TECHNOLOGICAL AND COST EFFECTIVE SELECTION PROCEDURE FOR RURAL ELECTRIFICATION SYSTEMS

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Abstract

In most of the countries cost of rural electrification from gird extension is very high. This is mainly due to improper planning and lack of knowledge on low cost distribution technologies. Most of the African countries have followed European standards for their medium voltage distribution networks. But these standards were developed for high density, high demand centers in European countries. This often leads to oversized distribution networks with unnecessarily high costs for rural electrification projects. Therefore benefit to cost ratio of these projects are very low. With deregulation and restructuring process, distribution companies may not invest on low benefit rural electrification projects. Hence it is essential to introduce low cost technologies in order to promote rural electrification projects.

The objective of this project is to help in reducing the high costs of electrification by introducing a technological and cost-effective selection procedure for rural electrification systems.

By analyzing various alternative methods introduced for rural electrification systems and comparing those with traditional distribution systems, an algorithm is developed to select optimum electrification method for rural areas based on their technology and cost. Based on this algorithm software is also developed to select the optimum network technology in more user-friendly manner.

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List of Abbreviations

A - Ampere
AAAC - All Aluminum Alloy Conductor
AAC - All-aluminum conductor
ACSR - Aluminium Conductor Steel Reinforced
ENPI - The European Neighborhood and Partnership Instrument
GMD - Geometric Mean Distance
GMR - Geometric Mean Radius
HV - High Voltage
IEA - International Energy Agency
kV - kilovolt
kVA - kilovolt-ampere
kW - kilowatt
kWh - kilowatt hour
LV - Low Voltage
m - meter
mm - millimeter
MV - Medium Voltage
NESC - National Electric Safety Code
NRECA - National Rural Electric Cooperative Association
OECD - Organization for Economic Co-operation and Development
REA - Rural Electrification Administration
SWER - Single Wire Earth Return
SWS - Shield Wire System
W - Watt
WEO - World Economic Outlook

1 INTRODUCTION

1.1 Background

Energy alone is not sufficient for creating the conditions for economic growth, but it is certainly a necessity. It is impossible to operate a factory, run a shop, cultivate crops or prepare foods without using some form of energy. Among various energy forms, electricity is considered as the most common form of energy for human activities. Access to electricity is highlyessential to human development as it is vital for numerous basic activities, such as lighting, cooking, refrigeration andrunning of household appliances. Also electricitycannot easily be substitute by other forms ofenergy. Individuals' access to electricity is one of the most firm andun-distorted indices of a country's energy poverty status.

Without a doubt providing electricity access is at the forefront of governments' preoccupations, especially in developing countries. As a result, a lot of rural electrification programs and electrification organizations have been developed in these countries to observe more carefully the status and the needs of rural development and electrification.

According to the study carried out by International Energy Agency (IEA) in 2009, the number of people without electricity access was 1.3 billion or almost about 20% of the world's population. Table 1.1 shows the world electricity access in 2009 collected from households, industry, national surveys and international sources.

Table 1.1 World Electricity access in 2009

	Population without electricity	**Electrification rate**	**Urban electrification rate**	**Rural electrification rate**
	million	%	%	%
Africa	587	41.8	68.8	25
North Africa	2	99	99.6	98.4
Sub-Saharan Africa	585	30.5	59.9	**14.2**
Developing Asia	675	81	94	73.2
China & East Asia	182	90.8	96.4	86.4
South Asia	493	68.5	89.5	59.9

Latin America	31	93.2	98.8	73.6
Middle East	21	89	98.5	71.8
Developing countries	1,314	74.7	90.6	63.2
World*	1,317	80.5	93.7	68

* World total includes OECD and Eastern Europe / Eurasia

Source: World Economic Outlook (WEO) -2011

From Table 1.1 it can be clearly observed that the electrification rates of rural areas are very low. In rural Sub-Saharan Africa it is about 14.2%. Therefore it is essential to pay more attention on rural electrification of Sub-Saharan African region.

What is Rural Electrification? It is somewhat difficult to define the term rural electrification precisely; it is interpreted and used with wide variations in different countries. Rural area can be defined as regions where agricultural activities are dominant, the ratio of labor to capital used in production is high, and incomes are low on average. Load densities in these areas would also be relatively low. This isdue to the low number of connections per km of line, low demand per connection and low customer load factor relative to urban areas. Therefore, for these areas costs per connection and cost per kWh supplied would be considerably high.Apart from that the operation and maintenance of rural networks will bemore problematic, and the quality of supply may also be lower.

Both investment and operation costs of rural electrification are always higher than in urban areas. Following are the reasons for those higher costs.

- Dispersed loads
- High line losses
- Higher service interruptions
- Expensive billing procedures
- Illegal connections
- Low load factor due to dominant domestic consumption and agricultural demand with seasonal effect

Rural electrification greatly increases the quality of life. Electric lighting brings benefits such as improved study environment and increased study time for school children, extended opening timeand greater security for small businesses. But electrification brings more than light. Second most common use of electricity is watching television which brings both information and entertainment. The people who live in rural areas highly appreciate these kinds of benefits and are willing to pay for them at any levels.Following are some furtherbenefits of Rural Electrification.

- Household benefits
    - Lighting
    - Cooking
    - Entertainment
    - Home appliances
    - Space heating, cooling and refrigeration
    - Water pumping
- Industrial benefits
    - Lighting
    - Motive power
    - Heating, cooling and refrigerating
    - Food Processing
    - Transport
- Commercial benefits
    - Lighting
    - Longer opening times
    - Air-conditioning and refrigeration
    - More attractive environments
    - More market opportunities
    - Improved audio and video opportunities
- Agricultural benefits
    - Water pumping
    - Parboiling, heating and drying

- Other benefits
    - Reduction of migration from rural to urban areas
    - Modernization
    - Socio-political effects such as political stability, minimizing disparities between urban and rural areas
    - Employment
    - Income distribution and social equity
    - Substitution for more costly energy sources
    - Improvement of quality of life and time savings
    - Minimizing of deforestation

1.2 Problem Identification

As discussed above, governments in developing countries,especially in African countries need to focus more on developing their rural electrification network. But in many countries cost of rural electrification from gird extension is very high. This is mainly due to improper planning and lack of knowledge on low cost distribution technologies.Many African countries have inherited European standards for their distribution networks. These standards were developed for high density, high demand centers in continental Europe. This has often resulted in oversized networks with unnecessarily high costs for connecting rural loads. Therefore benefit to cost ratio of these projects are very low. With deregulation and restructuring process, distribution companies may not invest on low benefit rural electrification projects. Hence it is essential to introduce low cost technologies in order to promote rural electrification projects.

1.3 Objective

From the Table 1.1 it can be clearly noted that the level of electrification in sub-Saharan Africa is low, with less than 15 percent of the rural households having access to electricity. One of the key barriers to accelerating access is the high cost of connections from the use of outdated, unsuitable, high-cost methods in electricity networks. A second key barrier is the small and dispersed nature of electricity demand, arising from low density of population and low income levels. This leads to high average costs of providing electricity service. The objective of this project is to reduce high costs in rural electrification systems by introducing a technological and cost-effective selection procedure for rural electrification systems.

It deals with analyzing technology and cost related issues in various alternative methods which are already introduced for rural electrification systems and compare those with traditional distribution systems to develop an algorithm to select optimum electrification method for rural areas based on their technology and cost. Based on this algorithm software is also developed to select the optimum network technology for a certain distribution network.

There are many low-cost methods that are worthy of consideration; this report focuses on four low-cost methods and one standard method that are likely to have a significant cost-reducing impact and are also likely to be widely applicable in sub-Saharan Africa. Following low-cost technologies are selected for the algorithm development.

1. Single Wire Earth Return (SWER) system
2. Single Phase two wire system
3. Shield Wire System (SWS)
4. Two Phase two wire system

1.4 Methodology

- Study low cost technologies involved in rural electrification.
- Compare those technologies with traditional systems and study the advantages and disadvantages of each system.
- Evaluate technical difficulties that can arise in each option and investigate the solutions for each technical aspect.
- Collect data on actual networks (where possible from different countries) and model the network for the study.
- Determine the most suitable technology that best fit for each section of the network
- Developing an algorithm and a software tool based on above findings.

2 LOW COST TECHNOLOGIES

There are many low-cost methods and techniques that are worthy of consideration, and should be considered in specific situations as the opportunities arise. In comparing the costs of different methods, it is important to avoid focusing only on initial capital costs. Instead, the cost comparison should be based on lifetime costs which consider the future capital costs (whether from depreciation or from system expansion with load growth) and operational costs.

This study focuses on four low-cost methods which are probable to have a considerable cost reducing impact and are also likely to be widely applicable in sub-Saharan Africa. They are:

1. Single Wire Earth Return (SWER) System
2. Single-phase two-wire System
3. Shield Wire System (SWS)
4. Two-phase two-wire System

2.1 Single Wire Earth Return (SWER) system

Single Wire Earth Return System (SWER) was first invented in New Zealand in 1925, and by the 1940s it was considered as the preferred solution for the economic extension of power distribution networks in the remote rural areas of both New Zealand and Australia. Currently, there are more than 200,000 km of SWER power lines spread throughout the rural areas of both countries [2].

Generally, the SWER installation costs are about one third of equivalent three-phase three-wire system and one half of the single-phase systems [2].This is basically due tothe use of single, light-weight conductorwhich ultimately allows for longer spans. As a result, SWER systems require approximately 50% fewer poles. Lighter poles, small pole top assembly and narrower right-of-wayare some other benefits which results a considerablecost reduction in SWER systems [3]. Even though,SWER required a low investment, the technology has not been widely integrated into distribution planning in sub-Saharan Africa. One major reason for this is the lack of sufficient technical knowledgein many utilities in the region.

The SWER systemcan be used to supply single-phase power to rural households from the main grid's MV network by usingthe earth as returning path. The most costly item in this systemis the isolating transformer. It is used to provide earth fault protection for the MV network. Without it, the return current through earth would flow back to the main threephase transformer resulting in high voltages supplied to equipment.In SWER system, reclosers, surge arresters and drop out fuses are used for protection as used in the traditional systems[1].

Figure 2.1 [1] shows a schematic diagram of a typical SWER distribution system. It consists of two phase conductors from the medium voltage (33 kV, 22 kV or 11 kV)networkwhich are connected to the isolation transformer that supplies single phase power at 19.1 kVor 12.7 kV. SWER step-down distribution transformers which have one or two outputs that are center tapped in a 240-0-240 V arrangement are used to supply power to the customers. The neural of the connected load is merged to the earth such that the return current flows into the earth back to the distribution transformer via electrodes implanted deep into the ground. It should also be noted that the Low Voltage (LV) earth at the distribution transformer is kept separate from the High Voltage (HV) SWER earth at the distribution transformer.

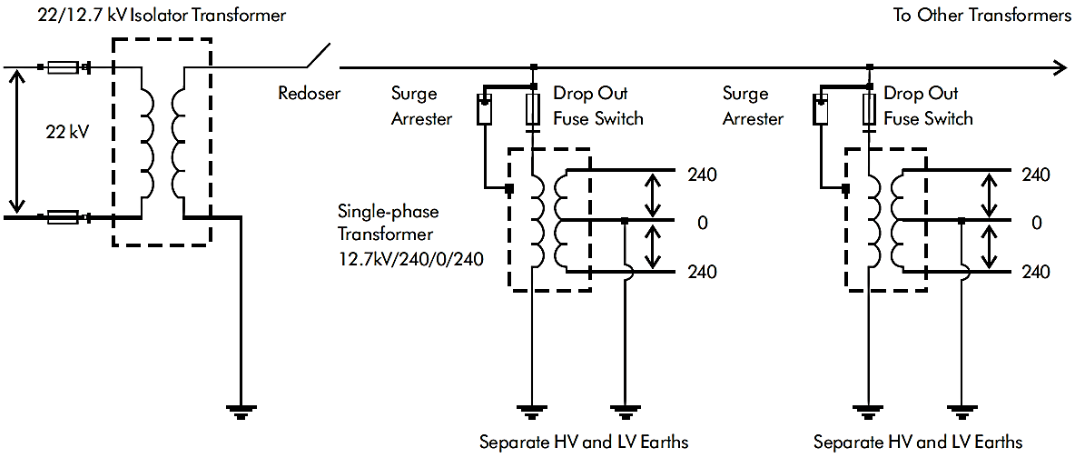


Figure 2.1Typical configuration of SWER distribution system

With the high cost of Isolation transformer and higher system losses, SWER is not economically feasible for grid extensions less than 6 km[4].The salient principle for adopting SWER for a certain area is the load to be met in that area. A maximum SWER capacity of 450 kVA limitedby 25 Amp at 19.1 kV is recommended.[2] If prospective loads within the next 10 years are likely toexceed the SWER capacity of the line, then a two-wire or a three-wire option should be investigated orflexibility to upgrade the system should be built into the design.

2.1.1 Isolating transformer

The isolating transformer is considered as the costliest and most technically complex component of the SWER system. These transformers are manufactured in sizes up to 400 kVA for 33 kV primary and 19.1 kV secondary[2].Special functions of the isolatingtransformer are discussed below [2].

- Voltage Selection - Regardless on which main MV grid it is tapped, the isolating transformer allows for the selection of voltage for the SWER network independent of that. Although 33 kV and 22 kV three phase lines can be used to supply the equivalent single phase 19.1 kV and 12.7 kV SWER respectively, an isolating transformer can be used to supply 19.1 kV from a 22 or 11 kV MV network.
- Restricts earth current - It restricts the SWER earth currents to the area between the SWER distribution transformers and the supplying isolating transformer which helps to reduce the interference with open wire communications.
- Earth fault protection - Isolating transformerprovides sensitive earth fault protection schemes on the primary MV three-phase network. This will help to prevent the sensitive protection schemes from detecting the earth return load currents of SWER as a permanent earth fault.
- Voltage Balance - Supply to the SWER system is taken by two phases of the primary MV network.So the isolating transformer permits better voltage balance on the feeders from the main transformer.

