisting of the following : (1) Prices of energy sources and appliances, (2) Economical characteristics, (3) Accessibility, (4) Infrastructure, (5) Demographic aspects and (6) Integrated Development Planning. Secondly the climatological conditions, measuring method with results and a load forecast of the area under study. The rainfall statistics of the two stations in the different areas are obtained from the Meteorological Institute of East Africa.

FIELD INVESTIGATIONS

First some figures about prices of energy sources and appliances in several cities in Tanzania :

Table 6.1 Prices of appliances and energy sources

	Charcoal	Kerosine (Tsh./ltr.)	Battery[3]	Light bulb (60W)	Radio
Mboga[1]	500 (bag)	-	-	-	-
Gairo[1]	1000 (bag)	180	-	-	-
Kibaha[2]	37 (½ kg)	124	143	213	7880
Morogoro[2]	17 (½ kg)	167	137	237	7917
Dodoma[2]	17 (½ kg)	146	145	222	7602
D'Salaam[2]	25 (½ kg)	120	144	204	6729

1 - At the time of the study
2 - Average over '93 [25]
3 - 1.5 Volts

The electricity tariff is uniform in Tanzania (see Appendix A.5). The only remarkable price fluctuations by region is charcoal.

6.1 FIELDWORK IN MBOGA

The following information was available before hand, both from documents of TANESCO and some additional data collected by myself. It is presented in a prepared schedule, following the theoretical model. Mboga is already electrified but not fully in operation at the time of the study.
The area is situated in the Coast region in Bagamoyo district. The project consists of the Mandera ginnery and the villages in Mioni division, Mbwewe, Kimange, Mioni, Msata, Lugoba and Mboga.

6.1.1 Power market survey

The village is situated along the Chalinze-Tanga road, seven major villages along the road are, Mbwewe, Kimange, Mioni, Msata, Lugoba and Mboga. Mioni is the divisional headquarters which is some 10 km of the main road.

Economic activities

Agriculture :
Most of residents are engaged in farming activities where food crops consists of cassava, sorghum, maize etc.. The cash crops consists mainly of simsim and cotton.

Industry :
Lumbering is one of the industrial activities although not on the scale comparing of the farming also grain milling is a activity of the area.

Commerce/Services :
These activities are shops restaurants and other commercial activities.

Infrastructure :
There are two generation sets in the area :
1 - Mandera ginnery has a 17 kVA generation set, although with unstable power and high running costs).
2 - At the R.C. Mission a 11.4 KVA diesel generation set is in operation close by Mandera.
A group of people working at the ginnery and the R.C. mission have thus already some experience with the use electricity. These two facilities can be electrified by the grid.

Accessibility :

- Mboga	: 14 km from Chalinze
- Lugobe	: 21 km from Chalinze
- Msata	: 35 km from Chalinze
- Mandera	: 47 km from Chalinze, 10 km from Mioni, 12 km from Msata
- Mioni	: 62 km from Chalinze, 19 km from Mbwewe
- Mbwewe	: 81 km from Chalinze

Most of the villages are situated along the main road to Tanga. They are accessible the whole year through for any means of transport. In relation to the utilisation of the SWER system, the distances exceed the limit of 50 km.

Demographic data :

	Inhabitants ('88)	Households
- Mbwewe :	13.830	
- Mioni :	14.115	2330
- Msata :	8.000	554
- Lugobe :	12.912	

The demographic data show scattered villages with a relatively small number of population. In relation to the SWER system it implies suitable conditions.

Integrated Regional Development Plans :
They were not mentioned in the study of Tanesco

All the villages are relatively small with the consequence of limited electricity demands per load centre (see load forecast). With respect to the distances between load centres and the small electricity demands the question rises if electrification in this area is justified.

Mboga village
The main reason of the existence of this village is the road. Before the population was scattered in the area, only after the main road to Moshi and Tanga was built, people came to live along side. This road is a kind of border were each side has its own history. On one side the buildings are dominantly made of stone, while on the other side traditional building materials are used. The reason for this division is the fact the stone houses where build for Jugoslavian road constructors. After they left the buildings were

occupied by the local inhabitants. The people who can afford charcoal and kerosine use it for cooking and lighting respectively, otherwise firewood is used for these purposes. The potable water is of poor quality, it can not be consumed in good health.
At the time of the study 9 houses where electrified and one mill was asking for a connection.

6.1.2 Climatological conditions

The division can be characterized by high temperatures and moderate rainfall (see Fig. 6.2) , usually coming down in the months January to May, as it lies within the coastal belt (see Fig. 6.2). The yearly average over the period ('74 - '85) was 770 mm derived from years with full records. Its terrain is relatively plain.

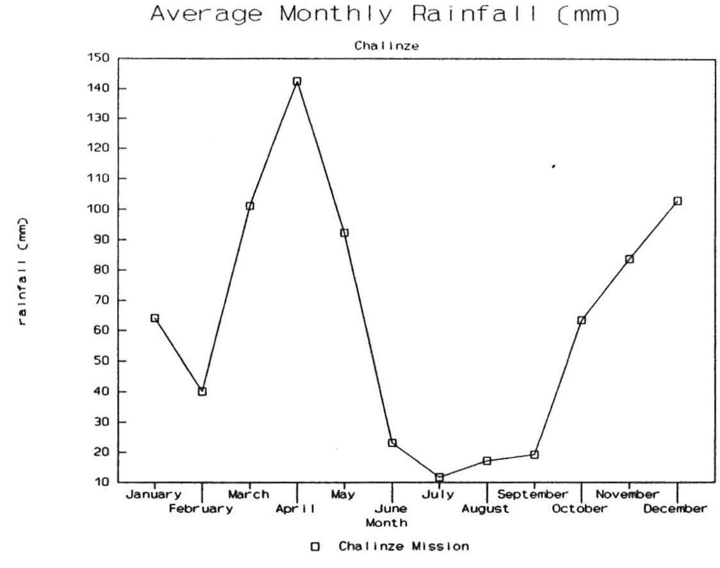


Figure 6.1 Average monthly rainfall in Chalinze

Table 6.2 Rainfall statistics Chalinze

Year	Jan.	Febr.	March	April	May	June	July	August	Sept.	Oct.	Nov.	Decemb.	total
1974	91.1	3.0	79.6	-	-	-	-	-	-	-	-	-	173.7*
1975	60.7	17.8	124.3	294.4	143.2	39.9	4.9	1.0	30.4	8.4	14.0	150.3	889.3
1976	14.4	100.0	63.8	130.1	67.0	16.5	7.4	9.7	19.1	19.8	18.8	30.9	497.5
1977	106.3	44.8	56.5	49.4	61.3	3.7	8.0	16.0	0.0	55.8	146.9	106.5	655.2
1978	65.8	23.7	113.5	88.2	63.7	7.3	0.0	10.8	19.3	0.0	102.8	137.5	632.6
1979	146.4	108.5	66.2	183.4	165.7	42.0	14.0	15.2	10.1	35.2	12.6	101.2	900.5
1980	42.1	75.6	130.2	98.4	59.2	2.1	0.0	46.9	11.1	40.4	146.7	69.0	721.7
1981	51.9	12.4	135.9	163.4	39.0	0.7	3.4	21.2	10.8	79.4	21.5	146.6	686.2
1982	6.3	0.0	105.6	133.0	87.3	59.3	37.1	44.0	68.0	236.4	89.1	42.5	908.6
1983	34.9	8.0	98.2	115.6	211.4	42.3	18.7	3.6	-	57.1	22.2	74.0	686.0*
1984	70.4	0.0	125.1	206.1	91.8	39.7	13.1	3.4	17.3	115.1	267.5	170.5	1120.0
1985	79.2	86.7	115.3	104.8	26.1	0.5	22.1	17.0	6.3	51.6	81.4	106.5	697.5
Average monthly	64.1	40.0	101.2	142.4	92.3	23.1	11.7	17.2	19.2	63.6	84.0	103.2	771

- : Missing values
* : Total with missing values

- Average yearly is calculated using year totals without missing values

6.1.3 Resistivity measurements at Mboga

Site description

In our case the site in Mboga was selected as near as possible to the road on a field that was available for us to undertake some measurements. Relating to the selection criteria mentioned in Chapter 4, the site is a plain field where no pipelines or telephone lines cross the site. The vegetation consisted of low grass. At one side a kind of cement floor did exist which belonged to an old building. There where some trees around and scattered over the place stones where found.
The field is divided into a matrix of seven by seven lines. The distances in the x-direction differed 4 meters while the distances of the measurement points in y-direction where divided in sections of 5 meters.

The total grid size thus created is *24 by 30 meters*. At every point three measurements took place with different spaces be tween the electrodes. The current electrode distance is always two times the distance between the potential electrode to the earth electrode. The distances are *5 m*, *10 m* and *15 m* between the potential electrode and earth electrode and thus *10 m*, *20 m* and *30 m* between the current electrode.

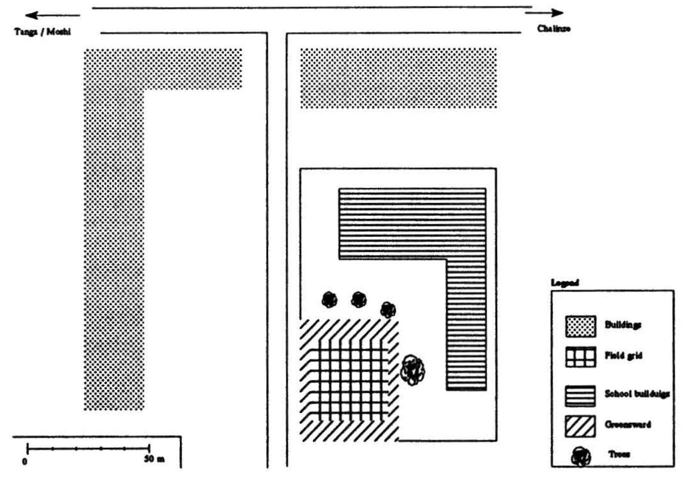


Figure 6.2 Situation in Mboga

The mapping of the data is performed by processing the collected resistance measurements with a spread-sheet program. Resistivity is computed and of each line a graphic can be produced. If one uses **Quatro-pro** or **WP-Presentations** three-dimensional graphics can be produced to obtain a graphical picture of the whole field. The next figures are examples of two dimensional surface graphics generated by **WP-Presentations.** These figures contain the average values of the three measurements taken at each point.

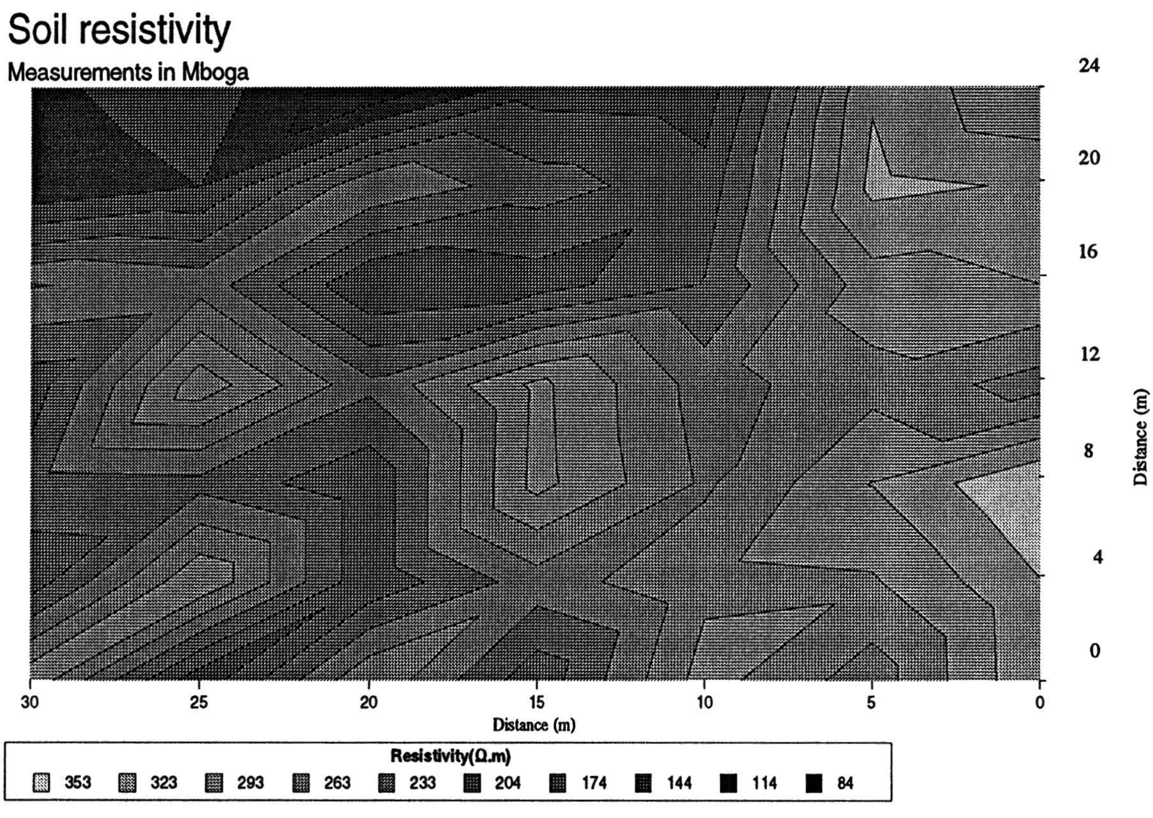


Figure 6.3 Resistivity map of Mboga

6.1.4 Load forecast

Table 6.3 Estimated load per village in kVA (kilo Volt Ampere)

Tariff	Mbwewe	Kimange	Mioni	Mandera	Msata	Lugoba	Mboga
Residential	120	15	105	25	40	100	40
Commercial	26	5	29	3	18	23	6
Industrial	12	1	3	2	4	4	1
Street lights	21	4	15	10	15	20	7
Total load (kVA)	216	36	247	95	164	'211	61

The initial load will be 650 kW and the load in year 15, 950 kW, assuming a power factor of 0.9

6.2 FIELDWORK IN GAIRO

The information of Gairo is obtained from an earlier feasibility study performed by Tanesco and some additional information collected at the time of the study. It is presented in a prepared schedule, following the theoretical model. Gairo is planned to be electrified in the future. It is situated in the Morogoro region in the district Kilosa. Gairo is well established township along the Morogoro Dodoma highway. It is situated 130 km west of Morogoro town and belongs to Kilosa district. The district is one of the five districts of the Morogoro region. It occupies the north western part of the region. Some other surrounding villages include Magubike, which is along the highway, some 40 km east of Gairo and Berega Hospital, located 30 km east of Gairo and 6 km north of the highway.

6.2.1 Power market survey

Economic activities

Agriculture :
This activity is practised on small scale basis, peasant farms, particularly true for the food crops, maize, rice, beans, groundnut, sunflowers and the cash crops sugar cane, sisal, and cotton. There are also some large plantations, owned privately or by public institutions, growing sugar cane and sisal. Maize beans and sun flowers are ample in the division and two godowns have been built for the storage of these products.
Another activity consists of livestock keeping, which contributes significant in the occupation of the residents in their means of living. The estimated number of cattle is 85.000 heads in Gairo and the surrounding area.

Industry :
As an effect of the high agricultural production in the district, several agro-based industries are active in the area, like cotton ginning, soap making, saw mills and textile activities with oil extracting mills, grain mills and workshops. There is a sisal decorticating factory to cater for the sisal estates, of which there are seven. There are also 8 handlooms for textile cloth, each of which can produce 3 sheets of cloth per day. One mechanical workshop making spare parts for a variety of machines exists.

Commerce/Services :
shops (60), hotels (20), guest houses (10), bars (8), filling stations (5), garages (3). There is one bank, a police station and a post office.

Infrastructure and Public Services :
A health centre, which can accommodate 40 patients, is situated in Gairo. It owns a diesel generator with a capacity of 35 kVA but it is not working due to high running costs. During an interview with a doctor at the hospital, I heard that the man who looked after the generator had left, which is another factor which must have some influence.
Gairo has a water supply system, but it only operates properly when the ground water level is sufficiently high. The windmill which pumps up the water has not the capacity to supply the water system. Most of the time, the water is transported by bicycles. The quality of the water is very good, it is potable without treatment.

Accessibility :
Distance to Dodoma 153 km (east) , 130 km west of Morogoro.
Pretty good road to the township accessible the whole year through.

Demographic data : *Population census 1988*
Kilosa district : 347.230 inhabitants
Gairo township : 9608 inhabitants
Households : 1615

These figures are dated from '88 so do not give relevant information about the actual situation. The number of inhabitants are assumed to be well over 10.000.

Integrated Regional Development Plans :
A secondary school was planned to be build in 1990/91 in Gairo township.