- Voltage control - Tapping ranges in isolating transformers willprovides cost-effective voltage control on the SWER system. This will allow fixed tap distribution transformers to be used on the SWER network.

The isolation transformer must carry both line charging current and the load current. Therefore the transformer impedances of the isolation transformer must be design carefully to lie within 3-4 % on rating to minimize losses[1].Figure 2.2 shows a typical SWER isolating transformer in Gerus substation, Namibia with two phase input and single phase out put.

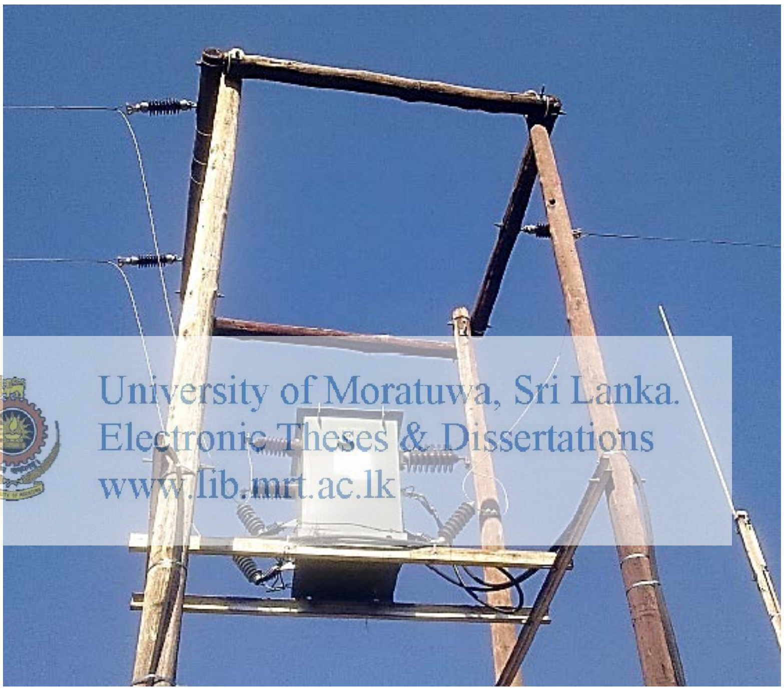


Figure 2.2Isolating transformer with two phase input and single phase output

2.1.2 Earthing System

Since earth is used as the return path,proper earthing is one of the most important requirements in SWER. Therefore earthing must be carried out with great carein order to provide safe and efficient system operation. At least two load current carrying earths are neededfor proper functioning; one on the supply side and the other on the load side [5]. This earthing system must be able to conduct both continuous load current and the occasional network fault currents. Thus, the continuity of the earthing system and its design within specification must be ensured at all times [2].

This current flow through the earth may result into dangerous potential gradients along the earth surface (step potential) and on the earthing rods (touch potential). To avoid these unsafe potentials, SWER system currentcarrying earths should be carefully designed such that the product of earth resistivity and load current is less than or equal to 25 V which is considered as the safe touch and step potential for both humans and animals [5]. Hence, soils with low earth resistivity allow for higher loads to be supplied.

The I^2R losses in form of heat through the earth may cause the earth to dry. This will increase its resistivity further which in turn will increase the I^2R losses leading to further drying and so on [5]. Therefore, loads in these systems are generally restricted to 450 kVA with current limited to 25 A at 19.1 kV. When the interference with open wire communications is expected, the limits are 200 kVA or current 8A [2].

Ground electrodes are used to connect the SWER system to the earth. The resistance of these electrodes should be as small as possible. Thisresistance is depends on the resistivity of the soil with which the electrode is in contact. The ground electrodes at the distribution transformer should have a resistance between 5 and 10Ω whereas the range for those at the isolation transformers should be 1 to 2Ω to prevent dangerous voltage gradients at ground level[2, 5].

To ensure continuous contact with low resistivity soils where the conditions of temperature and moisture content are more stable and much less influenced by variations in weather conditions and human activities, awell-designed grounding system is needed. This system should have the earth electrodes driven as deeply below the ground surface as possible, at least 3 – 5 m [6]. After installation, the earthing electrodes need to be protected against theft and vandalism.

The mechanical reliability of the earthing system is also important. Open circuits or poor earth connections significantly affect the operation of a SWER system. They can also produce dangerous touch voltages resulting in risk to safety of people and animals. Adequate protection of the earthing system is required where;

- (i) People pass by or have access to the general area
- (ii) Cultivation may disturb buried conductors
- (iii) Passing vehicles may hit the structure
- (iv) Vandalism or theft of copper earth conductors connecting the transformer to the earth system might occur.

Some advantages of SWER are its low initial capital cost, design simplicity, ease of construction, excellent level of reliability and low maintenance costs. Detailed descriptions of above advantages are given below.

Reduced capital cost –SWER system use only one conductor. As a result, there are less pole top equipment (one insulator and no cross arms). Very long spans can be achieved thus requiring fewer poles, insulators and other materials resulting in lower labor and material costs.

Design simplicity - It is a simple single-wire system supported on basic poles and with basic electrical protection. The only major concern in the design is ensuring that low-resistance earths are achieved both at the isolating transformer and the distribution transformers.

Ease of construction - With only one wire and simple basic pole supports, construction is much easier. Sagging and separation of conductors is not an issue. Many of the SWER lines in New Zealand and Australia have been erected by farmers with no previous experience in erecting power lines.

Reduced maintenance costs - SWER has fewer components than traditional systems, so clearly there are less things to go wrong. With a single wire, there are no problems with line clashing. Tree and vegetation management problems are also minimal. The only significant maintenance issue is the testing of earths. Isolation transformer earths should be checked annually and distribution transformer earths on a threeyear cycle basis [2].

Reduced bush fire hazard - Most bush fires are caused by sparking as a result of conductor clashing. With only one conductor, this does not occur.

Figure 2.3 and 2.4 shows SWER distribution transformer and a SWER line connection respectively.

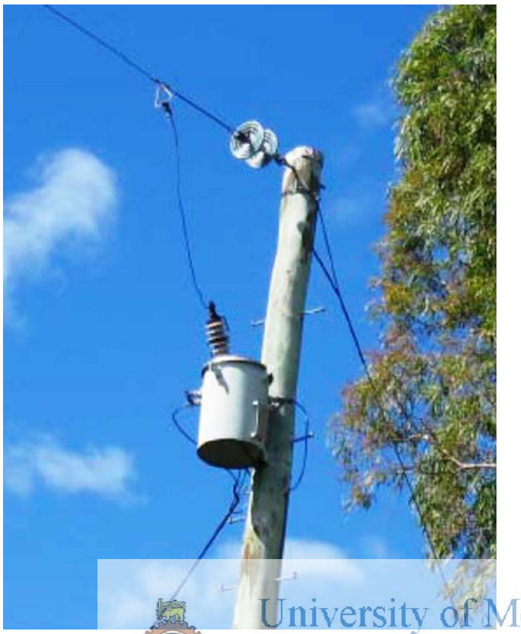


Figure 2.3SWER distribution transformer

Figure 2.4SWER line connected to pole

2.2 Single-Phase Two-Wire System

This technique was first used on 1930s by the Rural Electrification Administration (REA). This was popular due to its flexible design and low cost for connecting rural loads from American farms. Therefore it was soon adopted by the state utilities and developed into a National Standard. The North American standard builds on the four-wire Wye configured design, the fourth wire being Earth Return. The single-phase is then branched out using one of the phase lines and the neutral earthing wire.

Single-phase two-wire configuration is by now a well-established and proven technique used in many countries ranging from highly industrialized countries like the USA and Australia to developing countries like Tunisia, Ghana and Bolivia [2].

There is recognizable cost savings when reducing the number of lines from three or four to one conducting and one earthing wire. The key factors for cost savings are:

- Cost saving by reduction of conductors
- Shorter poles with longer spans - Since there is only one primary conductor, the distance to ground can be kept lower for the neutral wire, thus minimizing the needed ground clearance.
- Low cost single-phase distribution transformer

Also it should be noted that in single-phase two-wire system, the technical losses are often lower than the equivalent three-phase system[2]. This is with the exception of SWER where losses due to the earth return system are considerably higher.

Apart from those advantages, single-phase system hassome distinctive drawbacks. Singlephase faults cause highcurrents that should be returned through the neutral wire in order to prevent the risk of electrocution due to high phase-ground differences. Therefore, there is a risk of accidents if the neutral conductor is cut or is not earthed regularly. The technique should therefore be used wisely and in areas with low population density.

From a consumer's point of view, single-phase systems limit the use of three-phase motors and machines. Singlephase motors are, under normal market conditions, about 25-40% more expensive than the equivalent three-phase product[2].Apart from that, in many developing countries, single-phase motors are not available. This is due to the low demand for single-phase products because of widely utilized three-phase network. There are several ways of recreating the three-phase current for specialized machines or motors which are exceeding the normal single-phase motor range.

2.3 Shield Wire System (SWS)

This system was invented by Ghana's Volta River Authority and Professor Francesco Iliceto of Rome University. Shield Wire System highly suitable for lightly populated areas which are traversed by HV transmission lines. This system is best implemented with the construction of new transmission lines. Shield wire of a transmission line is normally grounded to provide lightning protection to the power line below it.

Transportation of power is the additional role. The shield wire with power imposed would still perform its purpose of protecting the power line against lightning strikes thus making it a dual use resource.

Presently, in Ghana, this system has been implemented on about 526 km of 161 kV lines. A total of about 30 communities and 10,000 households are being served by the scheme. SWShas been in commercial operation for almost 15 years now. The largest town served is Kintampo with a population of about 30,000 and located 58 km north of its sending substation, Techiman. The largest single loads include sawmills and the Tanoso water works, drawing up to 250 kVA [2].

The SWS has been able to bring good quality MV supply to communities up to 100 km away from the sending substation.It has been used to serve communities up to 20 km from the center line of the transmission line. The town of Buipe, which is located 104 km south of the sending substation at Tamale, is served by SWS. Currently, the maximum distance of any community from the take-off point at the transmission line is 21.5 km [10].

It is known that similar SWS have been deployed in Brazil, Ethiopia and Laos. In Brazil, the SWS has been implemented on about 370 km of 230 kV lines. In Ethiopia, the SWS has been installed on 200 km of 132 kV lines. In Laos, 190 km of 115 kV lines have been equipped with SWS to provide supply. It is, therefore, evident that the scheme can be deployed over a wide range of transmission lines voltages[2].

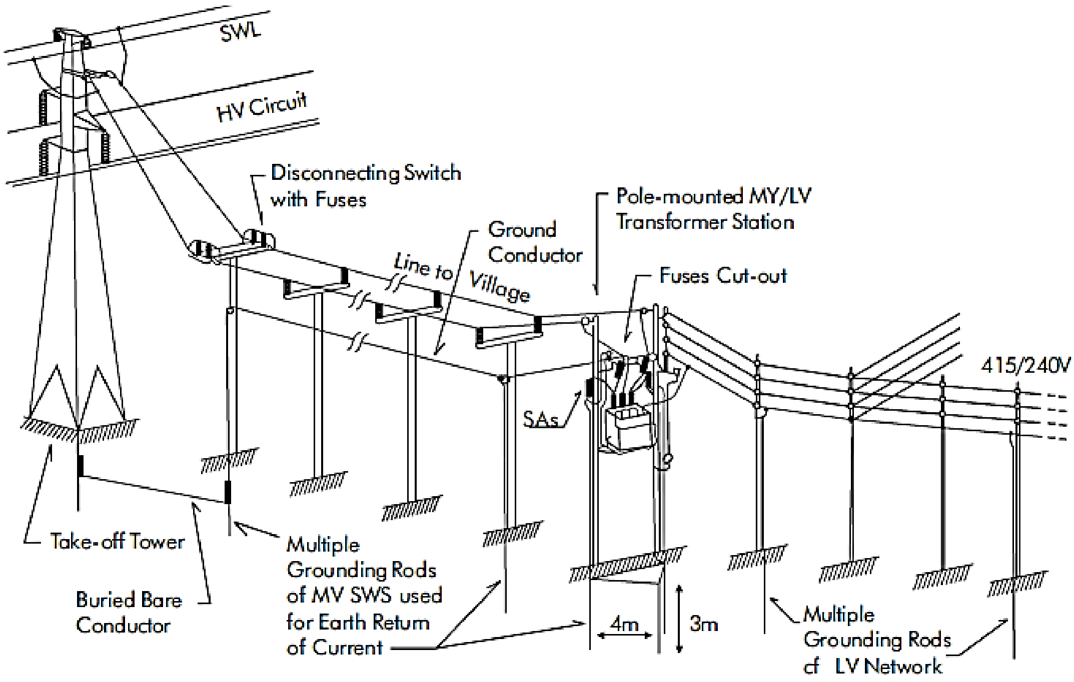


Figure 2.5 Configuration of SWS distribution system

Major deviation of SWS from the conventional system is the installation of an interposing transformer which can be produced by many transformer manufacturers. Most of the interposing transformers used for SWS in Ghana have been procured from Turkey.

Other minor equipment with special specification includes capacitors, lightning arrestors and the insulators with arcing horns. None of these present any significant challenge to manufacturers and are widely available.The implementation of SWS uses essentially the same LV distribution network within the communities. Thereis, therefore, no cost difference in the construction of the LV network.

By the dual use of the shield wire, the cost of sub-transmission towers, conductors, grounding mats and other materials can be completely avoided. The only element of incremental cost in the bill of materials above that of a conventional HV transmission line is from the replacement of insulators with those having appropriate arcing horns. On construction costs,one can expect that there is a small nominal increase in erection cost for a transmission line with insulated shield wires over the erection of a line without SWS.

2.3.1 Limitations and challenges

The design of each SWS application is, however, complicated by the earth-return of current, the voltage balancing needs and the interaction with the HV power circuit below. While the operation of SWS is simple and can be performed by regular distribution utility personnel, it is recommended that the design of each SWS application is undertaken by professionals with the required experience and expertise.

The load carrying capacity of a shield wire of 76 mm^2 ACSR is about of 9 MW. The loadcarrying capacity at a distance of 100 km is about 4 MW. It has been computed that at the distance of about 150 km from the sending substation, the capacity of the SWS is restricted to about 3 MW. These capacities have turned out to be more than adequate for its implementation in Ghana [11].

The main concern of potential consumers in the initial period was about the singlephase supply. The complaint against singlephase supply has been found to be only valid in the special cases where consumers requireusing three-phase motors. For the majority of users in the rural areas, the single-phase supply presents no limitation.

The dual use of the shield wire for power transfer at the same time as it performs the lightning protection role requires the insulators that are used for SWS to have arcing horns. The accurate setting of the arcing horn gap has been found to be critical for the satisfactory performance of the lightning protection function. During the installation phase, therefore, particular attention has to be paid by the contractor to ensure that the arcing horn gap is set accurately.

As stated earlier this system is best implemented while constructing a new transmission line. Therefore this system is not further considered for the algorithm development.

3 TECHNICAL ASPECTS

This chapter mainly focuses on technical aspects related to technologies described in previous chapter. Following key categories related to four selected categories are discussed under this chapter.

1. Line losses
2. Line end voltage drop
3. Power transfer capability

3.1 Modeling the Network

When modeling a network it is essential to calculate the line losses and the voltage drop of each and every section. Following simplified formulas are used to calculate above parameters.

Voltage drop line losses and of a short distribution line with a single load at its end can be represented by vector diagram in Figure 3.1.

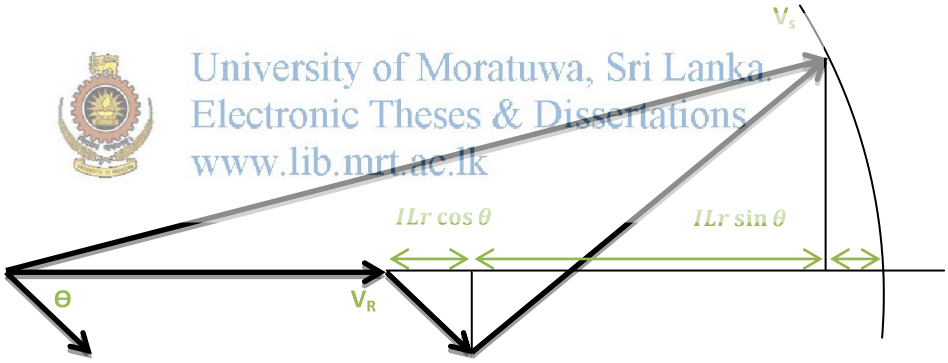


Figure 3.1 Vector Diagram of a single section power line

The line end voltage drop phase to neutral $\Delta V = IL(r\cos\theta + x\sin\theta)$

Power loss along a single conductor $\Delta P = I^2 rL$

Voltage drop and power loss for three phase and single/two phase can be represented by following equations.

$$\Delta V = K_1 IL(r\cos\theta + x\sin\theta) - - - - - - - - (1)$$

$$\Delta P = K_2 I^2 r L - - - - - - - - (2)$$

Where; K_1 =√3 for balanced three phase and 2 for single/two phase

K_2 =3 for balanced three phase and 2 for single/two phase

I = Line Current

r = Resistance in Ohm per unit length

L = Line Length

Ɵ = Power factor angle

Generally distribution line consists of a number of branches is located at various points along its length at uneven intervals. In such situations, the power flow characteristics including line end voltage drop and line losses can only be precisely determined by using suitable computer programs due to the iterative nature of the solution. For this project a simplified methodology is used to obtain an approximate solution which will yield results within acceptable accuracy limits.

To develop this methodology a distribution line modeled as a simple radial line with number of loads of equal magnitude separated from each other by equal distances as shown in Figure 3.2 is selected.

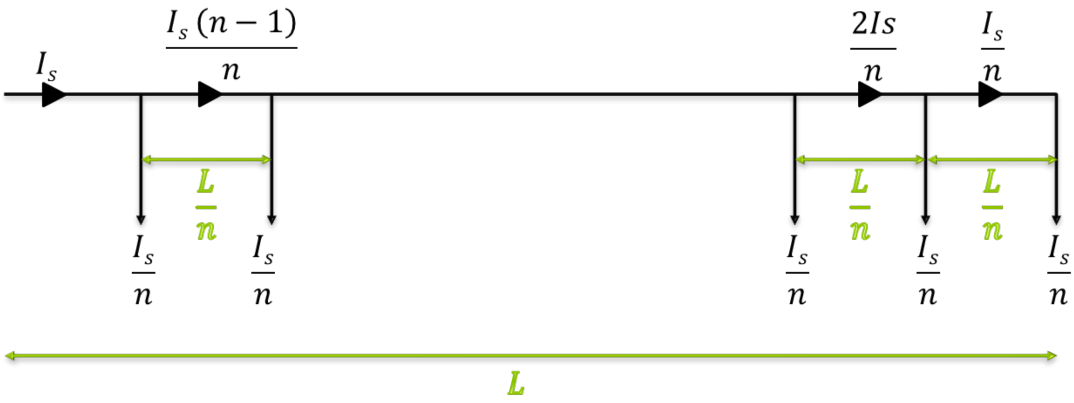


Figure 3.2Simple Distribution Network

The total length is taken as the radial length of the distribution line ignoring the branch lines. The number of sections will be determined according to the magnitude and the spreading pattern of the loads. In somesituations branch lines can be modeled separately and the total load of a branch taken as acting at the appropriate location along the main distribution line.

3.1.1 Power Loss

The power flow along each section of the model is the flow along the previous section less the load acting at the node at the beginning of the section. By neglecting the difference in the phase angle of the currents flowing along the various sections, following equation can be derived.

If number of sections	$= n$
Load at each node	$= \frac{I}{n}$

Current flowing along the sections, beginning with the start of the distribution line;

$$I\,, I\frac{(n-1)}{n}\,, I\frac{(n-2)}{n}\,, \dots.\dots.\dots, \frac{1}{n}$$

The power loss along the section $(i+1)$ will be;

$$3r\frac{L}{n}\left[I\frac{(n-i)}{n}\right]^2$$

The total line loss can be obtained by summing up losses in each section as follows;

$$\frac{3rL}{n}\left[I^2\frac{(n)^2}{n^2}+I^2\frac{(n-1)^2}{n^2}+I^2\frac{(n-2)^2}{n^2}+\ \dots\dots\dots+\frac{I^2}{n^2}\right]$$

$$3rLI^2\,\frac{[n^2n^2+(n-1)^2+(n-2)^2+.\dots\dots\dots\dots.+1^2]}{n^3}$$

$$3rLI^2\left(\frac{1^2+2^2+\ \dots..+n^2}{n^3}\right)$$

$$(Losses\ if\ the\ total\ load\ was\ at\ end\ of\ the\ line)\left(\frac{1^2+2^2+\ \dots..+n^2}{n^3}\right)--(3)$$

3.1.2 Line end voltage drop

The voltage drop in $(i+1)$ section will be;

$$\sqrt{3}IL\frac{(n-i)}{n}(r\cos\theta+x\sin\theta)$$

Line end voltage drop of the total line will be

$$\sqrt{3}\frac{L}{n}(r\cos\theta + x\sin\theta)\left[In + I\frac{(n-1)}{n} + I\frac{(n-2)}{n} + \cdots + \frac{I}{n}\right]$$

$$\sqrt{3}\frac{L}{n}(r\cos\theta + x\sin\theta)[1 + 2 + 3 + \ldots\ldots\ldots + n]$$

$$\sqrt{3}\frac{L}{n}(r\cos\theta + x\sin\theta)\frac{(1+n)}{2n}$$

$$(voltage\ drop\ if\ total\ load\ was\ at\ line\ end\,)\frac{(1+n)}{2n} - - - - - - - - - (4)$$

Using the above equations a set of multiplying factors are derived to convert the line losses and tail end voltage drop of a terminally loaded line to that of a symmetrical linear distributor of equally loaded. Table 3.1 contains all the multiplying factors for line end voltage and line losses.

Table 3.1Conversion Factors for Distribution lines

No. of Sections	**Multiplying factor**	
	Line End Voltages	**Line Losses**
Tail End Load	1	1
2	0.75	0.625
3	0.667	0.519
4	0.625	0.469
5	0.6	0.44
6	0.583	0.421
7	0.571	0.408
8	0.563	0.398
9	0.556	0.391
10	0.55	0.385
Uniformly Distributed	0.5	0.333

3.2 Voltage drop and power transfer capability

Under this section voltage drop and power transfer capability of three-phase three-wire, Two-phase two-wire, single-phase two-wire and SWER are discussed.

3.2.1 Three Phase System

Voltage Drop $\Delta V = \sqrt{3}IL(r\cos\theta + x\sin\theta)$

Power Transferred $P = \sqrt{3}VI\cos\theta$

PU Voltage drop for a given power load

$$\frac{\Delta V}{V} = \frac{\sqrt{3}PL(r\cos\theta + x\sin\theta)}{\sqrt{3}V^2\cos\theta} = \frac{PL}{V^2}(r + x\tan\theta)$$

Power that can be transferred for a given per unit voltage drop can be calculated as $P = \frac{\left(\frac{\Delta V}{V}\right)V^2}{L(r+x\tan\theta)}$

3.2.2 Two Phase System

Voltage Drop $\Delta V = 2IL(r\cos\theta + x\sin\theta)$

Power Transferred $P = VI\cos\theta$

PU Voltage drop for a given power load

$$\frac{\Delta V}{V} = \frac{2PL(r\cos\theta + x\sin\theta)}{V^2\cos\theta} = \frac{2PL}{V^2}(r + x\tan\theta)$$

Power that can be transferred for a given per unit voltage drop $P = \frac{\left(\frac{\Delta V}{V}\right)V^2}{2L(r+x\tan\theta)}$

A two phase line with the same PU voltage drop will be able to transport only half of the power of an equivalent three phase line.

3.2.3 Single phase two-wire System

Voltage Drop $\Delta V = 2IL(r\cos\theta + x\sin\theta)$; Here V is the line voltage

Power Transferred $P = VI\cos\theta$

PU Voltage drop for a given power load $\frac{\Delta V}{V} = \frac{2PL(r\cos\theta+x\sin\theta)}{V^2\cos\theta} = \frac{2PL}{V^2}(r + x\tan\theta)$

Power that can be transferred for a given per unit voltage drop $P = \frac{\left(\frac{\Delta V}{V}\right)V^2}{2L(r+x\tan\theta)}$

The power transfer is proportional to the voltage square and the power transfer capability of a single phase line with the same PU voltage drop will be 1/3rd that of a two phase line and 1/6th that of an equivalent three phase line.

3.2.4 SWER System

The voltage of the line will be considered as being phase to neutral (i.e. there is no voltage loss by the isolating transformer. Also the neutral is now at earth potential). Same relationships as for the single phase line can be used with following exception. The resistance of an SWER circuit is the resistance of the overhead conductor plus an allowance of 0.001f Ω/km (0.05Ω/km at 50 Hz) for the earth return path. Here f is the system frequency[12].

Return currents through the earth tend to flow at an average depth of 1500 m as compared with metallic return currents which are separated from the forward currents by one meter. This increased separation causes the reactance of the return circuits to be the order of 0.46Ω/km (calculations are given below) which is higher than the conventional metallic circuits.

Calculating inductive reactance of SWER line

The inductive reactance of a conductor on an overhead line may be divided into two components (1) the internal and external reactance to one meter radius due to Geometric Mean Radius (GMR), and (2) the inductive reactance spacing factor due to Geometric Mean Distance (GMD) between the conductor and its return path or neutral.

Therefore, Inductance reactance, $x_1 = A + B$

Where;

$A = 0.1446 \log_{10} \frac{1}{GMR}$ in Ω/km at 50 Hz

$B = 0.1446 \log_{10} GMD$in Ω/km at 50 Hz

GMR for SWER Lines

This factor is a function of physical and magnetic properties of the conductor and is constant for any given conductor provided that its properties remain unchanged due to current flow. GMR can be considered as the radius of a conductor assumed to have no internal flux but with the same inductance as the actual conductor with radius r.

$GMR = re^{-\frac{1}{4}} = 0.7788r ------(5)$

GMD for SWER lines

Following relationships are used to calculate the GMD for SWER line

$$GMD = Depth\ of\ return\ path = 93 \times \sqrt{\rho} ----- (6)$$

Where ρ is soil resistivity in ohm meter and for average soils it is about 250 ohm meter.

$$GMD = 93 \times \sqrt{250} = 1470\ m$$

$B = 0.1446 \log_{10} GMD$

$B = 0.1446 \log_{10} 1470 = 0.4579\Omega/\text{km}$

Therefore average value for GMD can be calculatedfrom above equation and it is about 1470 m. This increase in separation causes the reactance of earth return circuits to be of the order of 0.46 ohm/km (Higher than the conventional metallic circuits).

Using the equations developed earlier for two wire single phase line with modifications for the SWER condition gives the following relationships:

PU Voltage for a given power load $\frac{\Delta V}{V} = \frac{P}{V^2}(Lr + 0.05L_1 + Lx_1 \tan\theta) ----(7)$

Where $L_1$is the length of return path and x_1 is the inductive reactance of overhead SWER line.

4 ECONOMIC ASPECTS

With lower consumer density in rural areas, the cost of delivering power to a new customer has increased. Also these new consumers have low income and purchase less electricity. Withhigh construction costs per customer, low revenues and other associated costs while managing rural systems, electric utilities have found it even more difficult to meet demand for electricity in rural areas. Therefore selecting the most economical solution is vital, so this chapter covers the economic aspects related to the selected technologies.

Three-phase lines are techno-economically the most suitable for high loads, but for low loads, single or two-phase lines are sometimes even more suitable. The combined three-phase, two-phase system is flexible and it is easy to increase the capacity by adding a third conductor to a two-phase line. It is also somewhat easy and economical to extend the present network to some remote location by adding a twophase line to the existing main line.