In this aspect the development of the water supply system could be integrated with the electrification of the area. In the period of my visit at Gairo it came to my attention, as I spoke to an employee of the local bank, that a group of people was able to afford an electricity connection. If this village should be electrified, in any way, the related development perspectives would have a high chance to commence.
The utilisation of the SWER system is not a suitable method (see 6.4.2). Other possibilities for the utilisation of the SWER distribution system are perhaps the surrounding villages, Berega hospital for example, after electrification of Gairo with a conventional Three-Phase Three Wire distribution system.

During my stay in Gairo I visited a nearby village, Chakwale which was not included in the study by Tanesco. The goal was to get an idea of the possibility for electrification. It is some 15 kilometres from Gairo on a side way off the Morogoro Dodoma highway. Public transport is served by tractors which travel regularly from Gairo to Chakwale and visa versa. It is a small sandy road. There is a market place in the centre of the village where there are regular markets on saturdays. The cultivated crops consists of maize and sunflowers. An estimation of the load can be performed by the analyses of the inventory of potential electricity consumers :

Estimation of potential consumers in Chakwale :
- ± 30 Permanent houses;
- 1 Grain mill;
- Market place with some small shops surrounding it
- ± 10 Small shops;
- 4 Storage buildings for maize;
- 1 CCM building (small);
- 1 Dispensary;
- 1 Primary school;
- 1 Carpentry workshop;
- Some sewing shops.

6.2.2 Climatological conditions

Availability of reliable rainfall and fertile soil makes the district famous in crop production. Heavy rainfalls are experienced from January to April and temperatures are usually mild. From the data obtained from the agricultural office at Gairo the average annual rainfall is 528 mm.

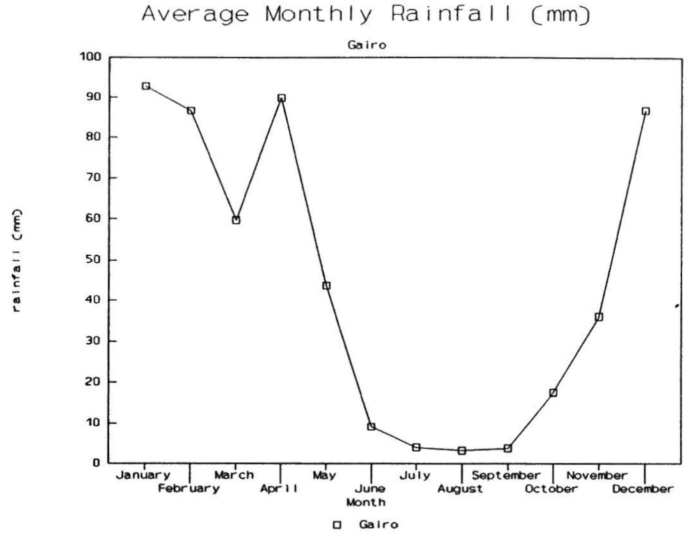


Figure 6.4 Monthly average rainfall in Gairo

Table 6.4 Rainfall statistics Gairo agricultural office

Year	Jan.	Febr.	March	April	May	June	July	August	Sept.	Oct.	Nov.	Decemb.	total
1980	195.8	58.4	122.3	78.0	41.1	0.0	0.0	15.0	0.0	0.1	17.4	98.2	620.3
1981	22.0	84.0	88.5	157.8	6.0	8.5	0.5	1.5	24.6	11.7	0.0	92.6	497.7
1982	40.0	52.8	53.1	59.7	39.9	27.5	-	-	2.0	76.9	111.1	111.9	574.9*
1983	64.3	27.4	87.6	9.7	105.2	12.6	20.5	0.0	0.0	9.0	7.8	116.1	460.2
1984	135.8	154.1	13.6	144.4	25.1	-	-	-	0.0	12.9	47.0	-	532.9*
1985	6.4	182.5	-	-	40.3	0.0	0.0	0.0	0.0	12.4	35.0	43.2	319.8*
1986	77.0	-	42.0	65.9	48.3	6.2	0.0	0.0	0.0	0.0	34.1	95.3	368.8*
1987	160.4	31.4	-	-	-	-	7.5	-	-	-	-	-	199.3*
1988	-	-	-	-	-	-	0.0	-	-	-	-	49.6	49.6*
1989	133.7	102.5	10.7	113.9	-	-	-	-	-	-	-	-	360.8*
Average monthly	92.8	86.6	59.7	89.9	43.7	9.1	4.1	3.3	3.8	17.6	36.1	86.7	528.1

- : Missing values
* : Total with missing values

- Average yearly is calculated using year totals without missing values

6.2.3 Resistivity measurements at Gairo

In Gairo the field was divided in a matrix of seven by seven lines in rectangular form. The distances in the x an y-direction where 5 meters, so a field of 30 by 30 metres was formed.
It was situated at a maize-field with some low vegetation growing almost everywhere, at the moment no maize grew on the field. This piece of land belongs to a primary school nearby. A water-pipe is running over a part of the field and another water-pipe runs besides the site along a path (see Fig. 6.6). To avoid the influence of these two pipelines the site was chosen at some distance away. We did choose this field despite the two pipe lines while it was the best place suitable to undertake the

measurements. The reason to choose this field consisted of the practical fact that it was situated in the middle of a load centre, in the direct surrounding where five guesthouses and three grain-mills. In the first place another site was selected at the border of the township on the property of the health-centre. This should be the second site to take readings but it seemed that this peace of land, a maize-field with almost no vegetation, was to sandy and loose. The resistance did exceed the maximum value of the scale, meaning a resistivity nearby the limit of 500 ohm.m.

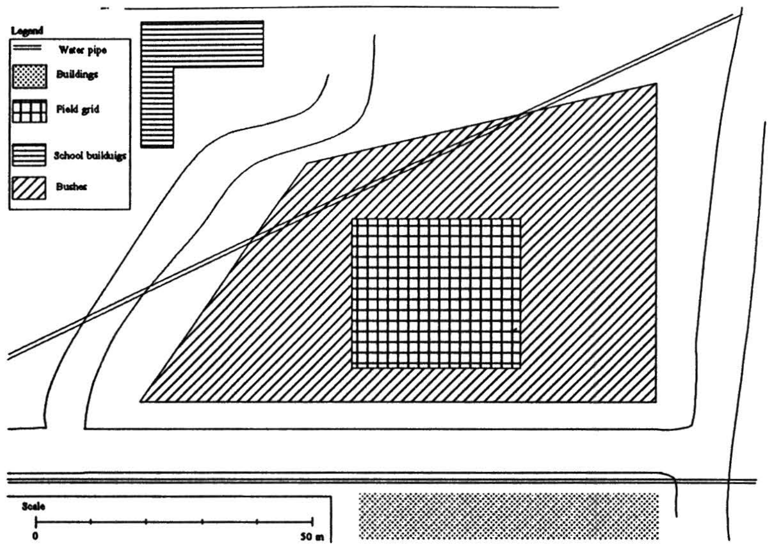
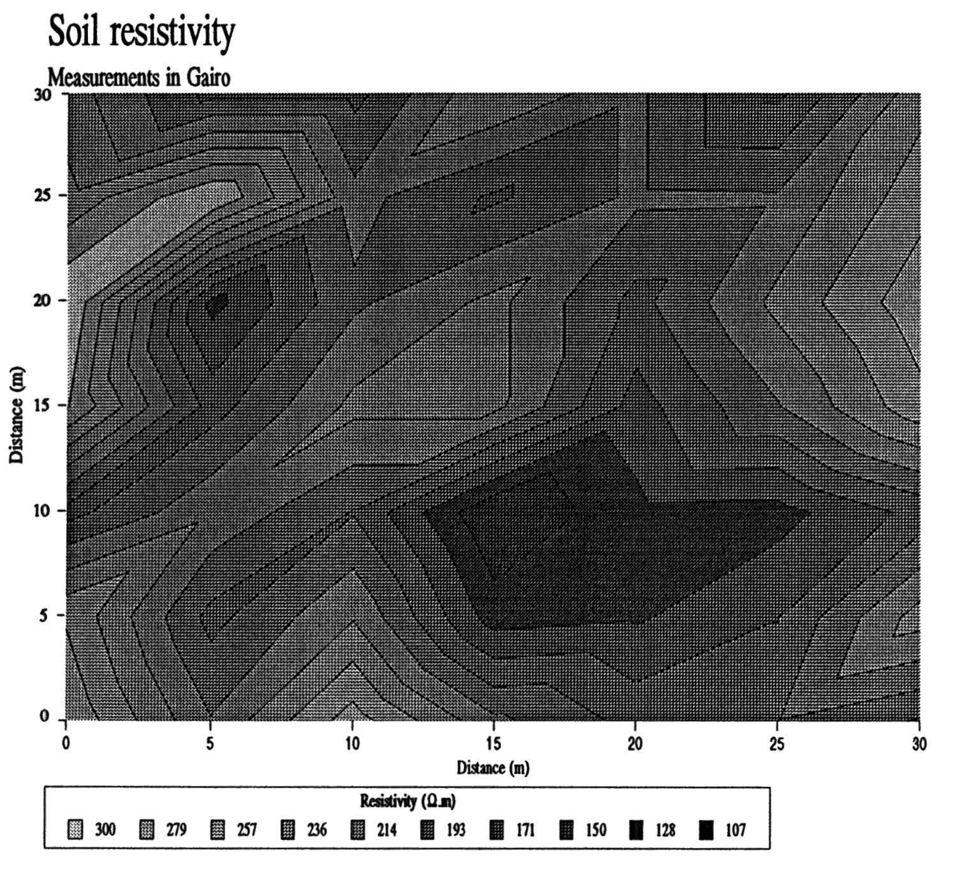


Figure 6.5 Situation in Gairo



Figfure 6.6 Resistivity map of Gairo

6.2.4 Load forecast for Gairo

Residential houses (tariff 1) :

Type	number	Demand per consumer (kW)	Load factor	load (kW)
Low	725	0.25	0.8	145
Medium	235	1.65	0.45	175
High	10	4.0	0.45	18
Total	970			338

The houses which can attain to TANESCO's standards for getting power supply. (based on ratio's per consumer groups)

Commercial (tariff 2) :

Type	number	Demand per consumer (kW)	Load factor	Max Demand (kW)
shops	60	6.25	0.4	150
hotels	20	12.5	0.4	100
guest houses	10	5	0.4	20
bars	8	5	0.4	16
Commercial centre	1	2.5	0.4	1
Garages	3	2.5	0.4	3
Petrol station	5	2.5	0.4	5
Health centres	1	60	0.5	30
Hospital	1	137.5	0.4	55
Dispensary	1	5	0.4	2
Primary school	1	5	0.4	2
Secondary school	1	75	0.4	30
Bank	1	6.25	0.4	2.5
Post office	1	6.25	0.4	2.5
Police station	1	5	0.4	2
RTC	1	5	0.4	2
Godowns	2	2.5	0.4	2
CCM office	1	2.5	0.4	1
Agricultural office	1	5	0.4	2
Total	120			428

Light Industrial (tariff 3) :

Type	number	Demand per consumer (kW)	Load factor	Max Demand (kW)
Oil mill	1	10	0.4	10
Grain mill	2	93.75	0.4	75
Workshop	3	12.5	0.4	15
Textile mill	1	12.5	0.4	5
Total	7			105

Public sector (tariff 4)

Type	number	Demand per consumer (kW)	Load factor	Max Demand (kW)
Street lights 10% of residential demand	50	0.2	0.5	10
Churches	7	5	0.4	14
Mosques	3	5	0.4	6
Total	60			30

Table 6.5 Load forecast (kW) of Gairo

Tariff group	(kW)
Residential	338
Commercial	428
Industrial	105
Public sector (street lights and religious centres)	30
Total load	901

Initial load of 901 kW, with a growth factor of 5 % per annum the load in year 10 will be, ≈ 1500 kW

6.3 EVALUATION OF THE CRITERIA ON THE NATIONAL LEVEL

Environmental conditions

Evaluation based on the average annual rainfall statistics, which should be greater than *750 mm*, only the project including Mboga corresponds with suitable conditions. Although it exceeds the minimum, looking at the individual averages per annum, the probability is not expected to exceed the required *750 mm*. This can also be shown by the rainfall probability map of Tanzania (Fig 4.11). In Gairo (Agricultural office), the annual average rainfall is *538 mm* and well below the limit of *750 mm*. If Berega hospital and Magubike are included with the electrification project of Gairo, investigations to electrify these two load centres with a SWER system from Gairo could be performed.

Economic profile

The economic profiles and subsequently the potential consumer groups are not the constraining factor in Mboga for the suitability of the system. The industrial sector is of limited size and most consumers are commercial and residential groups. In Gairo the demand is to large to utilize the SWER system.

Accessibility

The distance of the load centres to the main distribution line (< *50 km*) is in both cases a constraining factor. In Mioni division, Mioni itself is 62 km from Chalinze and Mbwewe 81 km. In Gairo the nearest distribution line is situated at Mpwapwa, at a distance of 65 km.
The electrification of Magubike and Berega hospital utilising a SWER distribution system from Gairo could be an option for the future.

Infrastructure

Infrastructural facilities in terms of water supply, education and health care in Mboga are the existence of one primary school and water holes for the water supply, which is of poor quality.
In Gairo a water supply system is present and the quality is good, a hospital with the capacity of 40 beds, a health centre and a dispensary exist and one primary and one secondary school.

Demographic aspects

From a demographic point of view large population centres are a constraining factor. In the rural areas this will only be of concern if the population in a project area is expected to grow rapidly. In the project including Mboga, the load centres are fairly small and could grow for some time and still not exceed the criteria for this system. Gairo is a commercial centre for the surrounding area and can be expected to grow. For the suitability of the SWER system, in terms of demographic aspect, it is not suitable to supply Gairo.

Integrated Regional Development Plans

An example of the integration of the electrification project with other facilities in the area in both cases, could be the improvement of the water supply. It can be concluded that, bearing in mind that the technical criteria related to the soil resistivity and distance from the main distribution grid are of major importance, these areas are not suitable

6.4 EVALUATION OF THE LOCAL CONDITIONS

With respect to the soil resistivity of the two sites, which indicate values within the limit of 500 Ω.m, it should be suitable but due to the measuring method no definite conclusions can be based on these measurements. As result of the method employed, only preliminary conclusions can be drawn. This method is only suitable for ground surveying and capable to indicate if a more comprehensive study is necessary.
The existence of conducting structures in the ground only in Gairo, the water pipelines are of concern. The power market surveys performed by Tanesco indicate that in the project area of Mioni division no problems should occur since the load per feeder (transformer) never exceeds 250 kW. In Gairo the total load exceeds the limit of 250 kW and the total initial load of 900 kW is too high for the SWER system to deliver.

6.5 OVERALL CONCLUSION

The evaluation of the two areas based on the criteria employed in this study can be summarized as follows:

Table 6.6 Summary of the conditions in Gairo and Mioni division (including Mboga)

Criteria	Gairo	Mioni division (including Mboga)
Environmental conditions (rainfall probability ≥ 750 mm)	rainfall probability < 750 mm	rainfall probability < 750 mm
Soil resistivity (≤ *500 Ω.m*)	within limits but only preliminary conclusion	within limits but only preliminary conclusion
Load forecast (*feeder areas ≤ 250 kW*)	Initial load too high	according to design of Tanesco, largest transformer is 200 kVA, thus not constraining factor
Economic profile *(division residential, industrial, commercial and public sector)*	not a suitable profile	suitable economical profile
Accessibility (*distance ≤ 50 km from main distribution network)*	exceeding 50 km	exceeding 50 km
Infrastructure (*water supply, health care, education*)	water supply system, hospital, 1 primary and 1 secondary school	1 primary school (Mboga), water is of poor quality
Demographic aspects (*population and growth*)	growth centre	scattered population

While an area should satisfy all criteria it is obvious that these two project areas do not possess suitable conditions to utilize the SWER (Single Wire Earth Return) distribution system.

7 PRELIMINARY GRID DESIGN

After an area is selected and a study of the area, including the estimate load and division of the different consumer groups is identified, a grid design has to be made. The system comprises the path from the main distribution line to the load centres (primary system), after which the voltage is stepped down by distribution transformers to feed the service lines to the consumers (secondary system).
The design procedure of a system can be divided in three consecutive steps [33], (1) **electrical design considerations**, (2) **mechanical design** and (3) **economic design.**

1 - this is generally based on acceptable values of voltage drop and those of energy loss. These considerations may be modified to accommodate desired protection, environmental and other requirements. The permissable values determine the size of conductors and the associated insulation requirements. The physical characteristics of the conductor have their impact on the mechanical design of a system.

2. - this involves the study of structures and equipment. It includes the selection of proper materials and their combination into structures and systems in such a manner as to meet the electrical design requirements, giving due consideration to matters of strength, safety, temperature variations, length of life, appearance, maintenance, and other related factors.

3. - this includes the investigation of relative costs of two or more possible solutions to the combined electrical and mechanical requirements of each individual type of system under study. The procedure to evaluate the most economical combination of elements in the system can be performed with *Kelvin's law* [33]. With this "law", that option is chosen where the annual charges on the cost of installation are compared to the annual cost of energy losses, where the two values are equal or nearly equal the most economical of standard sizes will be. Many factors intrude, however, to modify the applicable conditions. These factors concern generally to safety and environmental requirements as well as possible future demand for electric power.