SWER is sometimes a reasonable alternative, if the loads are low. The utilization of only one conductor decreases the investment costs of the system, but on the other hand, losses are high and any isolating transformers needed increase the costs. SWER also requires proper earthing and earth surface with adequately low resistivity year round.

Table 4.1 presents the relative load capacity of a conductorfor each system, using the same conductor.

Table 4.1Relative load capacity of different technologies

No	Type of Technology	Relative Difference in Load Capacity (%)
1	Three Phase Three Wire	100
2	Two Phase Two Wire	50
3	Single Phase Two Wire	26
4	SWER	29

The table indicates that three-phase system has the greatest load capacity. The twophase system has twice the load capacity of the singlephase two-wire system, which again has very similar figures to those of SWER depending on the earth resistivity and reactivity, earthing and the power factor.

The relative power losses are inversely proportional to the second power of the voltage. Therefore the losses in a two-phase system are twice as high as those in a three-phase system. The relative factor of a single-phase system is six, i.e. three times as high as in a two-phase line. The figure of a SWER line is still higher. However, the resistivity of the earth has a great influence on the last two systems, and hence in some situations the losses in a single-phase line are only about twice of those in a two-phase line.

The investment costs for three-phase lines are higher than for two or singlephase lines because they have three conductors, even though they can have a smaller cross sectional area for the same load carrying capacity. SWER has the lowest investment costs, but high losses and some disadvantages dealt with earlier.

Further comparison between twophase and singlephase lines indicates that savings in the insulation level of singlephase lines will be partly offset by the larger crosssectional areas of the phase conductors required to deliver the same load with equal voltage quality. There are no great differences in the substation structure, except sometimes in the earthing of the neutral point of the HV/MV transformer.

4.1 Performance and overall costs for the identified distribution solutions

Table 4.2 shows the cost of constructing a one km of line by selected four technologies. From the Table 4.2 it can be clearly seen that the lowest cost technology is SWER and Single-phase two-wire system, two-phase two-wire system are the next low cost solutions respectively.

Table 4.2Cost of different type of Systems

No	Type of Technology	Cost (USD)/km MV line
1	Three Phase Three Wire	13000
2	Two Phase Two Wire	9500
3	Single Phase Two Wire	8600
4	SWER	5200

Source:Paving the Way for the Mediterranean Solar Plan; ENPI 2010/248-486

4.2 Comparison of investment costs for different solutions

Depending on the distances to the consumers and loads to be supplied, different solutions could be used. Below, in Table 4.3 the investment costs for different type of villages are compared. This can be considered as a rough estimation for all the countries in the African region. Local conditions may have an impact on these costs.

Table 4.3Total investment cost for different distribution systems in USD

Type of Village	Technology			
	Three Phase Three Wire	Two Phase Two Wire	Single Phase Two Wire	SWER
100 customers 10 km line	300 000	230 000	210 000	220 000
100 customers 100 km line	1 400 000	1 100 000	1 000 000	660 000

Source: Paving the Way for the Mediterranean Solar Plan; ENPI 2010/248-486

4.3 Conclusion on performance and overall costs and recommendations

The most economic and technically feasible distribution solution depends on the number of customers to be connected, the distance between the connection points and the grid and the type of connection as discussed above.

For electrification of lightly populated rural areas located at least 30 km from the grid, SWER could be a used, as long as the total load is below 450 kVA. SWER could be a temporary or permanent solution depending on the development of the load. The main advantage with this solution is that it is easy to erect with low investment and if needed can be upgraded in steps, to two-phase and/or three-phase by adding cross-arms and more poles without squandering the initial investment. Due to problems with circulated currents, the system should be fed via an isolating transformer.

In order to take advantage of the transmission lines passing the areas to be electrified, the SWER system could be fed by an isolated shield wire. It should be noted that although SWER is a suitable option for several countries in the African region, it is most advantageousin lightly populated remote areas. In such areas, a combination of SWER together with local production based on renewable energy sources is both sustainable and economic. With these constraints Morocco, Algeria, Libya, Egypt, Jordan and Syria should be considered as primary targets for the SWER system.

4.4 Other Factors Affecting Cost

As noted in previous chapters, most salient factors responsible to the high cost of grid extension in rural areas are listed below.

1. Adopting European Standards - These standards are used to serve urban loads that do not take into consideration the unique design technologies introduced to rural areas. This increase the widespread use of three-phase lines and oversizing of transformers and conductors
2. Resource Optimization – This includes sub-optimal use of available materials and designs. E.g.: Use of shorter spans than possible, poor placement and sizing of transformers.

Following are some components that responsible for higher cost in rural electrification systems and design modifications for those components are also discussed.

4.4.1 Line Design

Rather than selecting alternative technologies to reduce the cost of rural networks, it is essential to ensure that the conductor, poles and pole top assemblies are used optimally and whether the line is designed and constructed efficiently. It is essential to check whether the spans are maximized to take the benefit of the strength of conductor while keeping adequate degree of safety. Realistic demand expected over the lifecycle of the system with acceptable losses should be determined accurately to select the most suitable conductor. Length and strength of the poles should be designed using realistic safety factors rather than going for urban area standards. Standardizing these designs will minimize the use of special engineering expertise which will ultimately save time and cost.

4.4.2 Cost of Poles

Poles are considered as the costliest single component required for grid expansion. Therefore to reduce the cost of rural electrification it is essential to focus on reducing the cost of poles. Following are some possible actions to reduce the cost of poles.

- Shorter poles
- Longer spans
- Alternative pole designs
- Local manufacturing of poles

Shorter Poles

Most of the African countries use poles that are significantlyhigher than necessary height to achieve the required ground clearance.Selecting the correct line to ground clearance will reduced the pole length and it will leads to lower cost. For example decreasing the length of a wooden pole from 12 m to 10 mreduces the cost of a pole by 24% and further reduction from 10m to 8 mdecreases the cost by another 28%.The total cost reduction will be 45%[13].Since the cost of polesis a major contributor to the cost of a line, this reduction must have a noticeable effect on the cost of grid extension.

But the extent by which pole height can be reduced is limited by the minimum acceptable clearance between the lowest conductor and the ground. National Electric Safety Code (NESC) in the USA, states that the minimum clearance between conductor (rated up to 22 kV) and the ground is 5.6 m when positioned above roads subject to truck traffic and 4.4 m above spaces reachable only by humans.

LongerSpans

Decreasing the number of poles per kilometer will further reduce the cost of poles. This can be achieved by longer spans. Allowable span is determined by several factors.

- Sufficient line-to-ground clearance for safety
- Sufficient line-to-line clearance to prevent clashing of the conductors
- Strength of poletop insulators

Longer span means larger sag. Therefore in order to maintain sufficient line-to-ground clearance, higher poles would be required. This will again increase the cost of a pole due to its increased diameter and length.

Figure No.4.1shows how the height of poles varies with the span in order to maintain the required ground clearance (5.6 m for this example) and its influence on the line cost. For this example ACSR three-phase three-wire conductors over leveled, unobstructed territory is assumed.

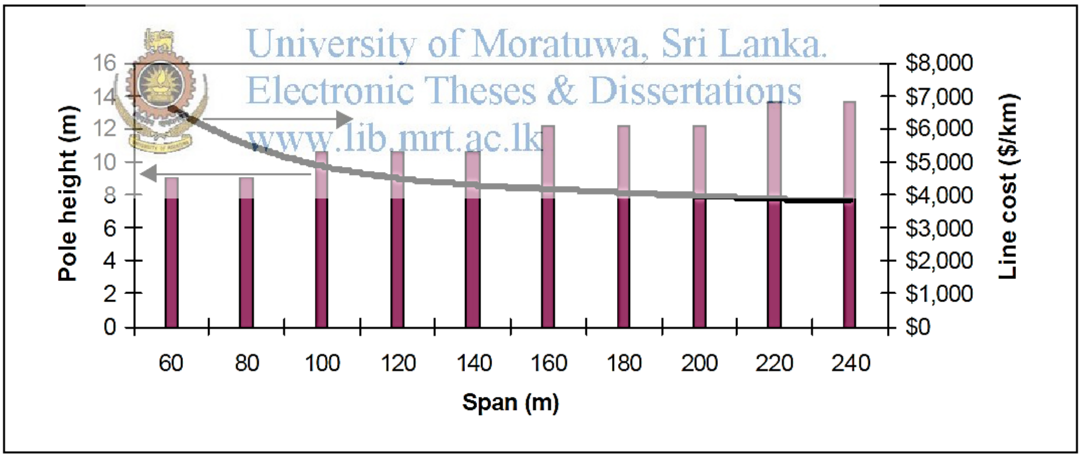


Figure 4.1 Relationship between pole span, pole length, and line cost

Bars in the above graph represent the height of pole required to maintain the necessary ground clearance for different spans. The effect of the span on the unit cost of construction is represented by the trend line descending to the right.

According to the above figure,cost of line construction decrease with increasing span, but that decrement becomes minor for larger spans. In fact, thedifficulty of finding higher poles prevents a longer span or increases the cost of the line. If the spans are shorter sag is also less. Therefore shorter poles can be used to maintain the minimum ground clearance requirements. These poles are less costly, but their increased number per kilometer will increase the total cost.

According to the above graph the lowest cost for the line can be achieved with spans closer to 200m. Butconsiderably shorter spans are frequently used due to unavailability of higher poles and construction simplicity. The use of long spans is also limited by the absence of flat terrain. However as this example illustrates, companies should consider considerably larger spans than that aregenerally used.

Alternative Pole Materials

Poles are generally made by concrete, wood and steel. There are certain advantages and disadvantages associated in each option. Therefore when selecting a material factors like cost, availability, topography of the area, transport facility and prevailing technology should be considered.

When reducing the cost of poles,the quality and strength of the pole must not be compromised. If a pole is replaced before its expected life due to poor quality, it will increase the pole cost for that line. The cost for labor will increase the cost further because replacing cost is considerably higher than its initial installation cost.

Following are someadvantages of concrete, wood and steel in pole construction.

Concrete

When the low cost wood poles are not available due to lack of suitable trees, steel-reinforced concrete poles are used as a common alternative. Materials for these poles are readily available for relatively low cost. But transportation cost of these poles is high and handling is also difficult because of their big weight and high breakage rate.

Wood

Treated wood poles are widely used in rural electrification projects due to following advantages.

- Poles can be a manufactured and treated locally
- Lightweight
- Less susceptible to breakage during transport and handling
- Easier to handle and climb
- Greater flexibility when placing of mounting bolts
- Facilitate for later modification in the field

Well-treated wood may last for decades, even in wet conditions. Initial decay is possible to occur at ground level, where moisture and air content is high. Furthermore, these poles will not adversely affected by airborne salt in coastal zones.

The most common problem in rural electrification projects is the inability of households to cover the connection cost as well as the energy cost. If these people can grow trees for poles it will provide an additional income to cover the cost of electrification. The main obstacle to the local wood pole production is the lack of existing forests with suitable trees. Trees can be planted specially for pole production, but adequate growing time is needed.

Steel

For mountainous territories without transportation facility steel poles are the only alternative. These poles can be fabricated in smaller sections that can be carried by porters on their back. The cost of these poles is somewhat high and these are susceptible to corrosion. Therefore appropriate precautions like galvanizing or painting need be perform in order to extend its life time.

4.4.3 Conductors

Conductorsare considered as the second costliest component. Copper, Aluminum, and Steelare the most commonly used materials used in the manufacturing of conductors. Figure 4.2 gives an indication about cost for conductors made of above materials.

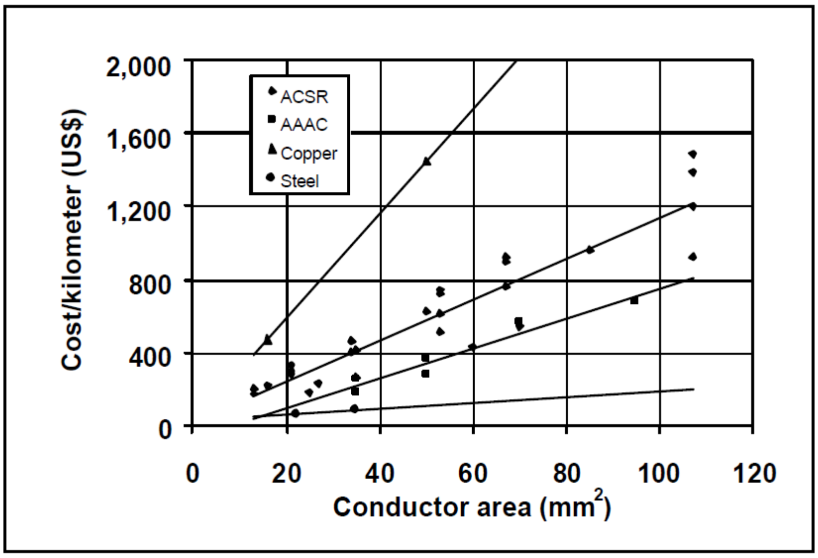


Figure 4.2 Relationship between conductor cost and cross sectional area

Size, number of conductors and materials used are the main factors that affect the life-cycle cost of the conductor. Therefore following precautions need to be taken to reduce the life-cycle cost.

Proper Sizing

Oversizing the conductor than necessary can incur higher costs. This cost will further increase by greater structural requirements for pole top assemblies and poles due to the use of heavier conductors.

To minimize the lifecycle cost of a conductor it is necessary to assess the realistic loads to be met by the line during its lifecycle. This can be done by surveying similar geographical areas that have already been electrified, with similar economic potential and these results can be used as a basis for assessing average initial loads. When projecting electricity demand for a new area factors as the presence of raw materials, the level of disposable income, access to the market for goods that might be produced locally and the potential for tourism must be considered.

After the nature of the loading has been determined, minimum cost can be assured by keeping the voltage drop at line end and energy losses along the line within acceptable limits.