For the purpose of this study a comparison will be made of three primary distribution systems, (1) **SWER (Single Wire Earth Return)**, (2) **Single-phase two wire** and (3) **Three-phase three wire**. In this chapter only the main differences in electrical and mechanical design is described. The aspects consists of conductor size, electrical protection and overhead construction.
The design of the secondary system will only be described briefly, the main goal is to compare the different primary systems in order to select the best option for a rural electrification project.

7.1 SECONDARY SYSTEM DESIGN

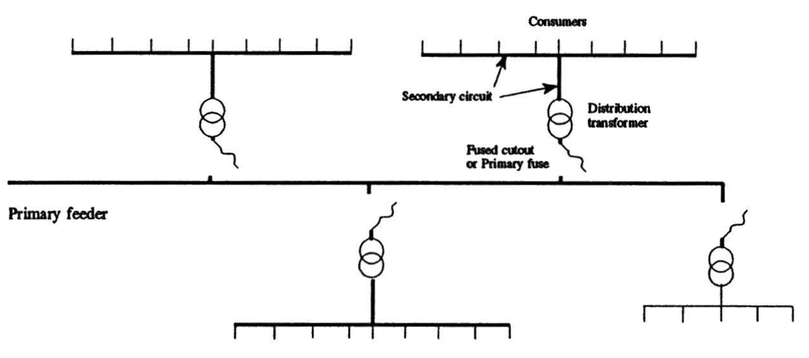


Figure 7.1 Secondary system design configuration

The design of the secondary system consists of choosing a distribution transformer which will feed the service area and selecting the conductor size of the secondary system. It can be accomplished in the following way [33]. Figure 7.1 shows the electrical equivalent of the secondary system. The number of consumers which will be connected to a secondary system is dependent on the geographical composition of the area involved or initially by limiting the amount of consumers that would be affected by the de-energisation of a transformer from whatever cause. The approximate total loads of these consumers is known and a transformer capable of serving this load is chosen. Placed in the centre of the mains, the distance to the remotest consumer is known. The tolerable voltage drop to the last consumer is assumed and the resistance of the secondary main from that point back to the transformer is calculated. The conductor

size matching this resistance (approximately) can be determined from tables of conductors and their characteristics. The conductor sizes are indicated in this fashion for a number of secondary mains. From an inspection, a limited number of "standard" sizes that satisfy the greater number of these is chosen. Where the standard is greater than required to serve the consumers on some mains, the excess capacity not only accommodates load growth but also results in a better voltage regulation and, in some situations, permits the installation of smaller size transformer. Where the standards are too small to satisfy the load requirements, the secondary main may be split into two or more sections and separate transformers installed to serve each section. The determination of distribution transformer standard sizes is accomplished in the same manner.
These procedures are economically justified from the resulting simplification of purchasing, stocking, installation, operation and maintenance practices, including the training and work practices of pèrsonnel and the selection and operation of equipment [33].

7.2 PRIMARY SYSTEM DESIGN

The primary system serves the load at a higher voltage than utilised for consumer purpose, from a substation to the load centres. The design and planning of these systems is more complex than the secondary systems as many more interrelated factors must be considered.
The determination of the most economical ***conductor size*** to carry the given load depends on the most economical load for a feeder, the division of loads between feeders and the most economical primary voltage. These are affected by the location and size of the supply substation, the arrangement of mains and sideways for polyphase circuits, including the selection of grounding technique, all modified by the standard sizes of conductors, equipment, code and local restrictions and regulations.
In the case of ***reliability***, emergency connections with other circuits, loop circuits (open and closed), primary network and throw-over arrangements for individual consumers may be considered.
The ***permissable voltage drop*** is affected by regulators (both at substations and on lines), capacitors and boosters.
The choice of ***primary voltage*** is dependent not only on the availability of standard methods and equipment but also on operating and maintenance procedures and its impact on other utilities.
All factors are subject to further modification to provide for future load growth and environmental requirements, and above all, for the safety for workers and the population. In the following three paragraphs

7.3 ELECTRICAL DESIGN

The electrical design is divided in the choice of conductor size and a description of the differences in electrical protection.

7.3.1 Conductor size

To determine the conductor in this case, certain assumptions are made for the sake of simplicity [33] :

- the ***loads*** distributed along the line can be considered as a single load at its end, or to the feed point on the distribution circuit.
- total ***energy loss*** in the line will be calculated according to the representing electrical schemes.
- the ***voltage drop*** over the line, to the end of the line, is will be calculated according to the representing electrical schemes.

To compare the SWER distribution system with the other two options, I propose the following method :

1. Create a set of criteria for *power loss, voltage drop, soil resistivity, earth-electrode potential*;
2. Assume certain values for *voltage level, power factor, distance between conductors, height of the conductors, distance to load centre(s), earth path (resistance and reactance)* and *grounding grid resistance*
3. Derivation of equations to determine conductor size for the *SWER, Single-Phase Two Wire* and *Three-Phase Three Wire* distribution system which satisfies the criteria;
4. Determination of the *SWER, Single-Phase Two Wire* and *Three-Phase Three Wire* electrical schemes.
5. Presentation of the delivery capacity by conductor size and per distribution system;

1. set of criteria

Table 7.1 Set of criteria

Criteria	Values
Power (Kw) loss	max 5 % of Power demand
Voltage drop	10 % of Primary voltage
Soil resistivity	500 Ω.m
Earth-electrode potential	50 V

2. Assumptions

Table 7.2 Assumption of a system configuration

System configuration	Assumptions
Voltage level	33 kV
Power factor	0.9
Height of the conductors	10 m
Distance between conductors	1 m
Distance to load centre(s)	10 - 50 km
Earth path	Re = $\omega\mu/8$ (Ω/km)
	Xe = $\omega\mu/2\pi$ ln (399.6/h $\sqrt{\rho/f}$
Grid resistance	1 Ω

- The power factor is assumed to be 0.9, which is typical for rural loads where most of the power is required for the lighting load [7];
- The height of the conductor above earth can be modified and is taken from reference [33];
- Distance to load centres is between a minimum and maximum (stated in chapter 4);
- Earth path are formulae mentioned earlier in paragraph 3.3 (equivalent depth of return);
- Grid resistance is a value that is likely to be within the safety margins with respect to soil drying out and surface potential rise.

3. Derivation of equations to determine conductor size

The conductor size could be chosen according to the conductor which can distribute the power demand to the load centres within the limits of the set of criteria. For the earth electrode (or earth electrode grid) a value of 1 Ω is assumed. The parameters of the earth path are then completed (see Fig. 7.2). The conductor size has to come up to the requirements with respect to carrying the load, a satisfactory voltage regulation and mechanically strong enough to support itself on overhead lines (for characteristics of conductor materials, see Appendix A.3). This leads, among other things, to a maximum load current (I_{load}) for the SWER system of :

$$I_{max} = \frac{\Delta V}{R_g} = \frac{50}{1} = 50\ A$$

The resistance per distribution line is calculated according to the following equations, for the three-phase system the equation of the resistance and inductive reactance of one conductor is given :

$$R_{SWER} = lR_c + lR_e + 2R_g$$

$$R_{Single\text{-}Phase\ Two\ Wire} = 2lR_c$$

$$R_{Three\text{-}Phase\ Three\ Wire} = 3lR_c$$

Where :

Rc	= conductor resistance (Ω/km);	*Rg*	= earthing electrode resistance;
Re	= earth path resistance (Ω/km);	*l*	= Distance to load centre;

The inductive reactance by conductor of the three distribution lines are the following :

$$X_{SWER} = lX_c + lX_e; \qquad X_{TwoWire} = 2lX_c; \qquad X_{Three\ Wire} = lX_c;$$

$$X_c = \frac{6.56 fL}{10^3}\ \Omega/km; \qquad X_e = f\mu_0 \ln\left(\frac{399.6}{h}\sqrt{\frac{\rho}{f}}\right);$$

$$L_{Two\text{-}Wire} = \frac{\mu_0 l}{\pi}\left(\ln\frac{d}{r} + \frac{1}{4}\right); \qquad L_{Three\text{-}Wire} = \frac{\mu_0 l}{2\pi}\left(\ln\frac{d}{r} + \frac{1}{4}\right)$$

Where :

$X_{(c,e)}$	=	Inductive reactance of the conductor and earth path respectively;
μ_0	=	permeability of vacuum
L	=	unit of inductance;
f	=	frequency;
ρ	=	soil resistivity
a	=	radius of conductor;
l	=	line length
d	=	distance between conductors;
h	=	conductor height above

The formulae for the unit of inductance are according to reference [34].

The load current by conductor size is calculated according to permissable power loss of 5 % :

$$\Delta P\ (power\ loss) = I_{load}^2 R_c = 0.05\, U I_{load} \cos(\phi)$$

$$I_{load} = \frac{0.05\, U \cos(\phi)}{R_c}$$

The power delivery capacity per system is calculated with the next equations :

$$P_{SWER} = U_f\, I_{load} \cos(\phi) = \frac{0.05\, U_f^2 \cos^2(\phi)}{R_{SWER}}$$

$$P_{Two\text{-}Wire} = U_l\, I_{load} \cos(\phi) = \frac{0.05\, U_l^2 \cos^2(\phi)}{R_{two\text{-}wire}}$$

$$P_{Three\text{-}Wire} = 3\, U_f\, I_{load} \cos(\phi) = \frac{0.05\ 3\, U_f^2 \cos^2(\phi)}{R_{three\text{-}wire}}$$

Where :

$cos\ (\phi)$	=	power factor (0.9);
U_l	=	line to line voltage - 33 kV for the Single-Phase Two wire system
U_f	=	phase to neutral voltage - 33 kV / √3 ≈ 19.1 kV for the Single Wire Earth Return (SWER) and Three-Phase Three Wire system
I_{load}	=	load current

Voltage drop (%) is calculated according to the following equation :

$$U_{loss} = \frac{I_{load}\ (R\cos(\phi) + X\sin(\phi))}{U} * 100 \quad per\ conductor$$

$cos\ (\phi)$	=	0.9 (power factor;
$sin\ (\phi)$	=	0.4;
R	=	R_{swer}, $R_{Two\text{-}Wire}$, $R_{Three\text{-}Wire}$
X	=	X_{SWER}, $X_{Two\text{-}Wire}$, $X_{Three\text{-}Wire}$
U	=	U_{SWER}, $U_{Two\text{-}wire}$, $U_{Three\text{-}wire}$

The data of calculations of delivery capacity, voltage drop and load current can be found in Appendix A.5, for the characteristics of the conductor materials I refer to Appendix A.3.

4 . The representing schemes of the distribution systems :