Number of Conductors

Number of conductors can be reduced by single-phase line extensions with suitable capacity or by using higher distribution voltages. Cost saving by changing distribution technology is widely covered in next chapter of this thesis.

Materials Used

Copper, Aluminum, and Steel are the most widely used materials for conductor manufacturing. Copper is the costliest of the three materials but it has the lowest resistivity. Even though it is costly, it is the most economical solution in cases where the local environment could lead to corrosion.

Aluminum is an inexpensive conductor with high conductivitytoweight ratio strengthtoweight ratio. Therefore it is the most widely used conductor in distribution systems. There are several forms, includingAll Aluminum Conductor (AAC), Aluminum Conductor Steel Reinforced (ACSR) and All Aluminum Alloy Conductor (AAAC). From above three ACSR is the dominant conductor because of its cost-effectiveness.

Cost of the steel conductor is also low and it has significant tensile strength for its weight. Therefore it permits higher spans which results reduced number of poles per kilometer. Disadvantages of steel include higher resistance and corrosion. Corrosion can be minimized by using galvanized conductor. These types of conductors are widely used with SWER systems to achieve higher spans.

4.4.4 Pole-top Assembly

Pole-top assembly includes insulators, cross arms and bolts and its cost is relatively low. Use of pin insulators rather than suspension insulators can reduce insulator cost. The required shoe support for the line, and the hardware required to attach this assembly tothe crossarm are more expensive for suspension insulators than pin insulators. Figure 4.3 shows the different between traditional and new pole-top assemblies.

Figure 4.3 Traditional design (L) and new design(R) of pole top assemblies

4.4.5 Line Configuration

As discussed earlier, most of the distribution systems inthe rural areas of African countries are generally use three phase system. This is because of the earlier practice found in urban areas which were the first electrified. This practice is higher in countries influenced by the European colonizing powers, in which the distribution systems are primarily based on a three-phase three-wire configuration.

To serve small loads at far distance from the main line with the smallest acceptable conductor, the capacity of a conventional three-phase three-wire system is still too high. Using single-phase system with a larger size conductor is still less expensive than using the conventional three-phase system. Increasing the operating voltage is another solution.

4.4.6 Line Voltage

Reducing the size of the conductor will largely reduce the cost of the electrification system. But this will increase the resistance of the conductor resulting increased energy loss and increased voltage drop along the line. This will adversely affect to the power quality of consumers, especially those are living near the end of the line.

As a solution one can increase the line voltage and this will decrease the current required to caterthe same demand. By doubling line voltage line current can be reduced to half. This will reduce energy losses and percentage voltage drop to one quarter their former values. Now the current is also reduced, a smaller and less costly conductor can be used to meet the same demand under the same conditions.

But present world standards limit distribution voltages to about 35 kV to ensure the safety of the human and to reduce higher costs in fault coordination. Above this voltage, it is essential to use large post or suspension insulators similar to transmission lines. Distribution transformers at higher voltages arenot readily availableand also more expensive.

5 ALGORITHM DEVELOPMENT

To develop the algorithm, following actual network from Uganda (Figure 5.1) is selected. Initially it is necessary to divide the network into several branches and required to name them accordingly.

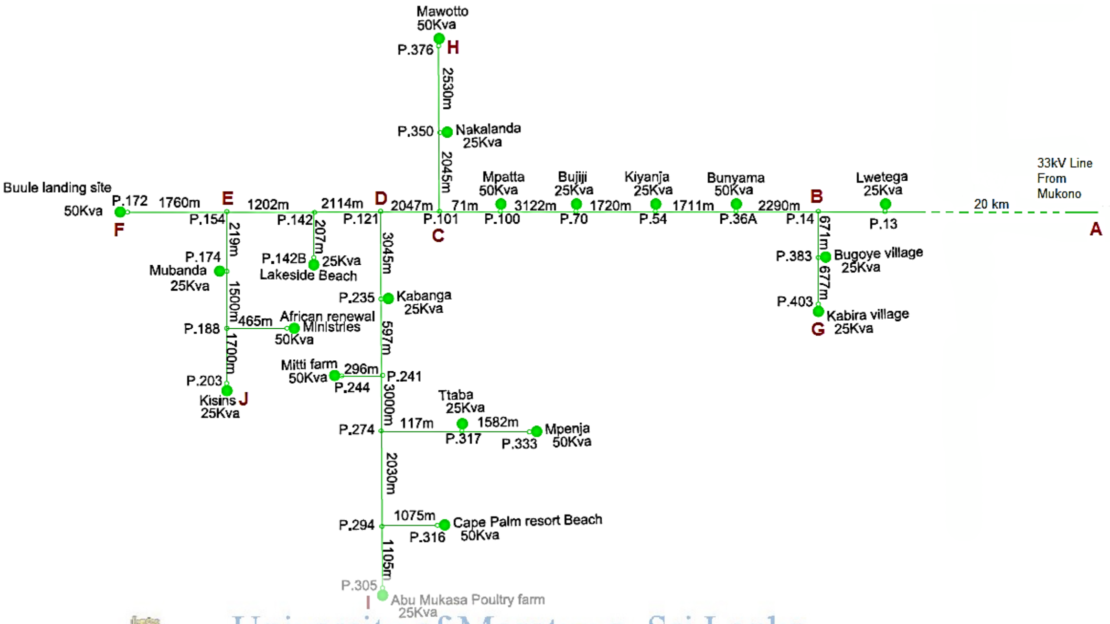


Figure 5.1Distribution Network in Uganda

As described in chapter 02 following details are needed for the calculation.

- Main system voltages, power factor
- Loads and Distances of each Section
- Technical specifications of available conductors
    - Cross sectional area and power transfer capability
    - Resistance per km
    - Reactance per km
- Power loss and Voltage drop factors (n Factor) for each section
- Acceptable Voltage drop and Power loss
- Special Constrains
    - Soil resistivity
    - Initial Voltage drop (At the beginning of the new network)
    - Annual Demand growth

For this example loads and distances of each section are given in Table 5.1.

Table 5.1Load and Distances of each Section

Section	Distance (km)	Load kVA	Load detail
AB	20	25	Towards B
BC	8.91	150	Towards C
CD	2.05	No loads	-
DE	3.52	25	Distributed
EF	1.76	50	Towards F
BG	1.35	50	Distributed
CH	4.85	75	Distributed
DI	12.85	225	Distributed
EJ	3.42	100	Distributed
Total	**58.44**	**700**	

From the above table it can be clearly seen that the main radial line of the network must be able to transfer 700 kVA. And it is given that the branch lines must be able to transfer their loads within 5 % voltage drop. Initial voltage drop of 33kV three phase line is given as 2% (at node A). Table 5.2 contains the required data of conductors which are selected as suitable conductors for designing the system. These conductors are widely used in rural networks of sub Saharan Africa and are readily available. Power factor is given as 0.85.

Table 5.2 Details of Available Conductors

Conductor	Cross Section (mm^2)	Rest/km (Ω/km)	Ract/km (Ω/km)	Current Rating (A)
Rabbit (ACSR50)	61.7	0.5426	0.3838	243
Dog (ACSR100)	118.5	0.2733	0.3633	390
Wolf (ACSR150)	194.4	0.187	0.3477	512

To calculate voltage drop and power loss,multiplying factor (n factor) for each section is needed. By observing the distribution patterns of each sections we can select the n factor. For example loads on the AB section is concentrates near B node.So it can be considered as a tail end load. By referring Table 3.1 we can find that the n factor for voltage drop and power loss (which is 1 for AB node). Table 5.3 gives the n factors for other sections in this network.

Table 5.3 Multiplying factors for voltage drop and power loss

Section	**Multiplying Factor**	
	Voltage drop (n_1)	**Power loss (n_2)**
AB	1	1
BC	1	1
CD	1	1
DE	0.75	0.625
EF	1	1
BG	0.75	0.625
CH	0.75	0.625
DI	0.6	0.44
EJ	0.667	0.519

Second step is to calculate the voltage drop and power loss of each and every system for each and every conductor. Calculation of Voltage drop and power loss for section AB for conductor ACSR100is given below.

5.1 Calculations for three-phase system

Length of section AB is 20 km and it should be able to transfer 700 kVA. Therefore current through the conductor can be calculated as,

Power Transferred $P = \sqrt{3}VI\cos\theta$

$$I = \frac{P}{\sqrt{3}V\cos\theta}$$

$$I = \frac{700\ kVA}{\sqrt{3} \times 33kV}$$

$$I = 12.25A$$

Per unit Voltage Drop

$$\frac{\Delta V}{V} = \frac{PL}{V^2}(r + x\tan\theta) \times n_1$$

$$\frac{\Delta V}{V} = \frac{700 \times 10^3 \times 0.85 \times 20}{33000^2}(0.27 + 0.36 \times 0.62) \times 100\%$$

$$\frac{\Delta V}{V} = 0.54\%$$

Power Loss$\Delta P = 3I^2 rL \times n_2$

$$\Delta P = 3 \times 12.25^2 \times 0.27 \times 20 \times 1 = 2.43kW$$

$$\frac{\Delta P}{P} = \frac{2.43}{(700 \times 0.85)} \times 100 = 0.41\%$$

Table 5.4 gives the voltage drop and power loss of all the sections for three phase system using ACSR100 conductor.

Table 5.4 Voltage drop and power loss for three phase system

Section	**Length (km)**	**Load (kVA)**	**Current (A)**	**Voltage Drop (%)**	**Power Loss (%)**
AB	20	700	12.25	0.54	0.41
BC	8.91	625	10.93	0.13	0.07
CD	2.05	400	7	0.03	0.02
DE	3.52	175	3.06	0.02	0.01
EF	1.76	50	0.87	0.00	0.00
BG	1.35	50	0.87	0.00	0.00
CH	4.58	75	1.31	0.01	0.01
DI	12.85	225	3.94	0.07	0.04
EJ	3.42	100	1.75	0.01	0.01

5.2 Calculations for two phase system

Length of section AB is 20 km and it should be able to transfer 700 kVA. Therefore current through the conductor can be calculated as, Power Transferred $P = VI\cos\theta$

$$I = \frac{P}{VI\cos\theta}$$

$$I = \frac{700\ kVA}{33kV}$$

$$\underline{\underline{I = 21.21A}}$$

Per unit Voltage Drop

$$\frac{\Delta V}{V} = \frac{2PL}{V^2}(r + x\tan\theta) \times n_1$$

$$\frac{\Delta V}{V} = \frac{2 \times 700 \times 10^3 \times 0.85 \times 20}{33000^2}(0.27 + 0.36 \times 0.62) \times 100\%$$

$$\frac{\Delta V}{V} = 1.07\%$$

Power Loss

$$\Delta P = 2I^2 rL \times n_2$$

$$\Delta P = 2 \times 21.21^2 \times 0.27 \times 20 \times 1 = 4.86kW$$

$$\frac{\Delta P}{P} = \frac{4.86}{(700 \times 0.85)} \times 100 = 0.82\%$$

Table No.5.5 gives the voltage drop and power loss of all the sections for two phase system using ACSR100 conductor.

Table 5.5Voltage drop and power loss for two phase system

Section	**Length**	**Load**	**Current**	**Voltage**	**Power Loss**

	(km)	(kVA)	(A)	Drop (%)	(%)
AB	20	700	21.21	1.07	0.82
BC	8.91	625	18.94	0.26	0.14
CD	2.05	400	12.12	0.06	0.05
DE	3.52	175	5.30	0.04	0.02
EF	1.76	50	1.52	0.01	0.01
BG	1.35	50	1.52	0.00	0.00
CH	4.58	75	2.27	0.02	0.01
DI	12.85	225	6.82	0.14	0.08
EJ	3.42	100	3.03	0.02	0.01

5.3 Calculations for single phase system

Length of section AB is 20 km and it should be able to transfer 700 kVA. Therefore current through the conductor can be calculated as,

Power Transferred $P = VI\cos\theta$

$$I = \frac{P}{VI\cos\theta}$$

$$I = \frac{700\ kVA}{\left(\frac{33}{\sqrt{3}}\right)kV}$$

$$\underline{\underline{I = 36.74A}}$$

Per unit Voltage Drop

$$\frac{\Delta V}{V} = \frac{2PL}{V^2}(r + x\tan\theta) \times n_1$$

$$\frac{\Delta V}{V} = \frac{2 \times 700 \times 10^3 \times 0.85 \times 20}{\left(\frac{33000}{\sqrt{3}}\right)^2}(0.27 + 0.36 \times 0.62) \times 100\%$$

$$\frac{\Delta V}{V} = 3.21\%$$

Power Loss

$$\Delta P = 2I^2rL \times n_2$$

$$\Delta P = 2 \times 36.74^2 \times 0.27 \times 20 \times 1 = 14.58kW$$

$$\frac{\Delta P}{P} = \frac{14.58}{(700 \times 0.85)} \times 100 = 2.49\%$$

Table No.5.6 gives the voltage drop and power loss of all the sections for single phase system using ACSR100 conductor.

Table 5.6Voltage drop and power loss for single phase system

Section	**Length (km)**	**Load (kVA)**	**Current (A)**	**Voltage Drop (%)**	**Power Loss (%)**
AB	20	700	36.74	3.21	2.49
BC	8.91	625	32.77	0.78	0.43
CD	2.05	400	20.97	0.19	0.14
DE	3.52	175	9.17	0.11	0.07
EF	1.76	50	2.62	0.02	0.02
BG	1.35	50	2.62	0.01	0.01
CH	4.58	75	3.93	0.06	0.04
DI	12.85	225	11.80	0.41	0.22
EJ	3.42	100	5.24	0.05	0.03

5.4 Calculations for SWER system

Calculation of reactance(x_1) per unit length for ACSR100 conductor

$x_1 = A + B$; Where A is the self inductance and B is the mutual inductance of the conductor

$$A = 0.1446 \log_{10} \frac{1}{GMR}$$

$$GMR = re^{-\frac{1}{4}} = 0.7788r = 0.7788 \times \sqrt{\frac{61.7}{3.142}} = 3.45m$$

$A = 0.1446 \log_{10} \frac{1}{0.00345} = 0.356\Omega/\text{km}$

Here GMD is referred as the depth of return path and;

$GMD = 93 \times \sqrt{\rho}$; Where ρ is soil resistivity in Ωmand for average soils it is about 250 Ωm.

$$GMD = 93 \times \sqrt{250} = 1470\, m$$

$B = 0.1446 \log_{10} GMD$

$B = 0.1446 \log_{10} 1470 = 0.4579\Omega/\text{km}$

$x_1 = 0.356 + 0.4579 = 0.8139\ \Omega/\text{km}$

For this example earth resistance for return path is taken as 15 Ω.

Power Transferred $P = VI \cos\theta$

$I = \frac{P}{VI \cos\theta}$

$I = \frac{700\ kVA}{\left(\frac{33}{\sqrt{3}}\right) kV}$

$\underline{\underline{I = 36.74A}}$

Per unit voltage drop

$\Delta V = 2IL(r \cos\theta + x_1 \sin\theta)n_1 + RIn_1$

$\Delta V = 2 \times 36.74 \times 20 \times (0.27 \times 0.85 + 0.81 \times 0.53) \times 1 + 15 \times 36.74 \times 1$

$\Delta V = 1519.27\, V$

$\frac{\Delta V}{V} = \frac{1519.27}{\left(\frac{33000}{\sqrt{3}}\right)} \times 100 = 7.97\%$

Power Loss

$$\Delta P = I^2 rL \times n_2 + I^2 R$$

$$\Delta P = 36.74^2 \times 0.27 \times 20 \times 1 + 36.74^2 \times 15 = 27.53kW$$

$$\frac{\Delta P}{P} = \frac{27.53}{(700 \times 0.85)} \times 100 = 4.63\%$$

Table 5.7 gives the voltage drop and power loss of all the sections for SWER system using ACSR100 conductor.

Table 5.7Voltage drop and power loss for SWER system

Section	**Length (km)**	**Load (kVA)**	**Current (A)**	**Voltage Drop (%)**	**Power Loss (%)**
AB	20	700	36.74	7.97	4.63
BC	8.91	625	32.77	2.72	3.25
CD	2.05	400	20.97	1.94	2.01
DE	3.52	175	9.17	0.70	0.88
EF	1.76	50	2.62	0.24	0.25
BG	1.35	50	2.62	0.17	0.25
CH	4.58	75	3.93	0.32	0.38
DI	12.85	225	11.80	1.17	1.20
EJ	3.42	100	5.24	0.36	0.50

After calculating voltage drop and power loss for every section, using all four technologies,network developing process can be started. Following is a brief description on how to traverse through the network while assigning the appropriate technology. Previous example is used to demonstrate the process.

First section of the network is AB. At the beginning the lowest cost technology is assigned for AB section. In this example it’s SWER. But from Table No.4.7, voltage drop percentage at node B is 7.97% which is not in the acceptable limit (5%). So we have to go for the next low cost technology. From Table No.4.6, Voltage drop percentage for single-phase two-wire system is 3.21% which is in acceptable limits.

So initially single-phase two-wire system is assign for AB section. When traversing through the main radial line, next section will be BC.

As stated earlier, the lowest cost option which is SWER is assign for BC section. Voltage drop for that section is 2.72% but the total voltage drop at node C will be 5.93% and it is higher than the 5%. So we can select next low cost option and now the total voltage drop will be 3.99% and it is acceptable. So we assign Single phase two wire system for BC. Then we can move on to our next node which is CD.

Same calculation can be applied to CD and one can found that single-phase two-wire system is possible with a voltage drop of4.18%. Next section is DE. For DE, SWER is possible with a voltage drop of 4.88%.

When traversing through the network there will be a situation that the selected technology for previous section is not viable. For example, if single-phase two-wire system is selected for section DE, after the DE section single-phase two-wire technology or SWER are the only options. Problem arises when the line end voltage of EF is greater than 5%. Then advancing the technology of previous node is essential. The iterative nature of this calculation is complex and time consuming. Therefore following algorithm is developed to simplify the calculations.

5.5 Flow Chart

To simplify the complex nature of the calculation a simplified algorithm is developed. Figure 5.2 shows the developed algorithm as a Flow diagram.

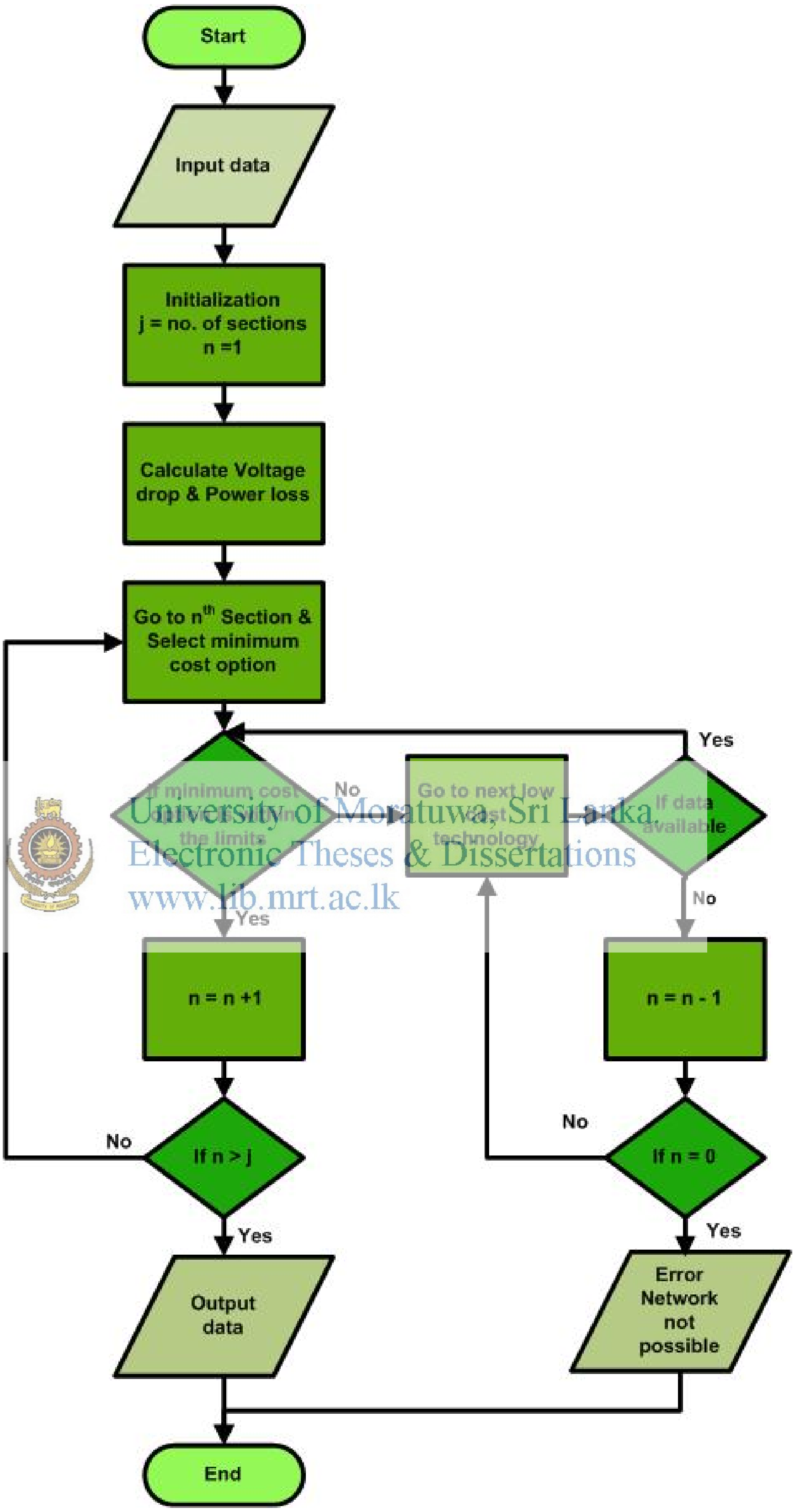


Figure 5.2Algorithm flow diagram

As shown in the above flow diagram initially it is needed to input data of the required network. This includes main system voltages, power factor and power transfer capability, loads and distances of each section, technical specifications of available conductors, power loss and voltage drop factors (n Factor) for each section, acceptable voltage drop and power loss, annual demand growth, soil resistivity and initial voltage drop at the beginning of the network.

Two variables (n, j) are used to traverse through the network and to terminate the process. Variable j is used to store the number of sections in the network and variable n is used to keep the value of current section. So the initial value for n is1. As the next step algorithm will calculate the voltage drop and line losses of every node. Then it will go to n^{th} section and select the minimum available cost option for n^{th} section. Initially n is 1 so algorithm will assign lowest cost technology for section 1. Next it will check whether this cost option is within the required constrains. If the result is true it will increase the value of n by1 to go to next section.

But if it is not in required constrains it will go to next low cost technology and will check for data availability. If data available it will again check whether they are within limits. If data is not available it will go to previous section by reducing the value of n by 1. But sometimes value of n may be 1. That means we are in the first node. Algorithm will identify this and will give an error message saying “Network Not Possible”. If this problem arises it is recommended to use higher capacity conductor for constructing the network

The algorithm will traverse through each and every section in the above manner and when n > j, that is when all the sections are filled it will give the output table. Final output table of the previous example is shown in Table 5.8.

Table 5.8 Output table

Section/ Node	**Load (kVA)**	**Distance (km)**	**Load Type**	**System Selected**	**PU Voltage Drop %**	**Loss (kW)**
A					2	
AB	700	20	End	3-Ph	0.55	2.46
B					2.55	
BC	625	8.91	End	S-Ph	0.78	0.43
C					3.33	
CD	400	2.05	End	S-Ph	0.19	0.14
D					3.52	
DE	175	3.52	Distributed	SWER	0.70	0.88
E					4.22	
EF	50	1.76	End	SWER	0.24	0.25
F					4.46	
BG	50	1.35	Distributed	SWER	0.17	0.25
G					2.72	
CH	75	4.58	Distributed	SWER	0.32	0.38
H					3.65	
DI	225	12.85	Distributed	SWER	4.69	1.20
I					3.93	
EJ	100	3.42	Distributed	SWER	0.36	0.50
J					4.58	
					Total system loss	**6.94**

Optimized diagram for the above network is shown in Figure 5.3.

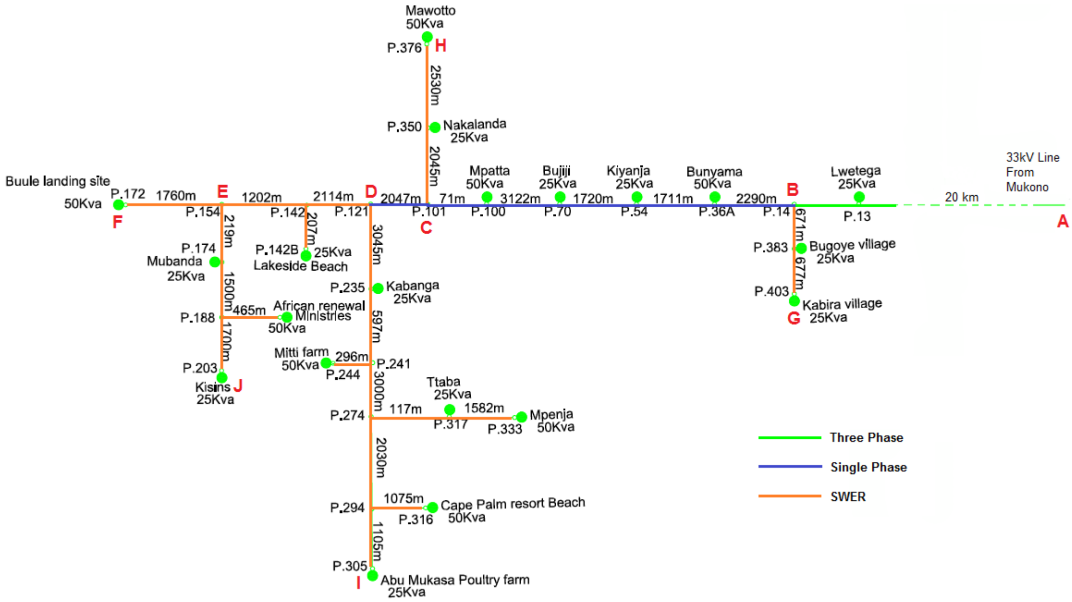


Figure 5.3Optimized Network

5.6 Cost Reduction

This network was originally designed with three phase three wire system. Cost figures in Table 4.2 are used for calculations.

Total length of the network = 58.44 km

Cost for unit length = 13 000 USD/km

Total approximated cost = 58.44 x 13,000 USD

= 7, 59,720 USD

If the network is designed using the optimization algorithm cost will be following.

Three phase three wire length = 20 km

Cost for three phase three wire = 20 x 13, 000 USD

= 2, 60,000 USD

Single-phase two-wire length = 10.96 km

Cost for Single Phase two wire = 10.96 x 8,600 USD

= 94,256 USD

SWER length = 24.48 km

Cost for SWER = 24.48 x 5, 200 USD

= 1, 27,296 USD

Total cost = 2, 60,000 + 94,256 + 1, 27,296 USD

= 4, 81,552 USD

Cost Saving percentage = (7, 59,720 - 4, 81,552) x 100 / 7, 59,720

= 36.6 %

For this network cost saving is about 36.6% which is about one third cost saving from the initial network model. Therefore by using this algorithm about one third of the cost can be reduced.