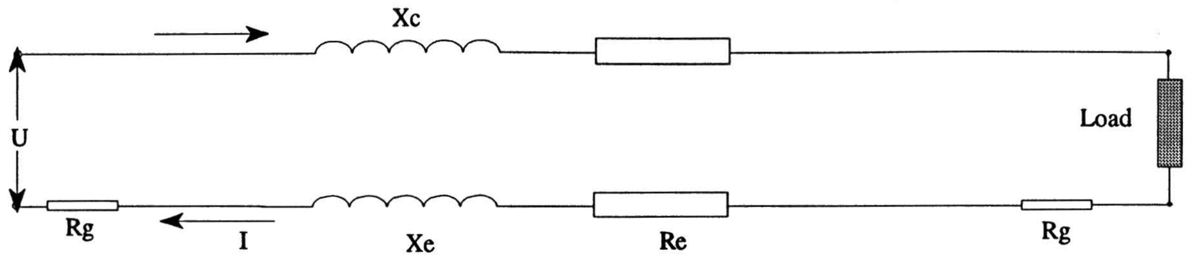


Figure 7.2 Electrical scheme of a SWER distribution line

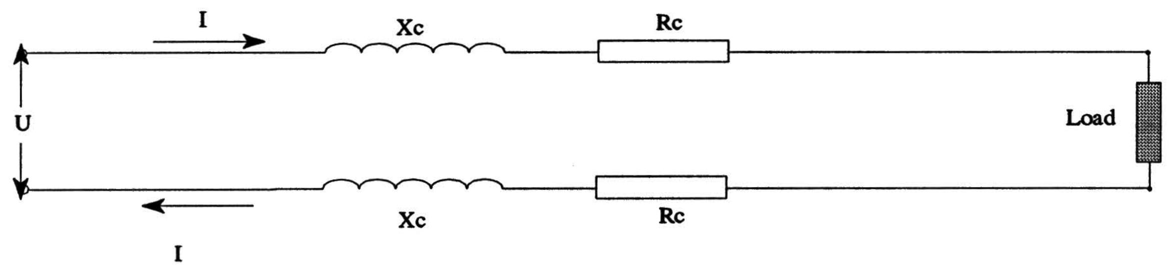


Figure 7.3 Electrical scheme of a **Single-Phase Two Wire** distribution system

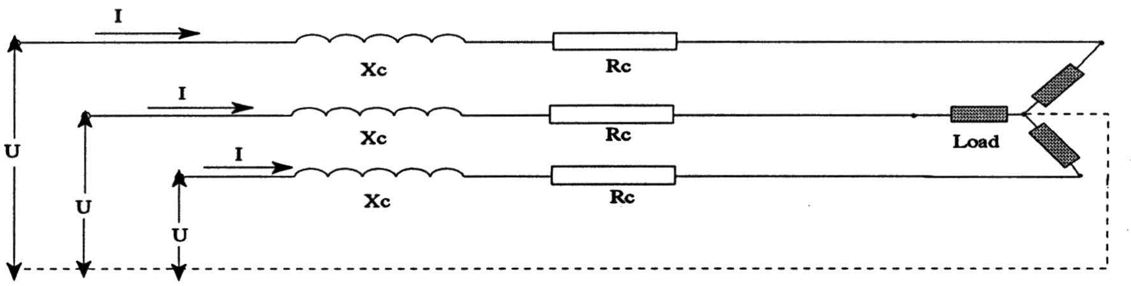
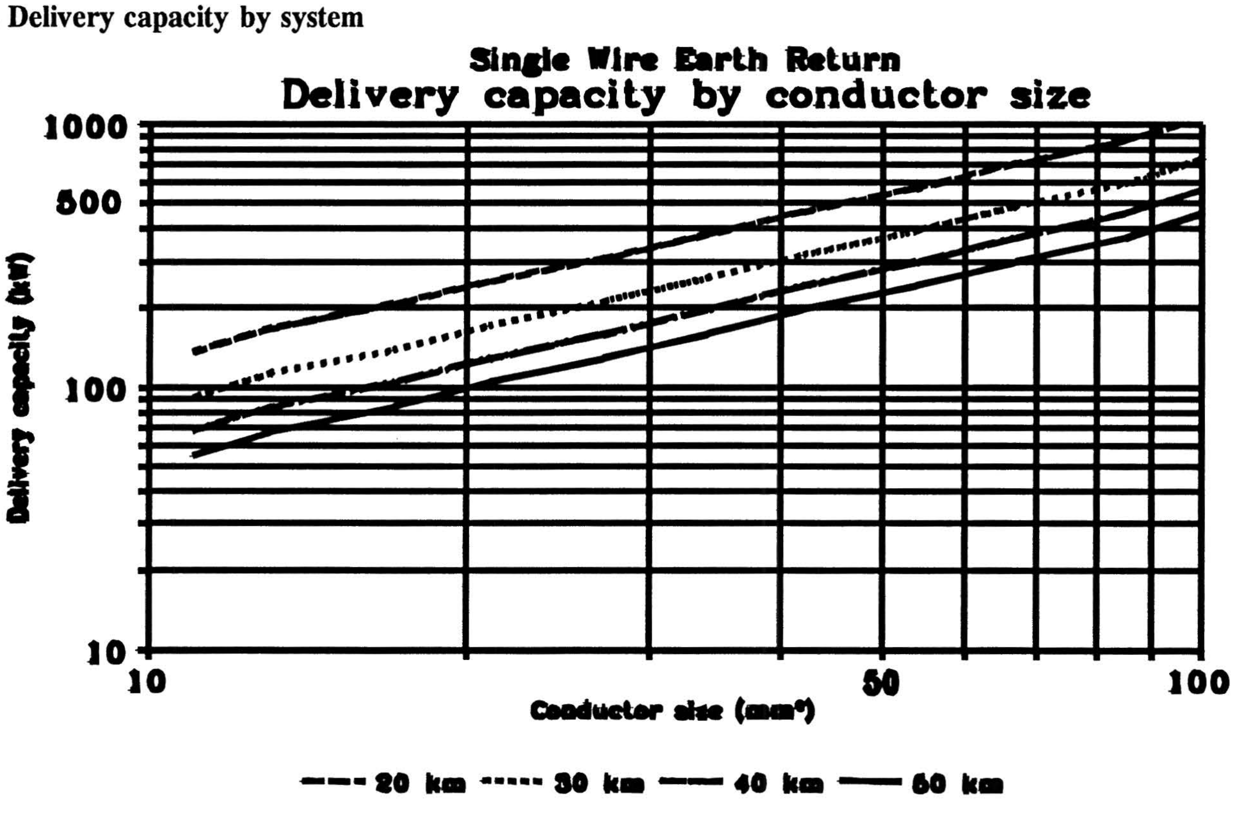
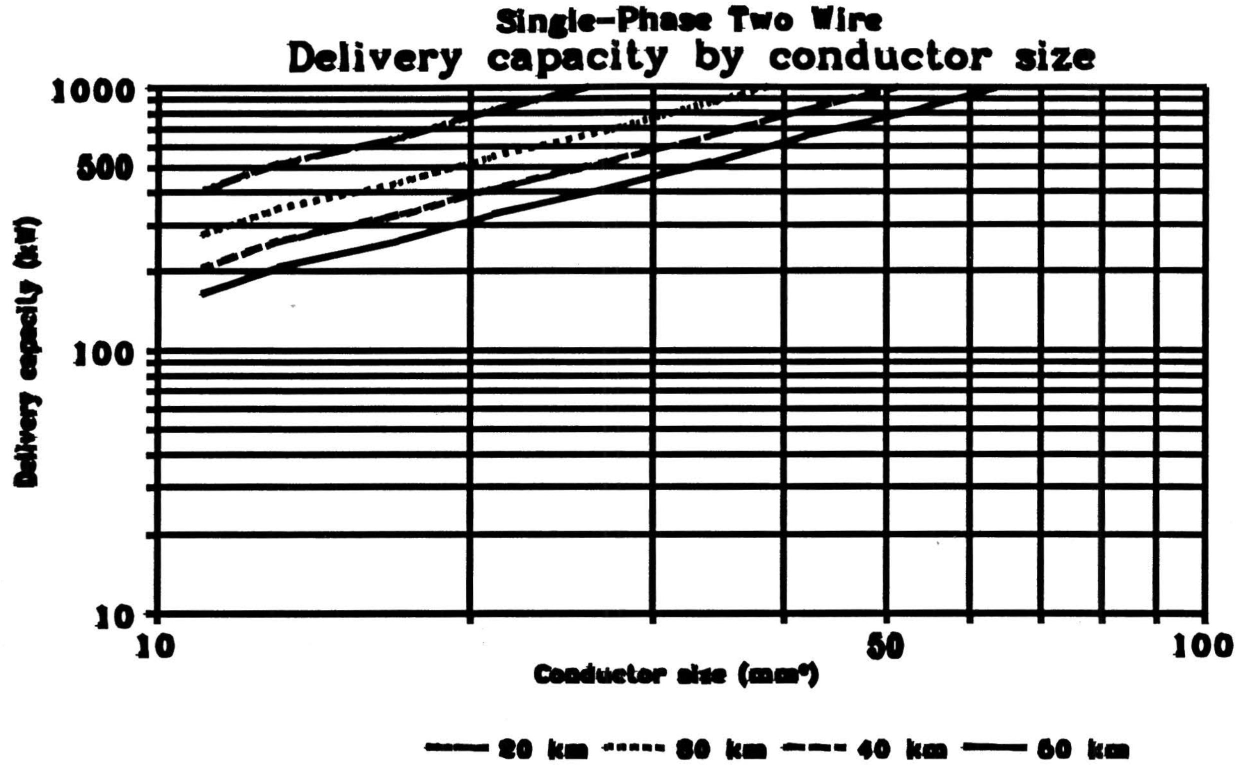
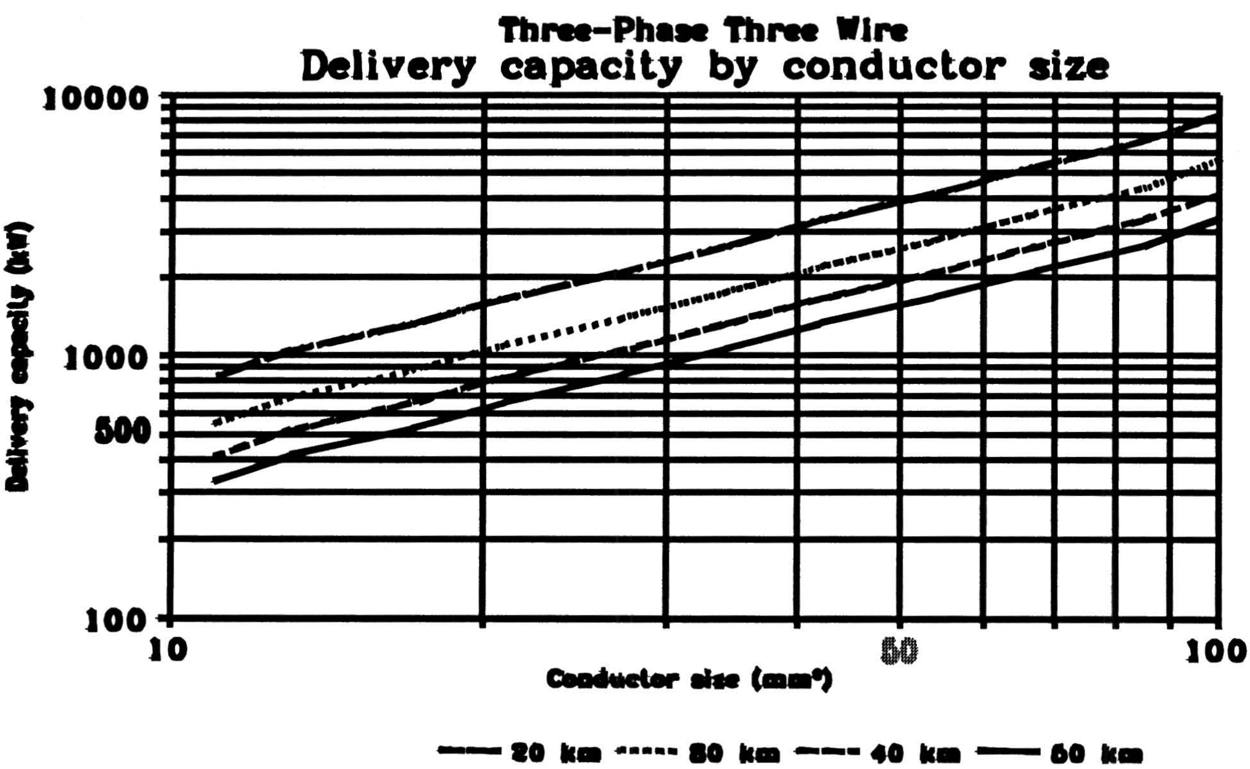


Figure 7.4 Electrical scheme of a Three-Phase Three wire distribution system

5. Delivery capacity by system




Single-Phase Two Wire
Delivery capacity by conductor size
1000
500
100
10
10
50
100
Delivery capacity (kW)
Conductor size (mm²)
20 km
30 km
40 km
50 km


Three-Phase Three Wire
Delivery capacity by conductor size
10000
1000
500
100
10
50
100
Delivery capacity (kW)
Conductor size (mm²)
20 km
30 km
40 km
50 km

7.3.2 Electrical protection

The electrical protection is of major importance and an integral part of the electrical system design. In the case of The Single-Phase two wire and Three-Phase three wire system the protection is located at the distribution transformer. In the Single-Wire Earth Return system the protection at the isolation transformer is an additional means of protection.

Distribution transformer

The distribution transformers are protected by a surge arrester and fused cut-out. The surge arrester performs the task of protection in the case of lightning or switching. The fuse protects them from overloads (as well as surge currents) and fault currents as result of faults in the secondary or in the transformer. The surge arrester and fuses are coordinated so that the arrester operates to drain the voltage surge before it can feed sufficient current through the transformer. Both are coordinated with the insulation of the line and transformer, but primarily with the latter.

Primary feeder line

Isolation transformer (SWER distribution system only)

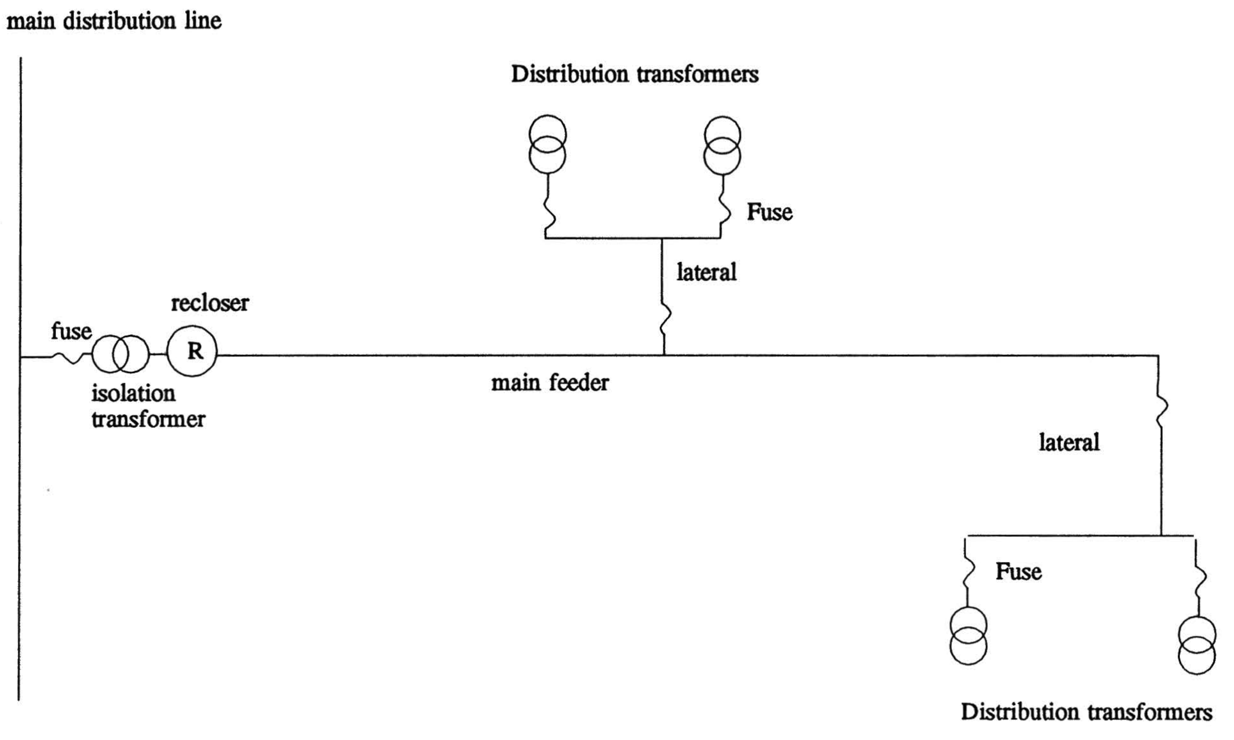


Figure 7.5 Electrical protection in SWER line

The isolation transformer is incorporated to ensure that the three-phase or single-phase lines which energize the SWER line do not carry zero-sequence (earth leakage) currents. This ensures the earth leakage protection may still be used on the conventional system.
By its nature, the only form of protection which can be applied for faults and line-down conditions is over-current, either by fusing or by the use of reclosers.
On the supply side the isolator is protected by fuses and the outgoing line by a recloser (see Fig. 7.5). The fuses are intended only to disconnect a faulted isolator and not to detect a sustained overload condition. This can result in a protection "black spot" where a high impedance fault does not operate the recloser and causes an overload condition on the isolator [6]. A high impedance fault can occur in the case of a short circuit from line to ground. The electrical protection of the two other systems consist of

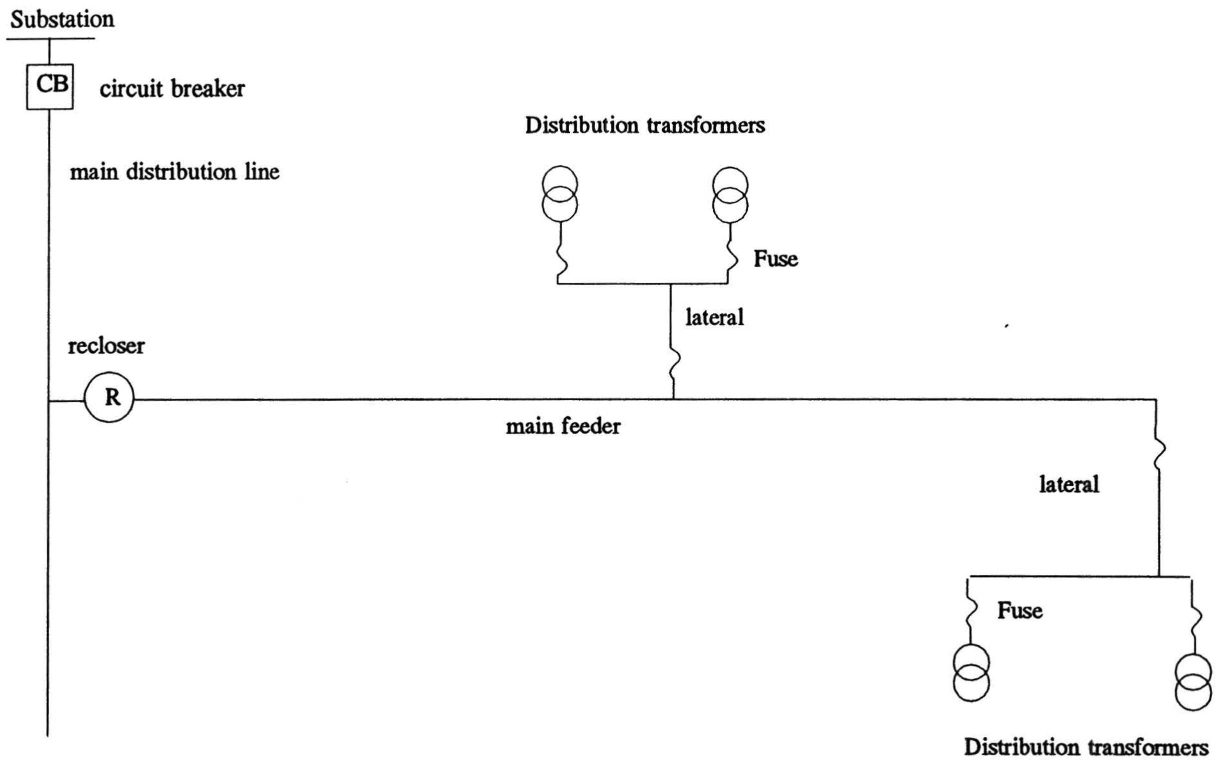


Figure 7.6 Electrical protection in two- and three-wire lines

reclosers, fuses and a circuit breaker at the sub-station of the main distribution line. Fuses on the laterals must coordinate with those associated with the primary main. The lateral fuse must blow after that of those of the distribution transformers and before the protective devices on the primary main operate (see Fig. 7.6). On the main, the fuses, reclosers and circuit breaker of the substation must coordinate which each other. Those farthest from the source operate first and those next farthest operate next and so on to the circuit breaker at the substation. If the SWER distribution system is compared with the two other options the following re,arks can be made :

- The SWER system compared with the Three-Phase Three Wire system leads to the observation that for the same conductor size the delivery capacity is a factor **7.5** times greater. The main differences of the two systems are thus in this situation :
  - the total length of wires (factor 3);
  - type of supply (Single-Phase versus Three-Phase);
  - additional isolation transformer and fuse in the case of the SWER system.

- If the SWER system is compared with the Single-Phase Two Wire system the difference in power delivery capacity is in favour of the two wire system (approximately a factor **3 to 4**). The main differences between the two systems for demand below 500 kw are :
  - the total length of wires (factor 2)
  - additional isolation transformer and fuse in the case of the SWER system.

7.4 Mechanical design of overhead construction

The design and construction of the overhead lines and their supporting parts must be such that, in addition to normal stresses and strains, they sustain safely abnormal conditions caused by nature and people. Supports for conductors and equipment must withstand the forces imposed on them, including their own weight.

To make a comparison the following features will be included :
The span is assumed to be the same for all three options (125 m).

- crossarms (the carrying structure for the conductors), varying with the number of conductors which it has to support.
- insulators (the electrical separator between conductor and supporting construction on the pole), varying with voltage level and conductor size;
- poles, dependent on the conductor size and amount of conductors to be supported.

If we look at figure 7.8 and take the situation in consideration with a maximum load of 444 kW (max for SWER at 50 km), a smaller conductor size for Single-Phase Two Wire as well as for the Three-Phase Three Wire system, the following remarks can be made :

Table 7.3 Comparison of overhead construction aspects with SWER

	Single-Phase Two Wire	Three-Phase Three Wire
Insulators	The force on the insulators as result of the conductor is smaller, the voltage level is the same so similar insulation level but less mechanical forces acting on the insulator.	The force on the insulators is in this case smaller compared to both other systems (one and two wire systems) with the same insulation level. The amount of insulators differ, however, a factor 3.
Crossarms	While two conductors need to be supported by the mechanical construction crossarms are necessary, while in the case of the SWER system crossarms can be left out.	Three wires must be supported by the pole, the crossarms must be capable to fulfil this requirement.
Poles	The amount of poles necessary for the line can thus be fewer, but every pole has to support two wires so the required mechanical strength does demand a pole of a higher class.	The amount of poles can be the same but the required mechanical strength will lead to a pole of lower class.