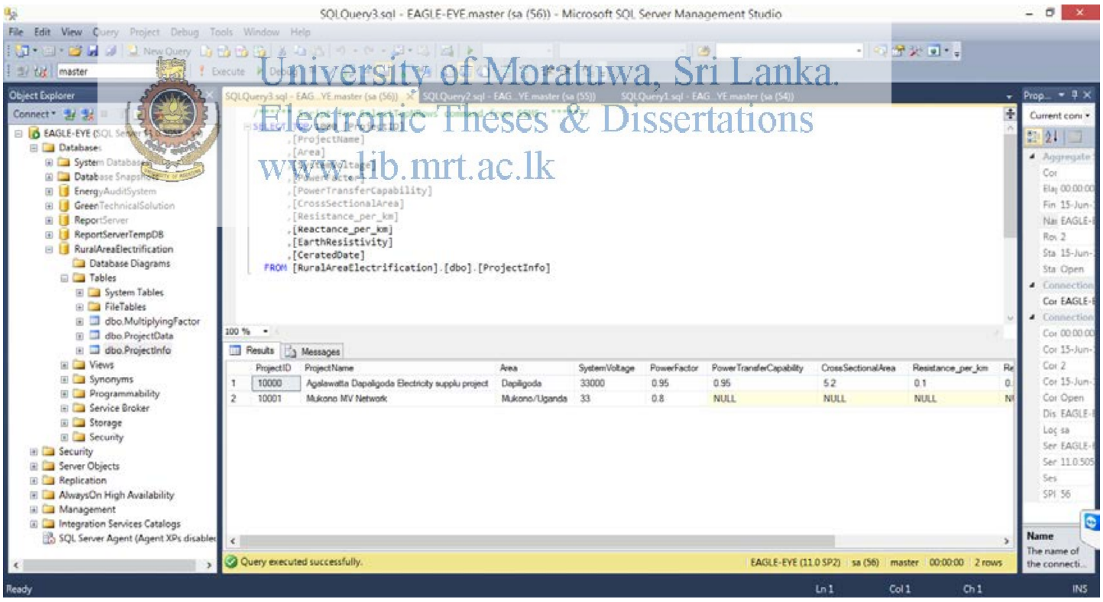
6 SOFTWARE DEVELOPMENT

To develop the software tool with GUI interfaces C# language is used. This is a desktop application which runs only on Windows operating system. System requirements to run this application are as follows.

- Operating System - Windows XP or higher
- Processor - Intel Pentium IV or higher
- Memory - 512 MB or higher
- Hard Disk Space - 20 GB

6.1 Data Base Structure

To store network data,three data bases which created using QSL were used. Data base shown in Figure 6.1 is used to store the network details of a new project. It includes project name, area, system voltage, power factor, conductor details and the earth resistivity. New entry will be created when starting a new project.



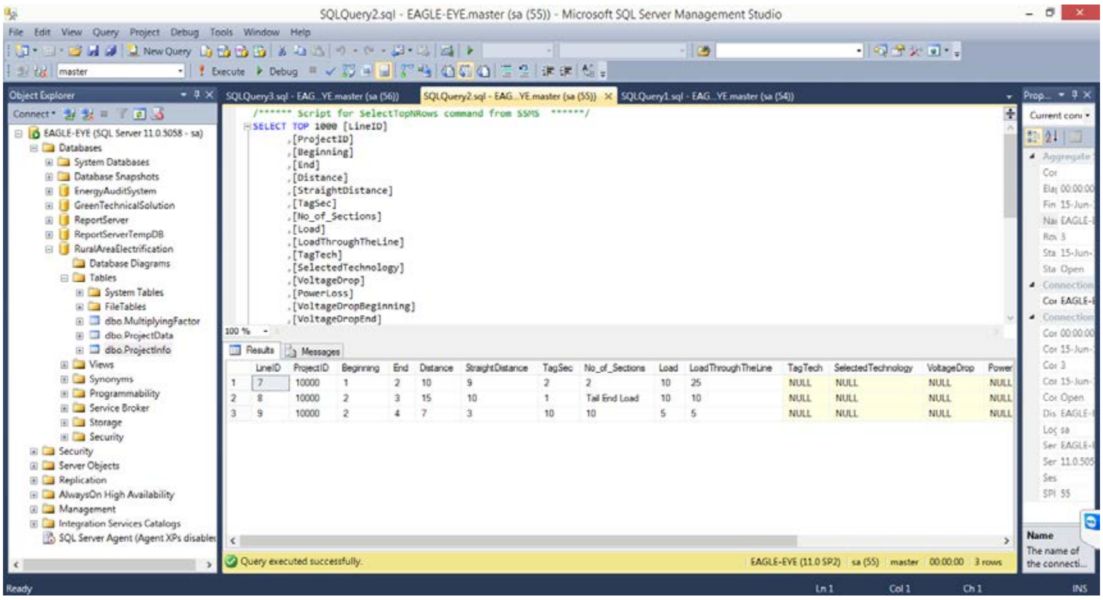
```
/****** Script for SelectTopNRows command from SSMS ******/
SELECT TOP 1000 [ProjectID]
      ,[ProjectName]
      ,[Area]
      ,[SystemVoltage]
      ,[PowerFactor]
      ,[PowerTransferCapability]
      ,[CrossSectionalArea]
      ,[Resistance_per_km]
      ,[Reactance_per_km]
      ,[EarthResistivity]
      ,[CeratedDate]
  FROM [RuralAreaElectrification].[dbo].[ProjectInfo]
```

	ProjectID	ProjectName	Area	SystemVoltage	PowerFactor	PowerTransferCapability	CrossSectionalArea	Resistance_per_km
1	10000	Agalawatta Dapaligoda Electricity supplu project	Dapiligoda	33000	0.95	0.95	5.2	0.1
2	10001	Mukono MV Network	Mukono/Uganda	33	0.8	NULL	NULL	NULL

Query executed successfully.

Figure 6.1Data base structure for a new project

Database shown in figure 6.2 is used to store data of sections in a single network. This will contain all the fields in input and output table of the project which includes beginning node, end node, distance, straight distance, load, selected technology, voltage drop and the power loss.



```
/****** Script for SelectTopNRows command from SSMS  ******/
SELECT TOP 1000 [LineID]
      ,[ProjectID]
      ,[Beginning]
      ,[End]
      ,[Distance]
      ,[StraightDistance]
      ,[TagSec]
      ,[No_of_Sections]
      ,[Load]
      ,[LoadThroughTheLine]
      ,[TagTech]
      ,[SelectedTechnology]
      ,[VoltageDrop]
      ,[PowerLoss]
      ,[VoltageDropBeginning]
      ,[VoltageDropEnd]
```

	LineID	ProjectID	Beginning	End	Distance	StraightDistance	TagSec	No_of_Sections	Load	LoadThroughTheLine	TagTech	SelectedTechnology	VoltageDrop	Power
1	7	10000	1	2	10	9	2	2	10	25	NULL	NULL	NULL	NULL
2	8	10000	2	3	15	10	1	Tail End Load	10	10	NULL	NULL	NULL	NULL
3	9	10000	2	4	7	3	10	10	5	5	NULL	NULL	NULL	NULL

Query executed successfully.

Figure 6.2 Section Details Data base structure

Figure 6.3 shows the initial interface of the software. Menu bar is equipped with File, Edit, Build, Tools and Help functions.

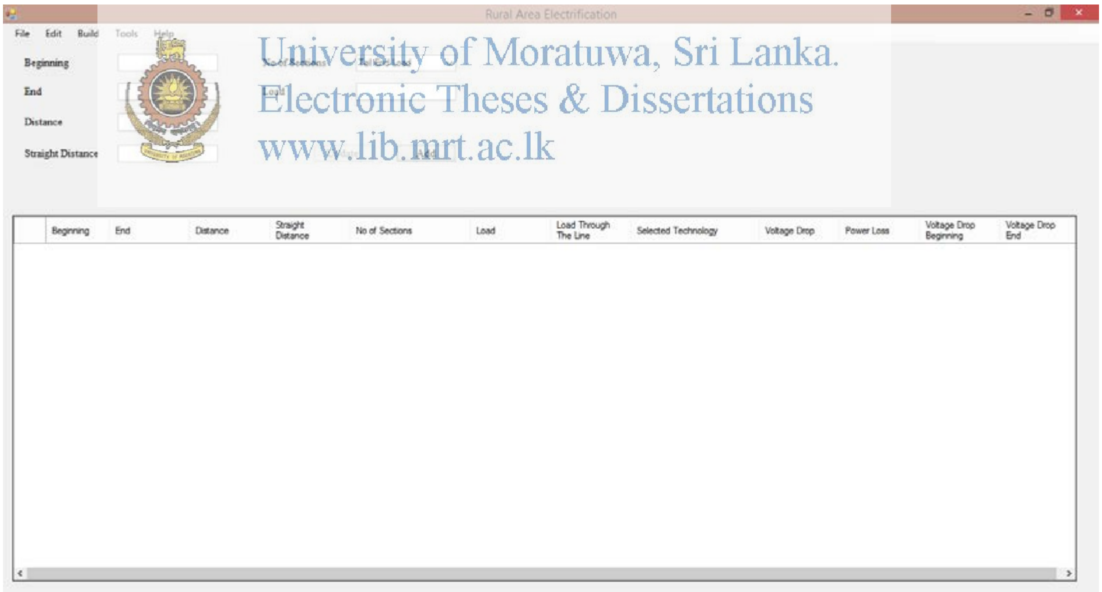
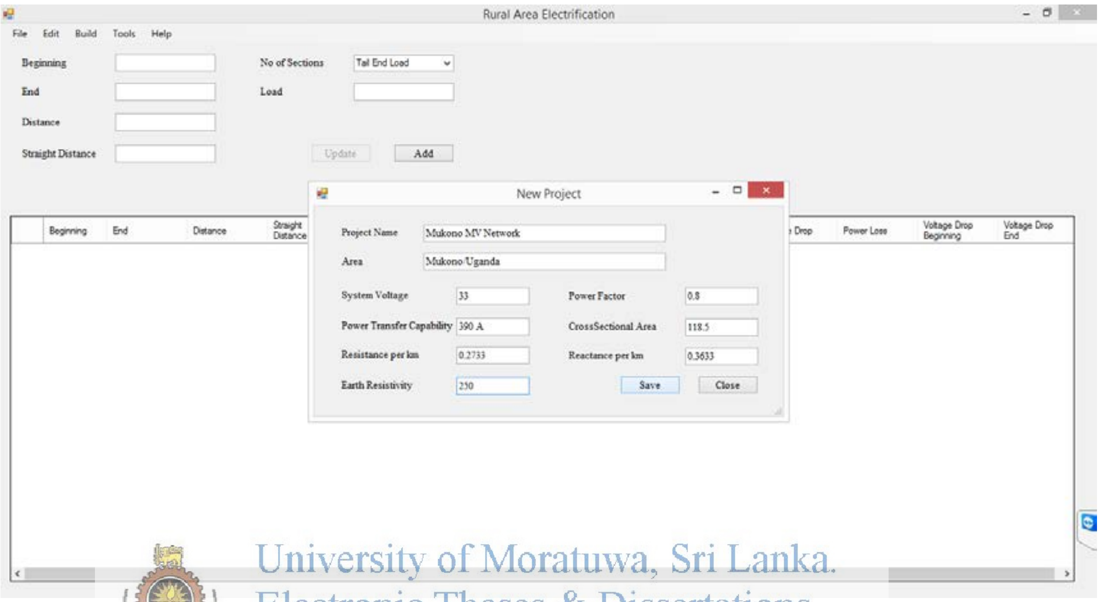


Figure 6.3Initial Interface

File menu has five sub-menus namely New Project, Open Project, Edit Project, Save and Save As. Edit menu is mainly focus on editing the line parameters of already opened project. It has Select All, Edit Line, Clear, Clear All, Remove, Remove All sub-menus. Build function is used to run the algorithm in already opened project. It has two sub menus, Build and Build and simulate.

6.2 Stating a new project

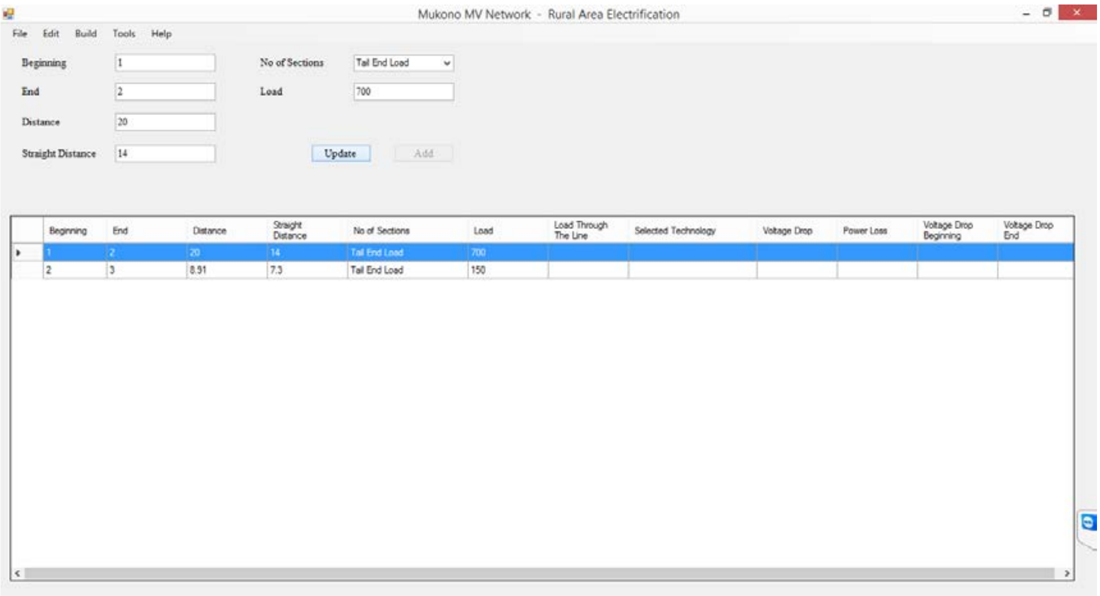
Starting a new project can be done by selecting File →New Project. Then the window in Figure 6.4 will appear.