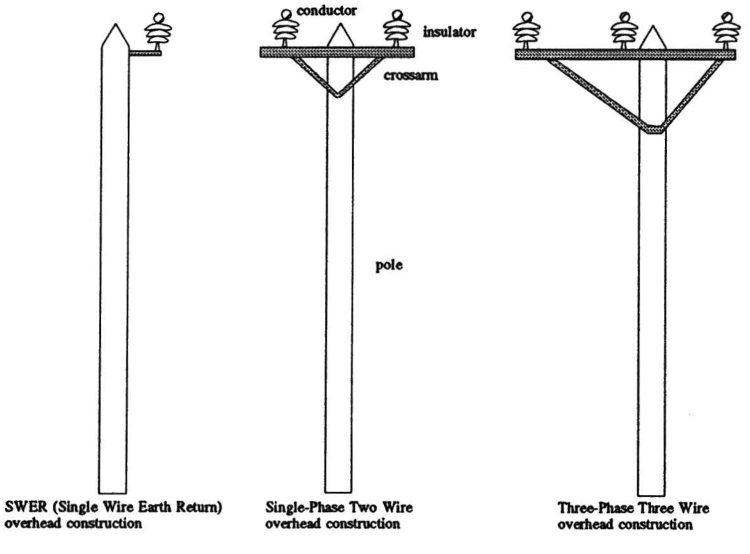


Figure 7.8 Overhead construction of the different distribution lines

8 ANALYSIS

The analysis in this study primarily concerns the suitability of SWER distribution systems for rural electrification in Tanzania. Where SWER is suitable (in the pilot areas SWER was in principle not suitable) it should be compared with two other ways of electrification : single-phase two wire and three-phase three wire systems

To simplify matters it is assumed that the three distribution systems mentioned do not affect the potential electricity demand in a specific area, the income for TANESCO will be the same for all these options. From this simple assumption it follows that the choice of a system primarily depends on the cost difference between the systems. The costs consist of (1) investment costs, (2) operation and maintenance costs and (3) electricity costs. The main factors determining these costs will be briefly described in the following paragraphs. In addition potential socio-economic benefits will have to be taken in consideration (see Chapter 5) and environmental issues (see chapter 4)

The emphasis on costs as the determining criterium for a choice between the three systems is justified by the following reasoning.

8.1 JUSTIFICATION

The most basic rule for accepting a project is that the **Net Present Value (NPV)** should be positive :

$$NPV = \sum_{t=0}^{T} \frac{(B_t - C_t)}{(1 + r)^t}$$

where B_t = benefits in year t;
C_t = costs in year t;
r = the discount rate;
T = time horizon

Both benefits and costs are defined as the difference between what would occur with and without the project being implemented. for the economic testing, B,C and r are defined in economic terms and appropriately shadow priced using efficiency border prices. In particular, the shadow price of r is the accounting rate of interest (ARI)[1]. If projects are to be compared or ranked, the one with the highest, and positive, NPV would be the preferred one. If for example $NPV_I > NPV_{II}$, then project I is preferred to project II, provided also that the scale and scope of each of the projects under review is roughly the same. Complications may arise in the analysis of interdependent projects.

The **Internal Rate of Return (IRR)** is also used as a project criterion. It may be defined by:

$$\sum_{t=0}^{T} \frac{(B_t - C_t)}{(1 + IRR)^t} = 0$$

Thus, the IRR is the discount rate at which the NPV is zero. The project is acceptable if the IRR > ARI, which in most normal cases implies that NPV > 0. Problems of interpretation occur if alternative projects have widely differing lifetimes, so that the discount rate plays a critical role.

[1] Shadow prices indicate the value of goods and services assuming no market distortions. While market prices are to be used for the financial evaluation, shadow prices reflect the value of project inputs and outputs better than market prices, and may be considered as their necessary correction for the economic evaluation. shadow prices are usually determined only for major production factors and project inputs and outputs, as well as when market distortions are significant.

Another frequently used criterion is the **Benefit Cost Ratio (BCR)** :

$$BCR = \frac{\left[\sum_{t=0}^{T} \frac{B_t}{(1+r)^t}\right]}{\left[\sum_{t=0}^{T} \frac{C_t}{(1+r)^t}\right]}$$

If BCR > 1, then NPV > 0 and the project is acceptable.

Each of these criteria has its strengths and weaknesses, but the NPV is probably the most useful. The NPV test may be used to derive the least cost rule in the case of this study. In the case of energy projects, the benefits of alternative technologies are often equal, they both serve the same demand. Then the comparison of alternatives is simplified. Thus :

$$NPV_I - NPV_{II} = \sum_{t=0}^{T} \frac{(C_{II,t} - C_{I,t})}{(1+r)^t}$$

since the benefit streams counteract. Therefore , if

$$\sum_{t=0}^{T} \frac{C_{II,t}}{(1+r)^t} > \sum_{t=0}^{T} \frac{C_{I,t}}{(1+r)^t}$$

then NPV_I > NPV_{II} and project II is preferable. In other words the project which has the lower present value of costs is preferred. This is called the least cost alternative (when benefits are equal). However, even after selecting the least cost technology, it would still be necessary to ensure that the project would provide a positive NPV.

8.2 MAIN COST FACTORS

1. Investment cost factors

	SWER	Single-Phase Two Wire	Three-Phase Three Wire
- Labour costs	Tsh./hour	Tsh./hour	Tsh./hour
- Transport	a) imported materials b) local materials	a) imported materials b) local materials	a) imported materials b) local materials
- Ground factor (clearance right of way)		depending on geography and land ownership	
- Span wide	125 m	125 m	125 m
- Voltage level	33 kV	33 kV	33 kV
- Number of conductors	1	2	3
- Conductor material	ACSR	ACSR	ACSR
- Conductor size	11 - 106 mm²	11 - 106 mm²	11 - 106 mm²
- Conductor price	\$/m (imported)	\$/m (imported)	\$/m (imported)
- Pole price	Tsh./m³ (local)	Tsh./m³ (local)	Tsh./m³ (local)
- Insulator price	33 kV type	33 kV type	33 kV type
- Pole material	Wood	Wood	Wood
- Permissable soil depth	6 m	6 m	6 m
- Average ambient temperature	25 °C	25 °C	25 °C
- Maximum ambient temperature	60 °C	60 °C	60 °C

Other investment cost factors ;

	SWER	Single-Phase Two Wire	Three-Phase Three Wire
- Earthing system	- extended - earth potential (U_e) < 50 V ($Rg \leq U/I_{load}$)	- satisfy to safety regulation	- satisfy to safety regulation
- Transformers 1) isolation transformer 2) distribution transformers	 - 1 per spur line - ≤ 250 KVA	 - none - demand dependent	 - none - demand dependent
- Electrical protection	- 1 fuse per transformer - 1 fuse (single-phase) per lateral - a recloser and fuse at isolation transformer	- 1 fuse (single-phase) per transformer - 1 fuse (single-phase) per lateral - a recloser at begin of spur line	- 1 fuse (three-phase) per transformer - 1 fuse (three-phase) per lateral - a recloser at begin of spur line
	- Surge,lighting arresters	- Surge or lighting arresters	- Surge or lighting arresters
- Other equipment	- Voltage regulators - Switches	- Voltage regulators - Switches	- Voltage regulators - Switches

2. Operation and maintenance costs :

With respect to the operation and maintenance costs it is assumed that the costs for the Single Wire Earth return (SWER) distribution system will be a major factor. The periodically inspection of the earthing system is of essential concern. This on view of energy losses ($E_{loss} = I^2_{load} * R * time$) involved with deterioration of the earthing system due to a increasing grid resistance (Rg) and possible hazardous situations for people and animals coming in the vicinity of the earth grid.

3. Electricity costs

Generation is assumed to be the same in all three cases since it serves the same demand. For a diesel power station the following costs need to be included :

a) Capital cost for diesel generator;
b) Fuel costs;
c) Transmission line, capital, operation and maintenance costs;
d) Power station operation and maintenance

If hydro-power is used the fuel costs are excluded and for item a, the capital costs for the hydro-power generator need to be used.

To finance rural electrification projects three types of finance can be distinguished: (1) foreign finance which can be in various forms from a 100 percent grant to a soft loan e.g. interest free loan, (2) finance from internal sources, either from the Treasury or raised internally within TANESCO and (3) "self help" financing through consumer contributions in the form of cash or necessary materials for the works.
These forms of finance are relevant for the construction of power houses, energy transformation, transmission and distribution works. In the construction of the service lines to the consumers, these are required to contribute a "fair" portion of the costs of the works [7].
In relation to the Single Wire Earth Return distribution system, the first financing form has, in my opinion, a minor chance to be supported. This technology is hardly used, experiences in developing countries are scarce so the risks are higher in such a project compared to the two other options. The financing organisations, country or countries will chose a distribution system that is commonly used with the least prospect of uncertainty. In the countries of the foreign financing organisations, Japan International Cooperation Agency (JICA), Danish International Development Agency (DANIDA) and the

Federal Republic of Germany (FRG) [7] no experiences with the utilisation of the Single Wire Earth Return distribution system exist. The sources for a rural electrification project are thus reduced to the other two forms, internal sources of TANESCO or the Government and "self help" financing.

8.3 POTENTIAL SOCIO-ECONOMIC BENEFITS

The socio-economic benefits can be divided by consumer group and type of electricity use. The benefits of the consumer could be attributed to lower economic cost of the new energy source compared to the traditional or prior used energy source, new types of economic or consumer activity and the availability of a high quality, more convenient source of energy (for a calculation method for residential benefits see Appendix B.2).
The **quantifiable benefits** can be divided in two components [29] :

1. **Substitutional benefits** - due to cost saving by using electricity in substitution for any other energy source, use of kerosine in the case of domestic and commercial consumers and diesel motive power for the industrial sector.

2. **Additional consumption of energy over and above the cost saving from the replacement of alternative energy described above** - in the domestic sector it could lead e.g to increased economic activity in the form of cottage industries, new electric pumps could increase farm yields.

A table with an summary of the quantifiable benefits by sector is presented next :

Table 8.1 Quantifiable benefits of electricity use by sector [30]

Sector	Quantifiable benefits	Substitute
Residential	- lighting - preparing meals - space heating, cooling, and refrigeration - home appliances - drinking water (pumping)	- liquid fuel, coal, biomass or gas - batteries, biomass or coal - liquid fuel for pumping
Light commercial	- lighting - space heating, cooling, and refrigeration - processing food	- liquid fuel, biomass or gas
Light industrial	- motive power	- liquid fuel
Agriculture sector	- water pumping for irrigation or private purpose - parboiling, heating and drying - milling, chaff cutting, threshing etc	- liquid fuel, coal, gas or muscle power - liquid fuel, coal or gas - liquid fuel, coal, biomass, gas or hydro and muscle power
Public sector	- lighting - water pumping	- liquid fuel, coal, biomass or gas - liquid fuel

9. CONCLUSIONS AND RECOMMENDATIONS

First I will summarize the main characteristics of the SWER system and the effects of the soil current.

Characteristics

- single-wire single-phase spur line between main distribution system and load centre.
- single-wire distribution line galvanically isolated by an isolating transformer at main distribution system.
- load current flows through the soil, from the earth electrodes in the ground, to the surrounding soil.
- soil between the isolating transformer (main distribution system) and distribution transformer(s), serves as return path of the load current.

Properties of the soil current

- local zone of influence (distribution and isolation transformer)
  - heating of surrounding soil;
  - Ground Potential Rise (GPR).
- return path between entrance and exit electrodes
  - the passage of the currents tends to take place by following the feeder lines at an average depth of several hundred of meters.
  - the resistance and the reactance along the line of this return path are dependent on the nature of the soil and the frequency of the current and are generally in the vicinity of a rather small fraction of an ohm per kilometre.
  - the tendency of the return current in the soil to follow the lines can be more or less falsified if they find other paths which are good conductors, such as metal conduits, cable sheathing, telephone lines, etc.
  - certain inconveniences may result from this, especially when the electrical continuity of these paths or their links with neighbouring ground electrodes is badly arranged [10].

The conditions to satisfy a safe operation of this system at National level can be divided in three aspects, (1) geophysical conditions, (2) the existence of conducting structures in the ground and (3) network conditions of the system. I will summarize these criteria beneath.

1. geophysical conditions

- permissable **soil resistivity** whole year through (maximum value of **500 Ω.m**);
- **rainfall probability** (**≥ 750 mm/year**);
- preferable **soil moisture regimes** (see figure 4.12).

2. lack of existing conducting structures in the soil

- telephone lines;
- pipe-lines;
- other electrical structures in the soil.

3. network conditions :

- course of the main distribution network
- line length (maximum of ≈ **50 km**, depending on physical conditions of the soil);
- power consumption (a maximum of **250 kW per distribution transformer** and total of around **500 kW** at a distance of **50 km**);
- three-phase loads (possible but requires additional equipment);
- voltage level (voltage level main distribution system equal to **33 kV** is assumed in this study);
- criteria for **load current** of the SWER system, $I_{load} \leq U_e/R_g$
  where U_e = **50 V** (Ground Potential Rise), R_g = grounding system resistance, **1 Ω** is assumed.

At local level, the soil resistivity can be decreased by injection of electrolytes such as common salt or sodium carbonate or the use of charcoal. Another possibility is the use of bentonite, a natural clay containing the mineral montmorillonite, which was formed by volcanic action years ago. Three-phase loads are not possible without conversion equipment, which results in the fact that no heavy electric appliances can be utilised.

According to the technical criteria at National level, an area of approximately 20 % is in principle suitable for the application of the SWER system.

In socio-economic point of view the following conclusions can be drawn. The socio-economic aspects of concern for this system are for the purpose of this study divided in 5 items, (1) economical characteristics, (2) accessibility, (3) infrastructure, (4) demographic aspects and (5) integrated regional development planning.

1. Economical characteristics :

- prices of energy sources and appliances
- location and classification of agricultural processing industries;
- location and classification of the light industrial establishments;
- location and classification of the light commercial establishments;
- classifying public lighting and water supply facilities;

The economic consumer groups which indicate the suitability of the SWER (Single Wire Earth Return) distribution system can be summarized as :

- **isolated agricultural/industrial establishments;**
- **light commercial/small scale industrial establishments;**
- **street lighting and public water supply.**

In relation to the development perspective of the SWER system, the economic structure is very important The existence of a substantial industrial sector is not appropriate for this system, except when the location of enterprises in this sector are more or less separated from other consumers and demand will stay within the limit during a longer period of time. The residential consumer group is treated as a separate group. This consumer group is not likely to restrict the suitability of the SWER distribution system, while only small loads are assumed per consumer.

2. Accessibility

- distance from main distribution grid (or generating station in isolated system);
- distance from major cities;
- distance between the major load centre and loads outside the village;
- state of the roads.

These data are essential for the design of the network. They could also be an indicator of the likelihood of electrification. Assume that in the nearest, electrified, population centre there is only a limited variety of appliances available in combination with poor public transport. If the distance to an isolated load outside the main load centre, e.g. agricultural processing enterprise or village, is far, electrification is not likely. Assuming that the roads are in a poor state, it follows that the construction of the distribution line will take more efforts. The perspective for this system is thus, among other things, determined by distances between load centres and in general the mobility of the population.

3. Infrastructure

- location and classification of the infrastructural facilities, water supply, schools, health care, banks, etc...

The classification is incorporated in the light commercial sector together with the public sector as defined for this study. It is dealt with as a separate aspect while it serves the goal to improve the standard of living of the rural population as a whole. It could improve the quality of the services by better lighting, water pumping and assuming power consumption is small a considerable part of these facilities could benefit.

4. Demographic aspects
- number people;
- division of population;
- growth rate.

The total number of the inhabitants is necessary to construct a sample and to make a preliminary estimate of the demand. The division of the population over the pilot area has two different functions, (1) grid design, (2) in combination with the location of the industrial, commercial and agricultural establishments to evaluate the suitability of the system (see item economic characteristics). A growth rate of the population is important in relation to the establishment of a growth factor of electricity demand.

5. Integrated Regional Development Plans
As mentioned before (see chapter 5), the existence of regional integrated development plans could be a tool to promote rural electrification. In practice it could mean that complementary measures are included in such plans. For example, credit access to farmers and light industrial entrepreneurs for the initial investment costs in electrical equipment. Local participation in the construction of the distribution system. Improving the accessibility during construction of the line (roads, telephone).

The proposed investigation method can be divided in two levels, (1) National level and (2) at Local level.

1. National level
Conform to the criteria mentioned with respect to, rainfall, soil moisture regime and the maximum distance from the National electricity grid an area, which is in principle suitable can be marked.

2. Local level
At local level, measurement of the soil resistivity with the application of the **Wenner** configuration are recommended. Collection of additional information like, type of soil, water table and data of existing conducting structures in the ground should be established.
At the same time, the socio-economic profile, division of the economic sectors in the area, is of importance.

If an area satisfies all the criteria mentioned, then it depends on the extra costs for an isolation transformer, a conductor with a relatively larger diameter and a extended earthing system of SWER related to the costs of a Single-Phase Two Wire distribuion system comprising two wires with a smaller diameter, a less extended earthing system and without an isolation transformer.

RECOMMENDATIONS

Before a preliminary design is considered an area need to satisfy the above mentioned technical criteria and socio-economic conditions.
In a preliminary design, of the distribution network, I propose the following procedure.
- Comparison on the differences with the two already utilised distribution systems for rural electrification in Tanzania.
- In a decision making process it is essential that the limitations of a SWER system are involved.

Some technical modifications to enhance the performance of the Single Wire Earth Return distribution system are summarized below :
- Increase the Voltage level from 33 kV to 66 kV, which could lead to loss reduction and so increasing delivery capacity;
- Improving voltage regulation leading to a reduction in the voltage drop and so permit longer distances.

I want to make a final remark, comparison of the SWER system with a Three-Phase system, is in my opinion not appropriate. They do not supply the same type of good (electricity), single-phase versus three-phase power.

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Appendix A.1

Calculated soil moisture regimes for Tanzania

Table 3.1 Determination of soil moisture regime according to Franklin Newhall system of calculation

Name of station	1 Moisture regime	2 con.d. M/D t>8	3 Temperature regime	4 Tentative subdivision of moisture regime	5 Cons. days in one year that SMC is partly moist summer	6 winter	7 Cum. days in one year that SMC is partly moist summer	8 winter	9 Cons. days in one year that SMC is compl. moist summer	10 winter	11 Cum. days in one year that SMC is compl. moist summer	12 winter	13 Cumulative days MSC in one year is Dry	14 Partly moist	15 Moist
Amani	UDIC	360	ISO HYPERTH.	TYPIC UDIC					180	180	180	180	0	0	360
Arusha	USTIC	348	ISO THERMIC	UDIC TROPUST.	180	123	180	168					12	89	259
Bagamoyo	USTIC	175	ISO HYPERTH.	ARIDIC TROPUST.	105	70	135	101					124	132	104
Biharamulo	USTIC	360	ISO HYPERTH.	UDIC TROPUST.					180	45	180	80	0	100	260
Bukoba	UDIC	360	ISO HYPERTH.	TYPIC UDIC					180	180	180	180	0	0	360
Chala	USTIC	187	ISO HYPERTH.	TYPIC TROPUST.	172	26	172	41					147	54	159
Chunya	USTIC	250	ISO HYPERTH.	TYPIC TROPUST.	180	55	180	70					110	53	197
Chwaka	USTIC	191	ISO HYPERTH.	TYPIC TROPUST.	105	86	145	143					73	113	175
Dar es Salaam	USTIC	197	ISO HYPERTH.	TYPIC TROPUST.	105	92	127	120					113	132	115
Dodoma	USTIC	185	ISO HYPERTH.	TYPIC TROPUST.	170	15	170	15					175	55	130
Ifakara	USTIC	277	ISO HYPERTH.	UDIC TROPUST.	180	82	180	104					76	80	204
Iringa	USTIC	272	ISO HYPERTH.	UDIC TROPUST.	180	77	180	92					88	87	185
Itaga	USTIC	267	ISO HYPERTH.	TYPIC TROPUST.	180	45	180	87					93	69	198
Kigoma	USTIC	267	ISO HYPERTH.	TYPIC TROPUST.	180	45	180	101					79	81	200
Kilindoni	USTIC	324	ISO HYPERTH.	UDIC TROPUST.	180	99	180	144					36	65	259
Kilwa	USTIC	148	ISO HYPERTH.	ARIDIC TROPUST.	135	15	175	38					147	148	65
Kisauni-airf	UDIC	360	ISO HYPERTH.	DRY TROPUDIC					105	75	166	131	0	63	297
Kondoa	USTIC	247	ISO HYPERTH.	TYPIC TROPUST.	180	52	180	67					113	97	150
Kongwa	USTIC	184	ISO HYPERTH.	TYPIC TROPUST.	169	15	169	15					176	55	129
Lindi	USTIC	201	ISO HYPERTH.	TYPIC TROPUST.	180	15	180	29					151	64	145
Lushoto	UDIC	360	ISO THERMIC	TYPIC UDIC					180	180	180	180	0	0	360
Lyamungo	UDIC	360	ISO HYPERTH.	TYPIC UDIC					180	180	180	180	0	0	360
Mafia	USTIC	320	ISO HYPERTH.	UDIC TROPUST.	180	95	180	140					40	63	257
Malangali	USTIC	258	ISO HYPERTH.	TYPIC TROPUST.	180	63	180	78					102	57	201
Masasi	USTIC	233	ISO HYPERTH.	TYPIC TROPUST.	180	38	180	53					127	73	160
Mbeya	USTIC	325	ISO THERMIC	UDIC TROPUST.	180	100	180	145					35	84	241
Mbulu	USTIC	355	ISO THERMIC	UDIC TROPUST.	180	120	180	175					5	100	255
Morogoro	USTIC	223	ISO HYPERTH.	TYPIC TROPUST.	135	88	155	110					95	116	149
Moshi	USTIC	219	ISO HYPERTH.	TYPIC TROPUST.	105	114	105	125					130	94	136
Mpwapwa	USTIC	229	ISO HYPERTH.	TYPIC TROPUST.	180	34	180	49					131	73	156
Mtwara	USTIC	231	ISO HYPERTH.	TYPIC TROPUST.	180	36	180	68					112	58	190
Musoma	USTIC	169	ISO HYPERTH.	ARIDIC TROPUST.	105	64	152	105					103	151	106
Mwanza	USTIC	311	ISO HYPERTH.	UDIC TROPUST.	180	86	180	159					21	115	224
Nachingwea	USTIC	244	ISO HYPERTH.	TYPIC TROPUST.	180	49	180	76					104	88	168
Ngomeni	USTIC	329	ISO HYPERTH.	UDIC TROPUST.	105	180	149	180					31	64	265
Njombe	USTIC	317	ISO THERMIC	UDIC TROPUST.	180	122	180	137					43	65	252
Old-Shinyanga	USTIC	234	ISO HYPERTH.	TYPIC TROPUST.	180	39	180	73					107	82	171
Same-Tanzania	ARIDIC	69	ISO HYPERTH.	WEAK ARADIC	69	15	101	25					234	126	0
Sao-hill	USTIC	337	ISO THERMIC	UDIC TROPUST.	180	112	180	157					23	91	246
Songea	USTIC	275	ISO HYPERTH.	UDIC TROPUST.	180	80	180	95					85	55	220
Tabora	USTIC	174	ISO HYPERTH.	UDIC TROPUST.	180	49	180	94					86	69	205
Tanga	USTIC	316	ISO HYPERTH.	UDIC TROPUST.	105	18	136	108					44	58	258
Tunduru	USTIC	136	ISO HYPERTH.	TYPIC TROPUST.	180	41	180	56					124	47	189
Ukiringuri	USTIC	256	ISO HYPERTH.	TYPIC TROPUST	180	45	180	76					104	82	174
Victoria-Gar	USTIC	317	ISO HYPERTH.	UDIC TROPUST.	105	180	144	180					36	83	241

Explination of the table

Column 1 : The moisture regime calculated on basis of the numerical data following the definitions of Soil Taxonomy.

Column 2 : Maximum number of consecutive days in a year that the moisture control section is moist in some or all parts at the time that the soil temperature at 50cm depth is higher than 8°C. To compute this number the program considers a period of two years so that the sequence is not broken by the change of the calender year.

Column 3 : Name of the soil temperature regime at the station, taking into account the results of the computation and applying the definitions of Soil Taxonomy.

Column 4 : Tentative subdivision of the moisture regime, following the key to tentative subdivision in the publication.

Column 5 : Maximum number of consecutive days that the moisture control section is moist in some or all parts during the six months following the summer solstice.

Column 6 : Maximum number of consecutive days that the moisture control section is moist in some or all parts during the six months following the winter solstice.

Column 7 : Number of cumulative days that the moisture control section is moist in some or all parts during the six months which follow the summer solstice.

Column 8 : Number of cumulative days that the moisture control section is moist in some or all parts during the six months which follow the winter solstice.

Column 9 : Maximum number of consecutive days that the moisture control section is completely moist during the six months following the summer solstice.

Column 10 : Maximum number of consecutive days that the moisture control section is completely moist during the six months following the winter solstice.

Column 11 : Number of cumulative days that the moisture control section is completely moist during the six months which follow the summer solstice.

Column 12 : Number of cumulative days that the moisture control section is completely moist during the six months which follow the winter solstice.

Column 13 : Number of cumulative days that the moisture control section is completely dry in one year

Column 14 : Number of cumulative days that the moisture control section is partly moist or partly dry during one year

Column 15 : Number of cumulative days that the moisture control section is completely moist during one year

Appendix A.2

Bessel function

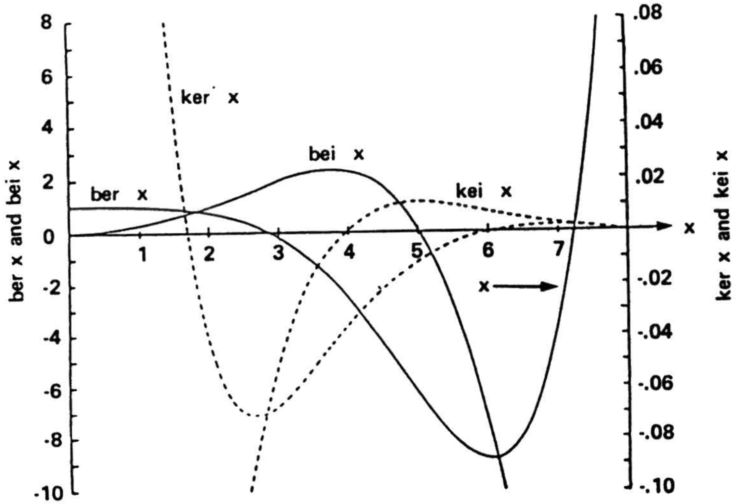

FIG. 3.5 Variation of the cartesian coordinates of the modified Bessel functions in the range ($0 \leq x \leq 8$).

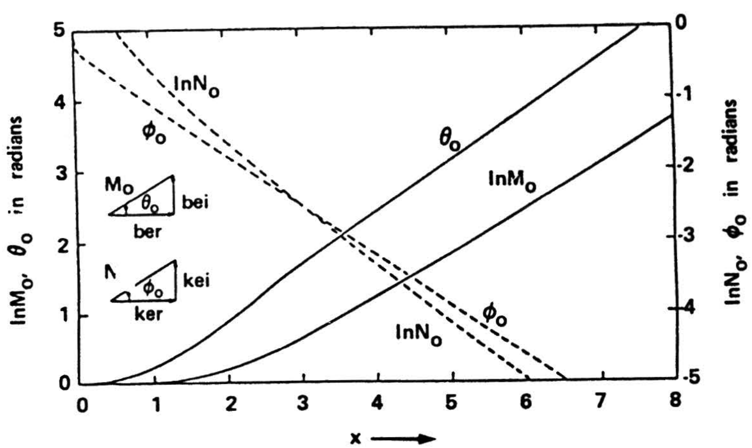

FIG. 3.6 Variation of the polar coordinates of the modified Bessel functions in the range ($0 \leq x \leq 8$).

Z	$M_o(z)$	$\theta_o(z)$	$M_1(z)$	$\theta_1(z)$	Z	$M_o(z)$	$\theta_o(z)$	$M_1(z)$	$\theta_1(z)$
.000	1.0000	.000	.0000	135.00	1.30	1.0438	23.75	6548	147.07
.025	1.0000	.009	.0125	135.00	1.35	1.0508	25.54	6808	148.02
.050	1.0000	.036	.0250	135.02	1.40	1.0586	27.37	7070	148.99
.075	1.0000	.081	.0375	135.04	1.45	1.0672	29.26	7333	150.00
.100	1.0000	.143	.0500	135.07	1.50	1.0767	31.19	7598	151.04
.125	1.0000	.224	.0625	135.11	1.55	1.0871	33.16	7866	152.12
.150	1.0000	.322	.0750	135.16	1.60	1.0984	35.17	8136	153.23
.175	1.0000	.439	.0875	135.22	1.65	1.1108	37.22	8408	154.38
.200	1.0000	.573	.1000	135.29	1.70	1.1242	39.30	8684	155.55
.225	1.0000	.725	.1125	135.36	1.75	1.1387	41.41	8962	156.76
.250	1.0001	.895	.1250	135.45	1.80	1.1544	43.54	9244	158.00
.275	1.0001	1.083	.1375	135.54	1.85	1.1712	45.70	9530	159.27
.300	1.0001	1.289	.1500	135.64	1.90	1.1892	47.88	9819	160.57
.325	1.0002	1.513	.1625	135.76	1.95	1.2085	50.08	1.0113	161.90
.350	1.0002	1.754	.1750	135.88	2.00	1.2290	52.29	1.0412	163.27
.375	1.0003	2.014	.1875	136.01	2.05	1.2509	54.51	1.0715	164.66
.400	1.0004	2.291	.2000	136.15	2.10	1.2741	56.74	1.1024	166.08
.425	1.0005	2.587	.2125	136.29	2.15	1.2986	58.98	1.1339	167.53
.450	1.0006	2.900	.2250	136.45	2.20	1.3246	61.22	1.1659	169.00
.475	1.0008	3.231	.2375	136.62	2.25	1.3520	63.46	1.1987	170.50
.500	1.0010	3.579	.2500	136.79	2.30	1.3808	65.71	1.2321	172.03
.525	1.0012	3.946	.2626	136.97	2.35	1.4111	67.95	1.2663	173.58
.550	1.0014	4.330	.2751	137.17	2.40	1.4429	70.19	1.3012	175.16
.575	1.0017	4.732	.2876	137.37	2.50	1.5111	74.65	1.3736	178.39
.600	1.0020	5.152	.3001	137.58	2.60	1.5855	79.09	1.4498	181.70
.625	1.0024	5.589	.3126	137.80	2.70	1.6665	83.50	1.5300	185.10
.650	1.0028	6.044	.3252	138.03	2.80	1.7541	87.87	1.6148	188.57
.675	1.0032	6.517	.3377	138.26	2.90	1.8486	92.21	1.7046	192.11
.700	1.0037	7.007	.3502	138.51	3.00	1.9502	96.52	1.7999	195.71
.725	1.0043	7.515	.3628	138.76	3.10	2.0592	100.79	1.9011	199.37
.750	1.0049	8.040	.3753	139.03	3.20	2.1760	105.03	2.0088	203.08
.775	1.0056	8.582	.3879	139.30	3.30	2.3009	109.25	2.1236	206.83
.800	1.0064	9.141	.4004	139.58	3.40	2.4342	113.43	2.2458	210.62
.825	1.0072	9.718	.4130	139.87	3.50	2.5764	117.60	2.3763	214.44
.850	1.0081	10.312	.4256	140.17	3.60	2.7280	121.75	2.5154	218.30
.875	1.0091	10.923	.4382	140.48	3.70	2.8894	125.87	2.6640	222.17
.900	1.0102	11.550	.4508	140.80	3.80	3.0613	129.99	2.8226	226.07
.925	1.0114	12.194	.4634	141.12	3.90	3.2443	134.10	2.9920	229.98
.950	1.0127	12.855	.4760	141.46	4.00	3.4391	138.19	3.1729	233.90
.975	1.0140	13.533	.4886	141.80	4.50	4.6179	158.59	4.2782	253.67
1.000	1.0155	14.226	.5013	142.16	5.00	6.2312	178.93	5.8091	273.55
1.025	1.0171	14.936	.5140	142.52	5.50	8.4473	199.28	7.9253	293.48
1.050	1.0188	15.662	.5267	142.89	6.00	11.5008	219.63	10.8502	313.45
1.075	1.0207	16.403	.5394	143.27	6.50	15.7170	239.96	14.8961	333.46
1.100	1.0227	17.160	.5521	143.65	7.00	21.5478	260.29	20.5002	353.51
1.125	1.0248	17.933	.5648	144.05	7.50	29.6223	280.61	28.2736	373.59
1.150	1.0270	18.720	.5776	144.46	8.00	40.8175	300.92	39.0696	393.69
1.175	1.0294	19.523	.5904	144.87	8.50	56.3585	321.22	54.0807	413.82
1.200	1.0320	20.340	.6032	145.29	9.00	77.9564	341.52	74.9742	433.96
1.225	1.0347	21.172	.6161	145.73	9.50	108.0038	361.81	104.0822	454.11
1.250	1.0376	22.017	.6290	146.17	10.00	149.8476	382.10	144.6708	474.28

Appendix A.3

Characteristics of conductor materials

Size	Both solid and stranded conductors						Solid conductor diameter, in	Stranded conductor	
	Cross section		Weight, lb/1000 ft*		Resistance, Ω/1000 ft at 20°C			Number and diameter of strands, in	Diameter, in
	cmil	in²	Cu	Al	Cu	Al			
—	1,000,000	0.7854	3026.9	921.6	0.010	0.017	—	61 × 0.128	1.150
—	750,000	0.5891	2270.2	691.2	0.014	0.022	—	61 × 0.111	0.998
—	500,000	0.3927	1513.5	460.8	0.021	0.034	—	37 × 0.116	0.813
—	350,000	0.2749	1059.4	322.5	0.030	0.048	—	37 × 0.097 19 × 0.136	0.681 0.678
—	250,000	0.1964	756.7	230.4	0.041	0.068	—	37 × 0.082 19 × 0.115	0.575 0.573
4/0	211,600	0.1662	640.5	195.0	0.049	0.080	0.4600	19 × 0.106 7 × 0.174	0.528 0.522
3/0	167,772	0.1318	507.9	153.6	0.063	0.102	0.4096	19 × 0.094 7 × 0.155	0.470 0.464
2/0	133,079	0.1045	402.8	122.0	0.078	0.128	0.3648	19 × 0.084 7 × 0.138	0.418 0.414
1/0	105,625	0.0830	319.5	97.0	0.098	0.161	0.3250	19 × 0.075 7 × 0.123	0.373 0.368
1	83,694	0.0657	253.3	76.9	0.124	0.203	0.2893	19 × 0.066 7 × 0.109	0.322 0.328
2	66,388	0.0521	200.9	61.0	0.156	0.256	0.2576	7 × 0.097	0.292
3	52,624	0.0413	159.3	48.4	0.197	0.323	0.2294	7 × 0.087	0.260
4	41,738	0.0328	126.4	38.4	0.249	0.408	0.2043	7 × 0.077	0.232
5	33,088	0.0260	100.2	30.4	0.313	0.514	0.1819	7 × 0.069	0.207
6	26,244	0.0206	79.5	24.1	0.395	0.648	0.1620	7 × 0.061	0.184
7	20,822	0.0164	63.0	19.1	0.498	0.817	0.1443	7 × 0.053	0.167
8	16,512	0.0130	50.0	15.2	0.628	1.030	0.1285	7 × 0.047	0.154

*For PE- and PVC-insulated conductors, add 550 lb per square inch of cross section for every 1000 ft.