Project Name: Mukono MV Network
Area: Mukono Uganda
System Voltage: 33
Power Factor: 0.8
Power Transfer Capability: 390 A
CrossSectional Area: 118.5
Resistance per km: 0.2733
Reactance per km: 0.3633
Earth Resistivity: 250

Figure 6.4 New project

Project name, area, system voltage, power factor, conductor details and the earth resistivity are specific to a certain project. After inserting above details to the new project window, input table can be obtained by pressing the save button. Figure 6.5 shows the data input window. To input data into the input table, form in upper section of the window can be used. As showing in Figure 6.5, by pressing “Update” button inserted data can be transferred to the input table.



Beginning 1

End 2

Distance 20

Straight Distance 14

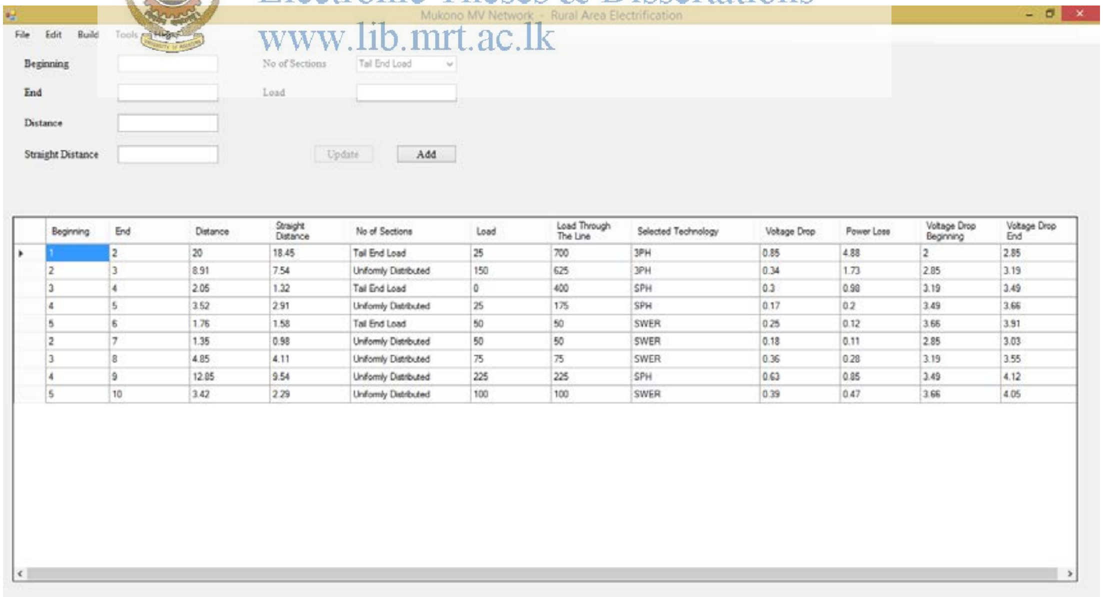
No of Sections Tail End Load

Load 700

Beginning	End	Distance	Straight Distance	No of Sections	Load	Load Through The Line	Selected Technology	Voltage Drop	Power Loss	Voltage Drop Beginning	Voltage Drop End
1	2	20	14	Tail End Load	700						
2	3	8.91	7.3	Tail End Load	150						

Figure 6.5 Data input window

After inserting the every section details to the window in Figure 6.5, output data table can be obtained by clicking Build →Build. The output table is shown in the Figure 6.6. Before building the project it is essential to save the inserted data. This can be done by clicking File → Save.



Beginning	End	Distance	Straight Distance	No of Sections	Load	Load Through The Line	Selected Technology	Voltage Drop	Power Loss	Voltage Drop Beginning	Voltage Drop End
1	2	20	18.45	Tail End Load	25	700	3PH	0.85	4.88	2	2.85
2	3	8.91	7.54	Uniformly Distributed	150	625	3PH	0.34	1.73	2.85	3.19
3	4	2.05	1.32	Tail End Load	0	400	SPH	0.3	0.98	3.19	3.49
4	5	3.52	2.91	Uniformly Distributed	25	175	SPH	0.17	0.2	3.49	3.66
5	6	1.76	1.58	Tail End Load	50	50	SWER	0.25	0.12	3.66	3.91
2	7	1.35	0.98	Uniformly Distributed	50	50	SWER	0.18	0.11	2.85	3.03
3	8	4.85	4.11	Uniformly Distributed	75	75	SWER	0.36	0.28	3.19	3.55
4	9	12.85	9.54	Uniformly Distributed	225	225	SPH	0.63	0.85	3.49	4.12
5	10	3.42	2.29	Uniformly Distributed	100	100	SWER	0.39	0.47	3.66	4.05

Figure 6.6 Output Window

6.3 Edit Project

Sometimes it is necessary to edit some details of a project. This alteration may be in the main project fields or in the section details. Edit function in the menu bar facilitates all those requirements by providing several sub-options which are required for editing. (Figure 6.7)

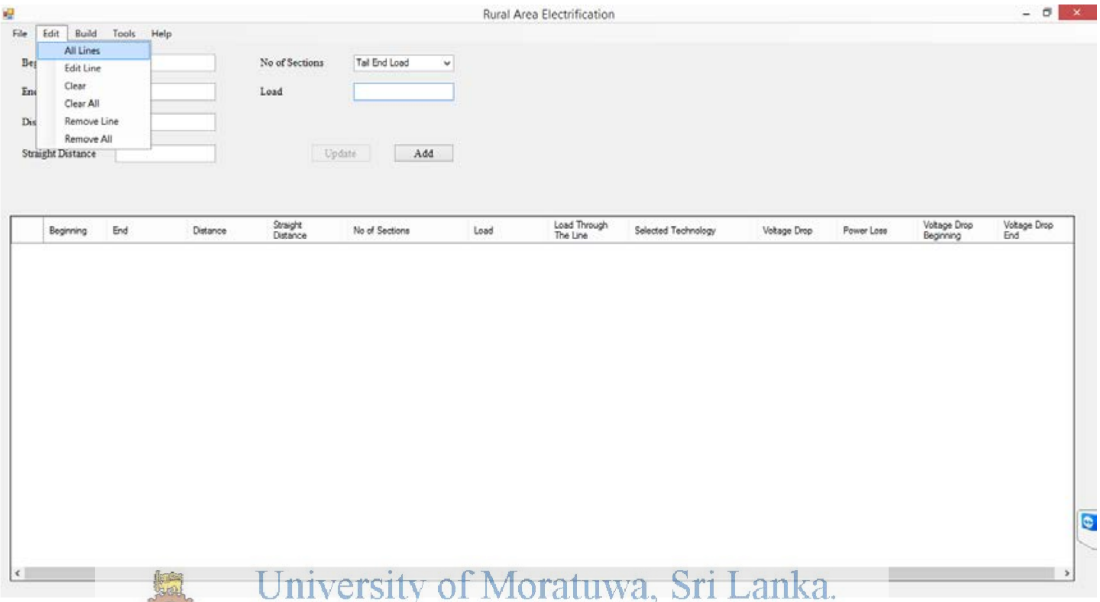


Figure 6.7 Edit Sub-menu

7 CLOSURE

7.1 Conclusion

The challenges of rural electrification still remain considerable, especially in Sub-Saharan Africa. The most significant reason for this problem is identified as the high initial cost due to improper planning and lack of knowledge on low cost distribution systems. Many low cast technologies were introduced but companies resort to conventional technology for developing the distribution network. Therefore, the main objective of this project was to combine several low cost technologies to obtain the optimized low cost network for rural distribution systems.

For this project four widely used technologies were selected, namely Single Wire Earth Return System, Single-phase two-wire System, Two-phase Two-wire System and Shield Wire System. Shield wire system was detached from further consideration because it is involved only in the design stage of a transmission line and is not very likely to occur. The three other technologies considered were evaluated for their technical and economical details.

In addition to considering the economic feasibility of selected three systems, several novel approaches were discussed to reduce the cost of rural distribution network further. Pole, conductor, pole top assembly, line configuration and line voltage are some key elements in a distribution network. Reducing their individual costs will certainly reduce the total cost of the system.

When selecting a technology, both economic and technical feasibility should be considered. One cannot select SWER only because of its low initial cost. There are several technical constraints incorporated with SWER. Therefore, constraints in both aspects were considered and embedded to the developed algorithm.

To check whether the designed line is technically suited, calculating the power loss and line end voltage drop is essential. When it comes to a line with several nodes, it is somewhat difficult to calculate those factors due to complicated calculations involved. To simplify this task a multiplying factor was introduced to calculated voltage drop and power loss so one can calculate those values more easily with minimum deviation from the exact solution.

Developed algorithm was tested using actual and hypothetical networks. One such example, an actual network in Uganda, is detailed in the thesis. The test results conclude that by using this optimization method, about 30 % cost saving can be achieved.

The algorithm was further enhanced by developing a software tool with GUI interfaces to represent it in more user-friendly manner. The software was developed using C# language and Data bases were created using SQL data base.

7.2 Future Developments

7.2.1 Practical Implementation

Developed algorithm only concerns on the theoretical aspects of developing a distribution network. But when it comes to practical situation, several other issues may arise. For example severe load imbalances may appear in the MV network due to the excess use of single phase power and this will leads to higher outage rates. Therefore additional analysis is needed before implementing the developed low cost network.

7.2.2 Optimizing of distribution transformers

In rural areas houses are scattered in a very large area. Using a single large distribution transformer may cause higher loss due to very long low voltage lines from transformer to rural houses. Rather than going for a single large transformer one can use several single-phase transformers for several houses which are in closer proximity. By this way huge losses in lengthy low voltage lines can be minimized.

7.2.3 Software Enhancements

Current software tool is incapable of drawing the network with GPS coordinates. If this software tool can be enhanced with a drawing facility, it would be more user-friendly and may take less time for manual data entry operation. It may also help to observe the network at its realistic condition.

References

[1] G. Bakkabulindi, “Planning Models for Single Earth Return Power Distribution”, Royal Institute of Technology, Stockholm, Sweden 2012.

[2] R. Karhammar, “Sub-Saharan Africa: Introducing low cost methods in electricity distribution networks.” Technical Report 104/06, Energy Sector Management Assistance Program (ESMAP), October 2006.

[3] N. Hosseinzadeh, J. Rattray, "Economics of upgrading SWER distribution systems", Power Engineering Conference, AUPEC '08, Australasian Universities, On page(s): 1 - 7, Volume: Issue: 14-17 Dec. 2008

[4] C. W. Holland. Single wire earth return for remote rural distribution - reducing costs and improving reliability, Technical report

[5] T. R. Brooking, N. Janse van Rensburg, and R. Fourie, “The improved utilisation of existing rural networks with the use of intermediate voltage and single wire earth return systems”, In AFRICON '92 Proceedings., 3rd AFRICON Conference, pages 228 –234, September 1992.

[6] J. Taylor and T. Effeny, “Service experiences with single wire earth return distribution in central Queensland”, In Proc. 7th CEPSI, 1988.

[7] P. J. Wolfs, “Capacity improvements for rural single wire earth return systems” In Proc. Power Engineering Conference, IPEC 2005, The 7th International, pages 1–8, 29 2005-Dec. 2 2005.

[8] N. Hosseinzadeh, J. E. Mayer, and P. J. Wolfs, 2011, “Rural Single Wire Earth Return distribution networks – Associated problems and cost-effective solutions”, Electrical Power and Energy Systems, vol.33, pp. 159-170

[9] G. Bakkabulindi, M. R. Hesamzadeh, M. Amelin, and I. P. Da Silva, "Optimization Models for Planning Rural Single Wire Earth Return Distribution networks",submitted to the journal of IEEE Transactions on Power Delivery, September 2012

[10] F. Iliceto, E. Cinieri, F.M.Gatta - "Rural Electrification of Developing Countries Using the Insulated Shield Wires Lines of HV lines. New Design Criteria and Operation Experience", CIGRE paper 37/38-03, 1994 Session, Paris

[11] F. Iliceto, Cinieri E., L. C. Hayford, G. Dokyi-"New Concepts on MV Distribution from Insulated Shield Wires of HV lines. Operation results of an experimental system and Applications in Ghana", IEEE Transactions on Power Delivery, Vol.4, N°4, October 1989, page. 2130-44

[12] *High Voltage Earth Return Distribution for Rural Areas*, 4th ed., The Electricity Authority of New South Wales, Australia, 1978, pp. 03–21.

[13] N. R. Karki, "Reducing the cost of Rural Electrification: A key to improve the quality of life in rural areas in developing countries", IEEE 2004 International Conference on Power System Technology - POWERCON 2004 Singapore

[14] G. Bakkabulindi, M. R. Hesamzadeh, M. Amelin, and I. P. Da Silva, “Planning algorithm for single wire earth return power distribution systems”, In Proc. IEEE Power and Energy Society General Meeting, San Diego, CA, July 22–26, 2012.

[15] N. Hosseinzadeh, P. Wolfs, "Distribution of Electrical Power to Rural Areas-Australian Experience and Implementation Possibility in Developing Countries" Central Queens land University, Australia

[16] *Reducing the Cost of Grid Extensionfor Rural Electrification*, NRECA International, Ltd., ESM227, February 2000.

[17] *Paving the Way for the Mediterranean Solar Plan*, The European Neighbourhood and Partnership Instrument (ENPI), ENPI 2010/248-486, October 2012.

[18] *Indicative costs for replacing SWER lines*, Department of Primary Industries, Melbourne, Australia, August 2009.

[19] J.E.Ramos,V. A. Pires, A.Piantini, P. F. Obase, A. S. Neto, T. O. de Carvalho, P. R. B. de Oliveira, "Analysis of the effect of lightning on the energized shield wire

line technology", Lightning Protection (XI SIPDA), 2011 International Symposium on, On page(s): 216 – 220

[20] *Guide for HV SWER Systems*, Electricity Engineers Association of NZ, October 2010.

[21] *Guides for Electric Cooperative Development and Rural Electrification*, Module 7, NRECA International, Ltd., 2011