To convert to metric system:

in² × 645 = mm²

in × 2.54 = cm

Courtesy The Anaconda Co., Wire & Cable Div.

Appendix A.4

Electricity tariffs in Tanzania

TANZANIA ELECTRIC SUPPLY COMPANY LIMITED

ELECTRICITY TARIFFS WITH EFFECT FROM JULY, 1993 BILLINGS
(38 % INCREASE = US CENTS 9 PER UNIT)

TARIFF NO. 1 RESIDENTIAL

Applicable to premises used exclusively for domestic and private residential purposes:

CONSUMPTION RANGE	CHARGING RATES	
0 - 100	0 - 100	Shs. 9.00 per KWH
101 - 7500	0 - 1000	Shs. 11.00 per KWH
	1001 - 2500	Shs.32.50 per KWH
	2501 - 7500	Shs.46.00 per KWH
Over 7500	0 - 1000	Shs.32.50 per KWH
	1001 - 7500	Shs.46.00 per KWH
	Over - 7500	Shs.90.00 per KWH

Service Charge per meter reading period:

0 - 1000 KWH	Shs. 200.00
Over - 1000 KWH	Shs. 1,000.00

TARIFF NO.2: LIGHT COMMERCIAL

Applicable to shops, restaurants, theaters, hotels clubs, harbours, schools, hospitals, airports, lodging houses, group of residential premises with one meter and on premises where similar business or trade is conducted and where consumption is less than 7,500 kilowatt hours per meter reading period:

CONSUMPTION RANGE	CHARGING RATES	
0 - 200	0 - 200	Shs. 17.50 per KWH
201 - 1000	201 - 1000	Shs. 35.00 per KWH
1001 - 2500	0 - 1000	Shs. 35.00 per KWH
	1001 - 2500	Shs. 62.50 per KWH
2501 - 7500	0 - 1000	Shs. 35.00 per KWH
	1001 - 2500	Shs. 60.00 per KWH
	2501 - 7500	Shs. 75.00 per KWH
Over 7500	0 - 1000	Shs. 35.00 per KWH
	1001 - 2500	Shs. 60.00 per KWH
	2500 - 7500	Shs. 75.00 per KWH
	Over 7500	Shs. 95.00 per KWH

Service Charge per meter reading period:

0 - 200 KWH	Shs. 500.00
Over 200 KWH	Shs. 2,000.00

TEMPORARY SUPPLIES:

Temporary supplies will be given on this tariff.

TARIFF NO.3: LIGHT INDUSTRIAL

Applicable to premises engaged in production of any article/commodity or in Industrial process where the main use of electricity is for motive power, or an electrochemical or elector-thermal process and where the consumption is less than 7,500 kilowatt hours (KWH) per meter reading period:-

CONSUMPTION RANGE	CHARGING RATES		
0 - 1000	0 - 1000	Shs.	15.00 per KWH
1001 - 2500	0 - 1000	Shs.	28.00 per KWH
	1001 - 2500	Shs.	60.00 per KWH
2501 - 7500	0 - 1000	Shs.	28.00 per KWH
	1001 - 2500	Shs.	60.00 per KWH
	2501 - 7500	Shs.	75.00 per KWH
Over 7500	0 - 1000	Shs.	28.00 per KWH
	1001 - 2500	Shs.	62.50 per KWH
	2501 - 7500	Shs.	75.00 per KWH
	over 7500	Shs.	95.00 per KWH

Customer service charge per meter reading period all consumers — Shs. 2,000.00

TARIFF NO. 4: LOW VOLTAGE SUPPLY

Applicable for general use where the consumption is more than 7,500 kilowatt hours per meter reading period:-

a) Demand charge — Shs. 2,750.00 per KVA of Billing Demand (B.D) per meter reading period.

The KVA Maximum Demand (M.D) indicator shall be reset every meter reading period.

b) Units charge:-

First 150 times B.D (KVA) units,	Shs. 46.00 per KWH
Next 150 times B.D (KVA) units,	Shs. 41.50 per KWH
Remainder of units	Shs. 37.50 per KWH

c) Customer service charge per meter reading period. — Shs.40,000.00

TARIFF NO. 4A: AGRICULTURAL CONSUMERS

Applicable to Agricultural consumers whose consumption is more than 5,000 units per meter reading period engaged in direct raw farm produce production and/or processing.

a) Demand charge: Shhs. 2,100.00 per KVA of Billing Demand (B.D) per meter reading period.

The KVA Maximum Demand (M.D) indicator shall be reset every meter reading period.

b) Units charge:-

First 150 times B.D (KVA) units,	Shs. 35.00 per KWH
Remainder of units	Shs. 30.00 per KWH

c) Customer service charge per meter reading period. Shs. 40,000.00

TARIFF NO. 5: HIGH VOLTAGE SUPPLY

Applicable for general use where power is metered at 11 kV and above.

a) Demand charge: Shs. 2,500.00 per KVA of Billing Demand (B.D) per meter reading period.

The KVA Maximum Demand (M.D) indicator shall be reset every meter reading period.

b) Units charge:

First 150 times B.D (KVA) units	Shs. 38.50 per KWH
Next 150 times B.D (KVA) units	Shs. 32.50 per KWH
Next 150 times B.D (KVA) units	Shs. 26.50 per KWH
Remainder of units	Shs. 20.00 per KWH

c) Customer services charge: per meter reading period. Shs. 40,000.00

TARIFF NO. 5A: HIGH VOLTAGE SUPPLY - ENERGY INTENSIVE CONSUMERS.

Applicable to high tension consumers whose demand is above 5,000 KVA and consumption above 800,000 KWH per meter reading period.

a) Demand charges: Shs. 2,250.00 per KVA of Billing Demand (B.D) per meter reading period.

The KVA Maximum Demand (M.D) indicator shall be reset every meter reading period.

b) Units charge:

First 150 times B.D (KVA) units	Shs. 35.00 per KWH
Next 150 times B.D (KVA) units	Shs. 30.00 per KWH
Next 150 times B.D (KVA) units	Shs. 26.50 per KWH
Remainder of units	Shs. 20.00 per KWH

c) Customer service charge per meter reading period. Shs. 80,000.00

TARIFF NO. 6: PUBLIC LIGHTING

Applicable to public lighting and places of worship:

All units Shs. 9.00 per KWH

TARIFF NO. 8: WATER SUPPLY ACCOUNTS

Applicable to all Public Water Supply pumping installations with consumption above 10,000 units per meter reading period.

a) Maximum Demand charge: Shs. 2,000.00 per KVA of Billing Demand per meter reading period.

The maximum demand indicator will be reset every meter reading period.

b) Units charge: Shs. 31.00 per KWH.

c) Customer service charge per meter reading period. Shs. 40,000.00

TARIFF NO. 9: ZANZIBAR SUPPLY

Maximum demand	Shs. 1,083.57 per KVA of Maximum Demand during each meter reading period.

The KVA maximum demand indicator shall be reset every meter reading period.

Unit charge:	Shs. 5.70 per KWH

Maximum Demand readings are taken at Mtoni substation while the units reading are taken at Ubungo substation.

NOTE:

1. Billing Demand (B.D) is the higher of the KVA Maximum Demand (M.D) during the month and 75% of the highest KVA Maximum Demand for the preceding 11 months; provided that during the first year of operation the Billing Demand shall be the higher of the KVA Maximum Demand during the month, and 75% of the highest KVA Maximum Demand recorded commencing from the month the consumer is connected.

2. Meter reading period is the period of time elapsing between any consecutive readings of the meter and/or maximum demand indicator installed by the Company but with exception of their first and last period; each such a period shall be as near to thirty days as possible.

3. These tariffs are applicable only to supply of electricity to consumers with power factor not lower than 0.95 in case of lighting loads or 0.9 in case of other loads, otherwise power factor surcharge shall be applied on the normal charges.

25th JUNE, 1993.

Appendix A.5

Computations of delivery capacity, load current and voltage drop per distribution system

SWER Delivery capacity											
Cond Size (mm2)	distance (km)										
	5	10	20	30	40	50	60	70	80	90	100
106	2874	1786	1017	711	546	444	373	322	284	253	229
85	2519	1520	848	588	450	364	306	264	232	207	187
67	2198	1292	708	488	372	301	252	217	191	170	153
54	1892	1085	586	401	305	246	206	178	156	139	125
42	1607	902	480	327	248	200	167	144	126	112	101
34	1350	743	391	266	201	162	135	116	102	91	82
27	1123	608	317	215	162	130	109	94	82	73	66
21	926	494	256	172	130	104	87	75	66	58	53
17	760	401	206	139	104	84	70	60	53	47	42
13	619	323	165	111	84	67	56	48	42	37	34
11	502	260	132	89	67	53	45	38	34	30	27

Single-Phase Two Wire Delivery capacity											
Cond Size (mm2)	distance (km)										
	5	10	20	30	40	50	60	70	80	90	100
106	16804	8402	4201	2801	2100	1680	1400	1200	1050	934	840
85	13179	6590	3295	2197	1647	1318	1098	941	824	732	659
67	10502	5251	2626	1750	1313	1050	875	750	656	583	525
54	8350	4175	2087	1392	1044	835	696	596	522	464	417
42	6622	3311	1656	1104	828	662	552	473	414	368	331
34	5251	2626	1313	875	656	525	438	375	328	292	263
27	4162	2081	1040	694	520	416	347	297	260	231	208
21	3295	1647	824	549	412	329	275	235	206	183	165
17	2615	1308	654	436	327	262	218	187	163	145	131
13	2075	1037	519	346	259	207	173	148	130	115	104
11	1645	823	411	274	206	165	137	118	103	91	82

Three-Phase Three Wire Delivery capacity											
Cond Size (mm2)	distance (km)										
	5	10	20	30	40	50	60	70	80	90	100
106	33608	16804	8402	5601	4201	3361	2801	2401	2100	1867	1680
85	26359	13179	6590	4393	3295	2636	2197	1883	1647	1464	1318
67	21005	10502	5251	3501	2626	2100	1750	1500	1313	1167	1050
54	16699	8350	4175	2783	2087	1670	1392	1193	1044	928	835
42	13244	6622	3311	2207	1656	1324	1104	946	828	736	662
34	10502	5251	2626	1750	1313	1050	875	750	656	583	525
27	8324	4162	2081	1387	1040	832	694	595	520	462	416
21	6590	3295	1647	1098	824	659	549	471	412	366	329
17	5231	2615	1308	872	654	523	436	374	327	291	262
13	4149	2075	1037	692	519	415	346	296	259	231	207
11	3291	1645	823	548	411	329	274	235	206	183	165

SWER load current											
Conduct Size (mm2)	distance (km)										
	5	10	20	30	40	50	60	70	80	90	100
106	168	104	59	41	32	26	22	19	17	15	13
85	147	89	49	34	26	21	18	15	14	12	11
67	128	75	41	28	22	18	15	13	11	10	9
54	110	63	34	23	18	14	12	10	9	8	7
42	94	53	28	19	14	12	10	8	7	7	6
34	79	43	23	15	12	9	8	7	6	5	5
27	66	35	18	13	9	8	6	5	5	4	4
21	54	29	15	10	8	6	5	4	4	3	3
17	44	23	12	8	6	5	4	4	3	3	2
13	36	19	10	6	5	4	3	3	2	2	2
11	29	15	8	5	4	3	3	2	2	2	2

Single-Phase Two Wire load current											
Conduct Size (mm2)	distance (km)										
	5	10	20	30	40	50	60	70	80	90	100
106	566	283	141	94	71	57	47	40	35	31	28
85	444	222	111	74	55	44	37	32	28	25	22
67	354	177	88	59	44	35	29	25	22	20	18
54	281	141	70	47	35	28	23	20	18	16	14
42	223	111	56	37	28	22	19	16	14	12	11
34	177	88	44	29	22	18	15	13	11	10	9
27	140	70	35	23	18	14	12	10	9	8	7
21	111	55	28	18	14	11	9	8	7	6	6
17	88	44	22	15	11	9	7	6	6	5	4
13	70	35	17	12	9	7	6	5	4	4	3
11	55	28	14	9	7	6	5	4	3	3	3

Three-Phase Three Wire load current per conductor											
Conduct Size (mm2)	distance (km)										
	5	10	20	30	40	50	60	70	80	90	100
106	653	327	163	109	82	65	54	47	41	36	33
85	512	256	128	85	64	51	43	37	32	28	26
67	408	204	102	68	51	41	34	29	26	23	20
54	325	162	81	54	41	32	27	23	20	18	16
42	257	129	64	43	32	26	21	18	16	14	13
34	204	102	51	34	26	20	17	15	13	11	10
27	162	81	40	27	20	16	13	12	10	9	8
21	128	64	32	21	16	13	11	9	8	7	6
17	102	51	25	17	13	10	8	7	6	6	5
13	81	40	20	13	10	8	7	6	5	4	4
11	64	32	16	11	8	6	5	5	4	4	3

SWER [Voltage drop (%)]											
Conduct. Size (mm2)	distance (km)										
	5	10	20	30	40	50	60	70	80	90	100
106	6.3	6.7	7.0	7.2	7.2	7.3	7.3	7.3	7.3	7.4	7.4
85	6.0	6.4	6.6	6.7	6.7	6.7	6.8	6.8	6.8	6.8	6.8
67	5.8	6.0	6.2	6.2	6.3	6.3	6.3	6.3	6.3	6.3	6.3
54	5.6	5.7	5.8	5.9	5.9	5.9	5.9	5.9	5.9	5.9	5.9
42	5.4	5.5	5.5	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6
34	5.2	5.2	5.3	5.3	5.3	5.3	5.3	5.3	5.3	5.3	5.3
27	5.0	5.0	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1
21	4.8	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9
17	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7
13	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6
11	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5

Single-Phase [Voltage drop (%)]											
Conduct. Size (mm2)	distance (km)										
	5	10	20	30	40	50	60	70	80	90	100
106	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6
85	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1
67	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7
54	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4
42	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1
34	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9
27	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8
21	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6
17	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
13	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4
11	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4

Three-Phase Three Wire [Voltage drop (%)]											
Conduct. Size (mm2)	distance (km)										
	5	10	20	30	40	50	60	70	80	90	100
106	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6
85	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1
67	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7
54	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4
42	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1
34	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9
27	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8
21	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6
17	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
13	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4
11	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4

Appendix A.6

National electricity grid

Appendix B.1

Questionnaires

==

Date : .. - .. - '94 Interviewer : Nr. :
Time : hour Township :

==

1 - General information of the household incorporating the following items :

1.1 - Age of head of the household : ....
1.2 - Place of birth : ....
1.3 - Town : ....
1.4 - District : ....
1.5 - Region : ....
1.6 - Elsewhere (specify) : ....
1.7 - Sex : O man / O woman
1.8 - Other inhabitants :

Relation to head of household	Sex	Date of birth Age(years)	Economic activity
1.______	O man, O woman	______	______
2.______	O man, O woman	______	______
3.______	O man, O woman	______	______
4.______	O man, O woman	______	______
5.______	O man, O woman	______	______
6.______	O man, O woman	______	______
7.______	O man, O woman	______	______
8.______	O man, O woman	______	______
9.______	O man, O woman	______	______
10.______	O man, O woman	______	______

Economic activities : worked - WRK, looking for work - LWK student - STU, home maker - HOM, other - OTH retired/too old - RTO, unable to work - UNW

1.9 - Education level of the head of the household
O - Primary school
O - Secondary school
O - On the job training
O - Vocational training
O - Technical colleges
O - University
O - Other (specify) : ....

2 - Economic activities :

2.1 - Profession : ....
2.2 - Sources of income (other than income of formal labour) : ....
2.3 - Family earnings per month : .... Tsh.
2.4 - Growing food on own piece of land, if yes see below

type, which crops	quantity	purpose(use)
O 1. maize	______	O-commercial/O-private/O-both
O 2. rice	______	O-commercial/O-private/O-both
O 3. wheat	______	O-commercial/O-private/O-both
O 4. beans	______	O-commercial/O-private/O-both
O 5. cassava	______	O-commercial/O-private/O-both
O 6. sorghum	______	O-commercial/O-private/O-both
O 7. sweet potatoes	______	O-commercial/O-private/O-both
O 8. ______	______	O-commercial/O-private/O-both

Interview Nr :

==

2.5 - Commercial activities of family members :

	activity	quantity	purpose(use)
O 1.	____________	________	______________________
O 2.	____________	________	______________________
O 3.	____________	________	______________________
O 4.	____________	________	______________________

3 - Energy use pattern :

3.1 - Amount of energy used per month regarding to source,and spending

type	quantity/month	unit	costs/month
O charcoal	________	____	________Tsh.
O fuelwood	________	____	________Tsh.
O kerosine	________	____	________Tsh.
O candles	________	____	________Tsh.
O batteries	________	____	________Tsh.
O electricity	________	kWh	________Tsh.

3.2 - Use of sources related to purpose of energy use,

purpose	energy source
O lighting	______________
O cooking	______________
O charcoal stove	______________
O firewood stove	______________
O kerosine stove	______________
O gas stove	______________
O heating	______________

3.3 - How are the sources obtained and how much time does it consume.

type	buying	gathering	time spent
O charcoal	O	O	afternoon morning hours
O fuelwood	O	O	... hours/day
O kerosine	O	O	... hours/day
O candles	O	O	... hours/day
O batteries	O		
O electricity	O		

4 - Housing conditions :

4.1 - Characteristics of the house (building materials for walls and roof),

O - wooden poles, mud and thatch
O - wooden poles, mud and iron sheets
O - mud bricks and iron sheets
O - burnt bricks and iron sheets
O - cement blocks and iron sheets
O - cement blocks and roof-tiles

- size of the house : .... m^2
- number of rooms : ....

4.2 - Sanitary conditions :

O - own flush toilet
O - shared flush toilet
O - pit latrine
O - other (specify) : ....

4.3 - Type of water supply (potable) :
- Connected to public water supply system : yes/no
  - O - piped water in house
  - O - piped water outside
  - O - well inside house
  - O - well outside
  - O - other (specify) : ....

- time spent for water supply : ..... hours/per day.

4.4 - Accessibility of the house, state of the nearby road system,
- O - tarmac
- O - murram
- O - all weather roads : bound surface
  - O - all weather roads : loose surface
  - O - dry weather roads
  - O - main tracks (motorable)
  - O - grass
  - O - other tracks and footpath

4.5 - Means of transportation :

type of transport	number
O pick-up	__________
O landrover/jeep	__________
O luxury car	__________
O bike	__________
O public transport	__________
O none	__________
O other (specify) :	
....	__________

4.5 - Ownership of house
- O tending : .... rent : .... Tsh./month
- O owning : ....

5 - Opinion of electricity :

5.1 - Knowledge of electricity use :
- O - hospital
- O - work
- O - other(specify) : ....

5.2 - Knowledge of electrical appliances and purpose of the appliances,

- Radio ->
  - O - radio
  - O - radio cassette
  - O - music system
- For cooking
  - O - hot-plate
  - O - oven (electrical)
- Large household appliances ->
  - O - water heater
  - O - refrigerator
  - O - deep freezer
  - O - washing machine
  - O - air-conditioner
- Small household appliances ->
  - O - immersion heater
  - O - electric iron
  - O - sewing machine
  - O - light bulb
  - O - tube light
  - O - kettle
  - O - fan

Interview Nr :

==

5.3 - What kind of benefits is one aware of :

O - safety on the streets at night (lighting)
O - quality improvement of lighting
O - longer working times at home
O - other reasons (specify) : ....
....

What is your opinion about electrification in the area :...
....
....
....

==

Date : .. - .. - '94 Interviewer : Nr. :
Time : hour Township :

==

1 - General overview of the establishment :

1.1 - The interviewed person :
- O - Owner
- O - Owners wife
- O - Manager
- O - Accountant/treasurer
- O - Employee
- O - Other (specify) : ....

1.2 - History of the enterprise :
- Date/year of start :
- Situation then;
  - number of employees : ....
  - production : .... units/month
  - growth over the years : .... %

1.3 Type of business :
- O - restaurant, bar, guesthouse
- O - milling place (agro-based processing)
- O - filling station
- O - shop (retail, wholesale)
- O - garage
- O - mechanical engineering
- O - carpeting working shop
- O - building and construction
- O - manufacturing
- O - farmer
- O - other (specify) : ....

1.4 - Ownership of business :

O - family	O - cooperative organis.
O - society(e.g. church)	O - parastatal
O - private(registered)	O - other(specify): ....
	....

If family, origin of owner :
- place of birth : ....
- town : ....
- district : ....
- region : ....
- elsewhere (specify) : ....

More enterprises in possession
- where (specify) : ....
- type : ....
- present resident : ....

2 - If the element of interest is an Institution this question will be the beginning :

2.1 - Function of the interviewed person : ....

2.2 - Type of Institution

O - dispensary	O - mosques/churches
O - post office	O - hospital
O - primary school	O - secondary school
O - bank (specify) :.................................	

Interview Nr :

==

3 - Energy use pattern :

3.1 - Energy sources presently used per month, and spending divided to source :

type	quantity/month	unit	costs(Tsh.)
O charcoal	________	____	________Tsh.
O fuelwood	________	____	________Tsh.
O kerosine	________	____	________Tsh.
O candles	________	____	________Tsh.
O batteries	________	____	________Tsh.
O electricity	________	kWh	________Tsh.

3.2 - Purpose of the energy use :

activity	energy source
O cooking	____________
O lighting	____________
O food processing	____________
O milling	____________
O chaft cutting	____________
O parboiling heating	____________
O pumping	____________
O drying	____________
O threshing	____________
O other (specify) :	
....	____________

- Efficiency factors of the different sources and convertors : by physical investigation

3.3 - When a generator is present, electricity utilisation :

3.3.1 - Reliability (continuity of supply) :

O - good
O - medium
O - bad

3.3.2 - Voltage fluctuations (quality) :

O - not at all
O - yes but no influence on appliances
O - yes and influence on appliances

3.3.3 - If grid supply comes available would you want connection :

O yes, O no

3.3.4 - Present type of electricity supply

O - three-phase only
O - single-phase only
O - both (single- and three-phase)

3.3.5 - Appliances :

O - small power tools (single-phase)
O - large power tools (three-phase)
O - pumps
O - other (specify) : ....

Interview Nr :

3.3.6 - Technical data of generator :

- Generator type	:	
- Speed	:	rpm.
- Capacity (KVA,kW)	:	kW/KVA
- Fuel consumption per month	:	ltr.
- Generated energy per month	:	kWh
- Lubricants consumption	:	ltr.
- Power factor kVA,kW,kVAR	:	

3.3.7 - acknowledged with TANESCO regulations with respect to connection to electricity : yes\no

4 - Housing conditions :

4.1 - Building materials :

O - wooden poles, mud and thatch
O - wooden poles, mud and iron sheets
O - mud bricks and iron sheets
O - burnt bricks and iron sheets
O - cement blocks and iron sheets
O - cement blocks and roof-tiles

4.2 - Size of the building

- number of rooms : ....

roomnr.	size	purpose
1.	________ m^2	________________
2.	________ m^2	________________
3.	________ m^2	________________
4.	________ m^2	________________
5.	________ m^2	________________
6.	________ m^2	________________

4.4 - Water supply

O - public system (piped water)
O - own tanks
O - from a well
O - other(specify) : ....

- Costs related to water supply : .... Tsh./month
- Quality of the water (potable?) :
  O good, O medium, O bad
- Purpose of water use :
  O - production process
  O - irrigation (farmers)
  O - service purposes
  O - private use

4.5 - Ownership of the building :

O - private owner (specify) : ....
O - government organisation (specify) : ....
O - other (specify) : ....
O - costs per month : .... Tsh./month
O - owned

Interview Nr :

5 - Production of the enterprises :

5.1 - Division of labour :

function	number	wages/month(Tsh.)
O skilled	________	________
O semi skilled	________	________
O unskilled	________	________
O administrative	________	________
O clerks (accountants, treasurers)	________	________
O staff (management)	________	________
O agricultural workers	________	________
O cultivators	________	________
O other workers	________	________

5.2 - opening hours : .... to ....
- days per week : .. days
- opening hours depends on :
  O - daylight O - regulations
  O - other (specify) : ....

5.3 - Production output per item (industrial) :

item	price/unit (Tsh.)	amount/month
O 1. ____________	____________	________ units.
O 2. ____________	____________	________ units.
O 3. ____________	____________	________ units.
O 4. ____________	____________	________ units.
O 5. ____________	____________	________ units.

5.4 - Delivered services (commercial and institutions) :

type of service	price/unit (Tsh.)	amount
O 1. ____________	____________	________ units.
O 2. ____________	____________	________ units.
O 3. ____________	____________	________ units.
O 4. ____________	____________	________ units.
O 5. ____________	____________	________ units.

5.5 - Cultivated crops (farmers) :

type, which crops	quantity	market	buyer	price/unit
O 1. maize	______	______	______	______Tsh.
O 2. rice	______	______	______	______Tsh.
O 3. wheat	______	______	______	______Tsh.
O 4. beans	______	______	______	______Tsh.
O 5. cassava	______	______	______	______Tsh.
O 6. sorghum	______	______	______	______Tsh.
O 7. sweet potatoes	______	______	______	______Tsh.
O 8. groundnuts	______	______	______	______Tsh.
O 9. paddy	______	______	______	______Tsh.
O 10. bulrush millet	______	______	______	______Tsh.
O 11. finger millet	______	______	______	______Tsh.
O 12. ______	______	______	______	______Tsh.

Markets : INT - international, REG - regional
Buyers : GOV - government, NAT - national, COP - cooperative org., COM - commercial, LOC - local, OWN - own means

Interview Nr :

===

5.5.1 Size of the planted area : .... ha.

5.5.2 How are the crops cultivated :
- O - mono culture
- O - mixed
- O - both
- O - Otherwise (specify) : ....

5.5.3 Available machinery :
- O - tractor
- O - ox
- O - manpower

5.5.4 Outstanding loans classified to purpose :
- O - farm machinery
- O - seasonal input
- O - transport
- O - storage
- O - livestock development
- O - farm development

What are the financial facilities
for the farmers to get credits: ....

5.6 - Is there a seasonal dependence in the performance of the enterprise if so ->
- Which seasons are dominant : ...... months or other unit
  O dry season, O rainy season
- Reason of dependency :
  - O - crop seasons
  - O - rainfall
  - O - temperature
  - O - other (specify) : ....
  - O - Other activities during off season periods :
    ....

6 - Accessibility :

6.1 - Type of roads in the area
- O - tarmac
- O - murram
- O - all weather roads : bound surface
  - O - all weather roads : loose surface
  - O - dry weather roads
  - O - main tracks (motorable)
  - O - grass
  - O - other tracks and footpath

6.2 - O - reliable the whole year through
- O - which periods bad condition : .... months (specify)
  reason of the bad condition : O rainy season
  O other : ....

7 Transport status :

7.1 - Dependence on transport in which degree ->
- O - Output materials
- O - Input materials
- O - Personnel transport
- O - Clients

Interview Nr :

==

7.2 - Means of transport owned by enterprise ->

	amount	purpose
O bus	__________	______________________________
O truck	__________	______________________________
O pick-up	__________	______________________________
O landrover	__________	______________________________
O luxury car	__________	______________________________
O other (specify) :		
....	__________	______________________________

7.3 - Depending on transport agencies ->

O - private (specify) : ....

O - governmental (specify) : ....

O - cooperatives (specify) : ....

8 - Knowledge or experience with electricity :

8.1 Electrification plans :

O - Plans within the enterprise to electrify in the future

how : O - own generation

O - grid connection :

O - local grid

O - national grid

8.2 - Do you know the following appliances :

Business machines

O - typewriters

O - calculators

O - duplicators

O - photocopier

Large power tools(3-phase)

O - welding equipment

O - lathe

O - saws and planes(bench)

O - compressor

Small power tools (1-phase) ->

O - battery charger

O - bench grinders

O - drills

O - Other (specify) : ....

Pumps ->

O - water pumps

O - fuel pumps

8.3 - Do you believe in the following benefits and profits of electrification

O - larger production (reliable energy source)

O - longer opening times (service sector, lighting

O - better quality of products and services

O - efficiency improvement (cost reduction)

O - safety on the streets at night (lighting)

O - other reasons (specify) : ....

....

What is your opinion about electrification in the area :...

....

....

....

Appendix B.2

Computation method of socio-economic benefits

Appendix B.2

The benefits of rural electrification can roughly be divided in substitutional and additional benefits. Consumption patterns of residential and light commercial consumers is shown in the next Figure.

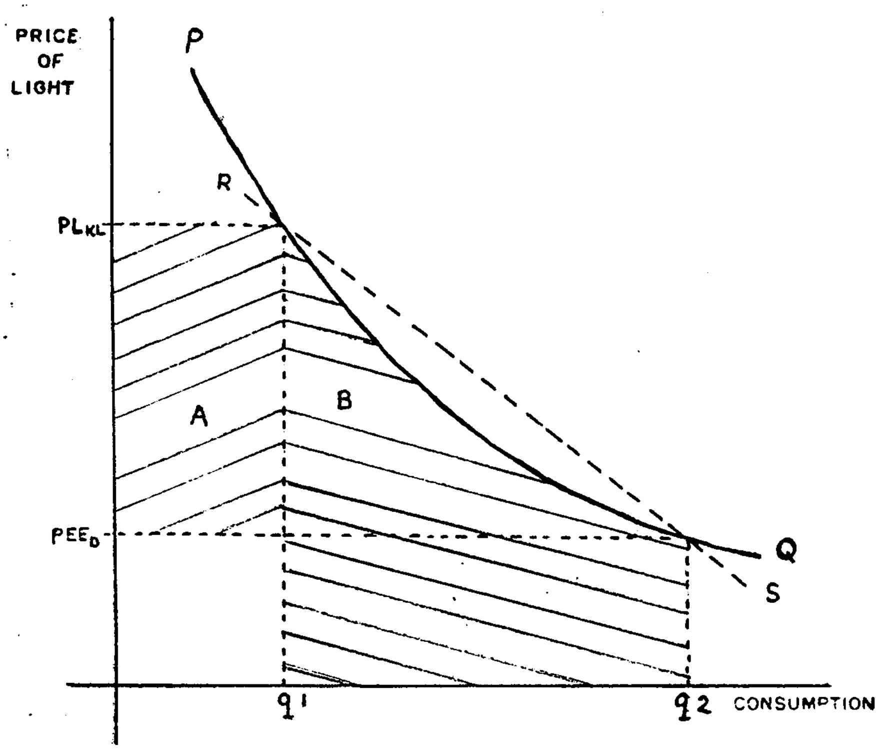

Figure B.1

PL_{KL} = price of energy for kerosine lighting;
q_1 = amount of energy consumed for lighting where kerosine is used;
PEE_D = price of energy for electric lighting;
q_2 = amount of energy used for lighting when using electricity.

After electrification it is assumed that the price of light will decrease from PL_{KL} to PEE_D. The consumption can go up from q_1 to q_2. Then :

Substitutional benefit = $(PL_{KL} - PEE_D)q_1$
= area A

Additional consumption benefit = area B

For the sake of simplicity it is assumed that the curve PQ can be approximated by a straight line RS and the benefits are calculated accordingly

THE NATIONAL GRID SYSTEM